Enhance Human-Computer Interaction through Wearable Haptic Interface Design

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Abstract

Advancements in wearable computing have led to the introduction of haptic user interfaces, providing touch feedback through electronic devices such as smartwatches and head-mounted displays. These interfaces have versatile applications, facilitating remote communication, entertainment, and internet browsing. However, existing interfaces often trigger a single haptic sensation on human skin using rigid actuators, neglecting the potential of utilizing different types of tactile sensations. This thesis proposes that by designing haptic interfaces targeting both discriminative and affective touch perceptions, wearable and mixed-reality haptic interfaces can be significantly improved. The main contributions include:

Three-Dimensional-Printable Soft On-Skin Actuators for Wearable Computing: The thesis introduces FLECTILE, a 3D-printable, skin-attachable electromagnetic actuator. This actuator employs soft, stretchable, and biocompatible materials, providing wearability on various body locations and enabling directed interactions in diverse wearable computing scenarios.

Design of an On-Skin Interface Component with Multiple Tactile Stimuli: In this thesis, DragTapVib, a haptic actuator capable of producing three tactile sensations based on discriminative touch and affective touch - vibration, dragging, and tapping is described. The actuator allows for precise and expressive interactions on different body locations, enhancing the haptic experience in applications like on-skin notifications and gaming.

Investigate Affective Touch and Discriminative Touch as a New Pathway in Passive Haptic Learning: Previous studies in passive haptic learning (PHL) have yielded remarkably robust results and revealed great potentials with this technology. However, it is worth noting that previous studies have consistently utilized vibration as the primary signal for passive haptic learning. This thesis first proposes three wearable systems leveraging discriminative touch and affective touch - vibration, stroking, and tapping, respectively. Then, this thesis explores the potential of affective touch (stroking and tapping) in passive haptic learning, which has previously focused mainly on discriminative touch (vibration). The findings suggest that affective touch can be equally efficient and may offer additional benefits in the learning process.

Enhance User Experience through the Integration of Wearable Haptic Interfaces with Other Interaction Technologies: This thesis investigates the integration of wearable haptic interfaces with other interaction technologies, such as visual and auditory feedback and mixed reality technologies, to enhance the overall user experience. By exploring these combinations, the thesis contributes to the advancement of haptic user interfaces and offers potential ways to enrich human interactions with technology through a diverse range of haptic sensations.

In conclusion, this thesis represents a significant step forward in the design and implementation of haptic user interfaces, envisioning a future where wearable computing systems offer multiple on-skin interactions and augment human physical, cognitive, and perceptual capabilities. By targeting both discriminative and affective touch perceptions, these haptic interfaces have the potential to revolutionize human-computer interaction and enhance how we interact with the real environment leveraging haptic technology in various application domains.

Zusammenfassung

Der Fortschritt im sogenannten tragbaren Komputersystem (wearable computing) führt zur Einführung der haptischen Benutzerschnittstellen, die über elektronische Geräte, beispielsweise Smartwatches, und am Kopf befestigte Displays eine haptische Rückmeldung an Benutzer geben. Diese Schnittstellen sind vielseitig einsetzbar und erleichtern die Kommunikation, Unterhaltung und das Surfen im Internet. Die aktuellen Schnittstellen, die oft durch einen steifen Aktuator erzeugt werden, können nur eine einzige haptische Rückmeldung an der Haut vom Benutzer geben. In diesem Fall wird es ignoriert, verschiedene Typen von der haptischen Rückmeldung zu generieren. Diese Dissertation stellt darauf hin, dass das tragbare Komputersystem und die mix-realisierte Benutzerschnittstelle durch Design der zwei Schnittstellen signifikant verbessert werden, die besonders für diskriminierende und affektive Haptik entwickelt werden. Hauptsächliche Beiträge umfassen folgende Aspekte:

Dreidimensionale, druckbare, weiche Aktuatoren im tragbaren Komputersystem: Diese Dissertation führt einen druckbaren elektromagnetischen Aktuator FLECTILE ein, der einfach durch 3D Drucker bei der Nutzung von einem weichen, dehnbaren, und biokompatibelen Material gedruckt werden kann. Deswegen könnte dieser gedruckte Aktuator auf vielen Köperstellen eingesetzt werden, um die Interaktion mit einer bestimmten Richtung in verschiedenen Szenarios, in denen das tragbare Komputersystem benutzt wird, zu ermöglichen.

Design von der an der Haut eingesetzten Schnittstellenkomponente mit multihaptischen Stimuli: Ein haptischer Aktutor, DragTapVib, wird hier vorgestellt. Drei haptische Rückmeldungen können durch DragTapVib, basierend auf diskriminierender und affektiver Haptik (Vibration, Ziehen und Klopfen), generiert werden. Dieser Aktuator kann nach den Bedürfnissen der verschiedenen Koeperstellen eingesetzt werden, sodass das haptische Erlebnis verbessert wird, wie zum Beispiel die Benachrichtigung beim Spielen einer Computerspiele.

Neuer Weg für das passive haptische Lernen (PHL): diskriminierende und affektive Haptik: Vorherige Erforschungen im PHL-Bereich waren erfolgreich und weisten das riesige Potential des passiven haptischen Lernens auf. Bemerkenswert ist, dass vorher nur Vibration als Hauptsignal von PHL galt. Aus diesem Grund werden in dieser Dissertation drei tragbare Komputersysteme (Vibration, Streicheln und Klopfen) auf der Basis von diskriminierender und affektiver Haptik erzeugt und weiter über ihr Potential diskutiert. Da konzentrierten die vorherigen Erforschungen sich nur auf diskriminierende

Haptik (Vibration). Schliesslich, die Forschungsergebnisse zeigen, dass affektive Haptik genau wie diskriminierende Haptik effektiv ist und Extra-Vorteile beim Lernprozess im Vergleich zu der diskriminierenden Haptik besitzt.

Verstärken des Benutzererlebnisses durch Integration der tragbaren haptischen Schnittstellen und anderer interaktiver Techniken: In dieser Dissertation wird über die Integration von tragbaren haptischen Schnittstellen und andere interaktive Techniken diskutiert, wie zum Beispiel, die Integration von visueller und akustischer Rückmeldung mit der mix-realisierten Technik, um das bessere Erlebnis an den Benutzer zu bringen. Die Erforschung solcher Kombinationen beschleunigt die Entwicklung der haptischen Benutzerschnittstelle und mehr potentielle Integrationsmethoden sind dabei angeboten.

Zum Schluss wird betont, dass das Design und die Implementierung der haptischen Benutzerschnittstellen in dieser Dissertation einen wichtigen Fortschritt machen. In der Zukunft, die tragbaren Komputersysteme bieten mehr andere Interaktionen an, um die körperlichen, kognitiven und perzeptiven Fähigkeiten zu verstärken. Durch die gezielte diskriminierende und affektive Haptik haben diese haptischen Schnittstellen das Potenzial, die Mensch-Computer-Interaktion zu revolutionieren und haptische Technologien zu nutzen, um die Art und Weise, wie wir mit der realen Welt interagieren, in verschiedenen Bereichen zu verstärken.

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Part I

INTRODUCTION AND FOUNDATIONS

1 Introduction

"Touch is communication on the most basic level. The need for touch is a necessity throughout our lives, from birth to death, which serves to sustain us emotionally and physically."

— Phyllis Davis, The Power of Touch [24]

From the dawn of humanity, the skin has been our conduit to the world—a vessel that carries the nuances of touch, warmth, and connection. In the era of digital landscapes and immersive experiences, the quest to translate the richness of tactile interactions into the domain of technology has captivated the imagination of researchers and innovators. Haptic user interfaces emerged as the bridges, the transducers, that have the power to make these intangible digital realms palpable, tangible, and intimately felt. The human skin, the largest body organ, plays a crucial role in perceiving different tactile stimuli (e.g. tapping [59, 94], stroking [41], dragging [36], stretch and squeeze [62] etc.) for our daily interactions with the environment. With the advancements in technology (e.g. the size and cost of the micro-controllers and hardware being smaller and cheaper), haptic user interfaces have been gradually introduced to enhance our sensory experiences, providing touch feedback through electronic devices. Meanwhile, this provides enormous opportunities to investigate how to design and develop haptic actuators and haptic interfaces to thoroughly utilize the various human senses of touch. However, the current haptic interfaces are limited in their ability to trigger only one on-skin sensation with a single device, using rigid structures, and often do not fully meet the user's usage scenarios and needs.

To this extent, this thesis presents a hypothesis that by designing haptic user interfaces using actuators that specifically target discriminative and affective touch perceptions, we can significantly improve wearable and mixed-reality haptic interfaces. This thesis embarked on an innovative exploration at the intersection of technology and tactile experiences. With the human skin serving as both a canvas and a gateway, this thesis seeks to: (1). design and investigate haptic actuators that generate a variety of stimuli on the human skin without requiring complex fabrication steps; (2). synthesize the haptic actuators into haptic interfaces and apply this in state-of-art passive haptic learning works; (3). enhance sensory experiences through the use of haptic user interfaces and other interaction technology.

1.1 Motivation and Aims

The desire to enhance human interaction with technology by harnessing the potential of haptic sensations is deep-rooted. In the increasingly digital world, the tactile dimension of human experiences often takes a backseat, limiting the richness and intuitiveness of human-machine interactions. The skin, our body's largest sensory organ, often goes unnoticed in our daily lives despite its vital role, which opens up exciting possibilities. By designing the on-skin haptic actuators more accessible and user-friendly, we aim to democratize their usage and promote their integration into various applications. In addition, we aim to expand beyond the conventional reliance on discriminative touch as the predominant human sensory sensation. Our focus lies in the design and advancement of haptic interfaces that incorporate both discriminative touch and affective touch. This approach seeks to enhance haptic experiences, rendering them more organic, immersive, and emotionally engaging [66]. Furthermore, the exploration of how haptic interfaces can harmoniously combine with other interaction technologies, such as visual and auditory feedback, provides users with holistic and captivating experiences. We strive to create a seamless fusion of sensory modalities that enhances overall user satisfaction. This thesis seeks to push the boundaries of haptic user interfaces, envisioning a future where technology not only engages human single sensation but does so in a more diverse and enriching manner.

1.2 Contribution

The main contributions of this thesis are as follows:

- **Three-Dimensional-Printable Soft On-Skin Actuators for Wearable Computing**

  Based on a design space for 3D-printed interactive devices, the first contribution is FLECTILE, a wearable 3D-printable, skin-attachable electromagnetic actuator. The main innovation of the actuator is the design of the 3D-printable soft electromagnetic inductor with 3D-planer helical coils made from soft, stretchable, and biocompatible materials. The actuator is fully elastomer-based and cheap. Moreover, the actuators could be manufactured in batch-size one rapidly using standard DIY equipment with the open-sourced instruction we provided. To ensure high wearability on various body locations, FLECTILE has a small and soft form factor that exhibits the potential to facilitate directed interaction and can be applied to a diverse array of wearable computing scenarios.

- **Design of an On-Skin Interface Component with Multiple Tactile Stimuli**

We contribute DragTapVib: a haptic actuator that could robustly produce three sensations relevant to the discriminative (vibration) and affective touch (dragging and tapping) respectively. This actuator is also based on the electromagnetic force, extending the electromagnetic actuator approach. We present the design, fabrication, and actuation mechanisms of our device, and provide open-sourced materials to the community of wearable computing. We identify the characteristics of stimuli, the participants' preferred locations, and detail on the user's perception and discrimination performances of three different stimuli. Based on the findings of quantitative user studies, we demonstrate this interaction technique in two application examples: on skin notification with the fusion of multiple information streams and enhance the gaming experience. DragTapVib allows for precise and expressive interactions on different body locations to produce a more natural and immersive haptic experience.

- **Investigate Affective Touch and Discriminative Touch as a New Pathway in Passive Haptic Learning**

  Passive haptic learning (PHL) is one approach to lower the barriers and costs to maintain a new skill. In this method, a user is able to acquire skills by receiving tactile stimulation without perceived attention. However, all previous research put much effort into using discriminative input, particularly vibration, as the tactile simulation. The utilization of affective touch such as stroking and tapping. remains largely unexplored within the field of PHL. Thus, our primary goal is to investigate the different performances when people use stroking, tapping, and vibration as learning stimuli in passive haptic learning respectively by conducting a series of user studies. To induce affective touch, we first engineer two wearable interfaces that render a soft stroking sensation and tapping on the user's fingers respectively. Then, we replicated the wearable interface that delivers vibration to the user's fingers based on prior research. The study indicated that the affective touches (stroking and tapping) could work as efficiently as the commonly used discriminative touch (vibration), and the affective stimuli may teach more notes to the participants. The results also give insights that the affective touch could offer a multitude of potentials to extend the perception of human reality and enable the users to benefit with the assistance of haptic devices.

- **Enhance User Experience through the Integration of Wearable Haptic Interfaces with Other Interaction Technologies**

  We investigate the effective integration of haptic interfaces with other interaction technologies, including visual (auditory) feedback and mixed reality technologies, to enhance the overall user experience. By exploring these combinations, we seek to contribute to the advancement of haptic user interfaces, offering the potential to enrich human interactions with technology through a diverse range of haptic sensations.

1.3 Publications

The following list gives an overview of the papers previously published at conferences in the field of human-computer interaction. Substantial portions of this dissertation were derived from the pertinent papers listed below and organized into a cohesive monograph structure.

- P1: **Likun Fang**, Tobias Röddiger, Hongye Sun, Norbert Willenbacher, Michael Beigl. *FLECTILE: 3D-printable soft actuators for wearable computing*. In Proceedings of the 2020 ACM International Symposium on Wearable Computers (*ACM ISWC'20*). ***Best paper award***.

- P2: **Likun Fang**, Timo Müller, Erik Pescara, Yiran Huang, Nikola Fischer, Michael Beigl. *Investigating Passive Haptic Learning of Piano Songs Using Three Tactile Sensations of Vibration, Stroking and Tapping*. In Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies, Vol. 7, No. 3. (*IMWUT*).

- P3: **Likun Fang**, Ting Zhu, Erik Pescara, Yiran Huang, Yexu Zhou, Michael Beigl. *DragTapVib: An On-Skin Electromagnetic Drag, Tap, and Vibration Actuator for Wearable Computing*. In Proceedings of the Augmented Humans International Conference (*ACM AHs'22*).

- P4: **Likun Fang**, Dominik Flohs, Erik Pescara, Ting Zhu, Michael Beigl. *Investigation of On-Skin Electromagnetic Actuator for Signaling Direction via Tactile Cues*. In Proceedings of the International Conference on PErvasive Technologies Related to Assistive Environments (*ACM PETRA' 22*).

- P5: **Likun Fang**, Reimann Malte, Erik Pescara, Michael Beigl. *Investigate the Piano Learning Rate with Haptic Actuators in Mixed Reality*. In Proceedings of the Augmented Humans International Conference (*ACM AHs'22*).

- P6: **Likun Fang**, Erik Pescara, Patrick Karl Reiter, Michael Beigl. *How Could I Learn Rhythm Better? Investigating Three Learning Signals for Passive Haptic Learning in Different Contexts*. In Proceedings of the International Conference on PErvasive Technologies Related to Assistive Environments (*ACM PETRA' 23*).

1.4 Structure of This Thesis

This thesis is structured as follows (see Figure 1.1):

- **Chapter 2** discusses the fundamental background of human skin. It starts with the anatomy of the skin, the somatosensory system, and the sense of touch. Then, it presents a comprehensive overview of the human factors that must be considered during the design process of a wearable device. Afterward, it details the state-of-the-art haptic wearable devices, and actuation mechanisms leveraged in haptic interfaces to generate sensations.

- **Chapter 3** proposes FLECTILE, a novel class of skin-worn electromagnetic actuator that could be placed on the various locations of the human body. It is a flexible, soft, and lightweight actuator, made of biocompatible material. A conducted user study revealed that the vibrations produced by the actuator were distinctly perceptible to the 6 participants across various conditions, including observing, hovering, and resting states.

- **Chapter 4** contributes DragTapVib, an extended on-skin electromagnetic actuator to deliver discriminative and affective touch to the users. It has a minimal physical footprint to fit deformable, and small body locations. It exhibits the capability to deliver consistent output in terms of dragging, tapping, and vibration. This chapter concludes with a user study involving 12 participants. The findings indicate that all participants demonstrated a clear ability to perceive and distinguish among the three distinct sensations at both of the specified body locations.

- **Chapter 5** first introduces three wearable haptic interfaces that leverage affective and discriminative touch for passive haptic learning (PHL). A significant limitation of prior research in passive tactile learning is addressed in this chapter, wherein all previous studies have exclusively utilized vibrotactile stimuli. The efficacy of Passive Haptic Learning (PHL) is systematically evaluated through the application of novel actuators, presenting alternative methods to traditional vibration, namely tapping and stroking. By contrasting the discriminative haptics of previous work with the new model of emotional haptics, this work provides a more comfortable, pleasurable experience for PHL and creates potential for PHL in multiple senses. The findings underscore the comparable effectiveness of tapping and stroking in comparison to vibration, without introducing additional disruption.

- **Chapter 6** demonstrates the application scenarios about how haptic technology could be integrated with other interaction technologies. We first investigate how different learning signals—haptic, auditory, and the combined synergy of haptic and auditory cues—impact participants' performance in mastering the rhythm of piano note sequences through passive haptic learning (PHL). A total of 24 participants were invited, and distributed across three equitably sized groups. These participants underwent an instructional session wherein they were taught a straightforward rhythm using a combination of haptic, auditory, and haptic-auditory signals. After this learning phase, the subjects were evaluated on their ability to accurately reproduce the acquired rhythms, employing both a keyboard and a ukulele. Then we explore the potentialities of both mixed reality (MR) and haptic learning, resulting in the creation of a novel piano learning application. Through a comprehensive investigation involving 16 participants evenly distributed into two groups receiving haptic cues and virtual cues respectively, the efficacy and utility of the developed piano application were rigorously evaluated. The resultant study outcomes cast a positive light on the potency of the integrated on-skin actuators, with the anticipation that this work might catalyze subsequent iterations of these actuators, thereby developing a realm of engaging and efficacious learning environments.

- **Chapter 7** summarises and concludes this thesis's main findings, and gives out an outlook on possible future work directions.

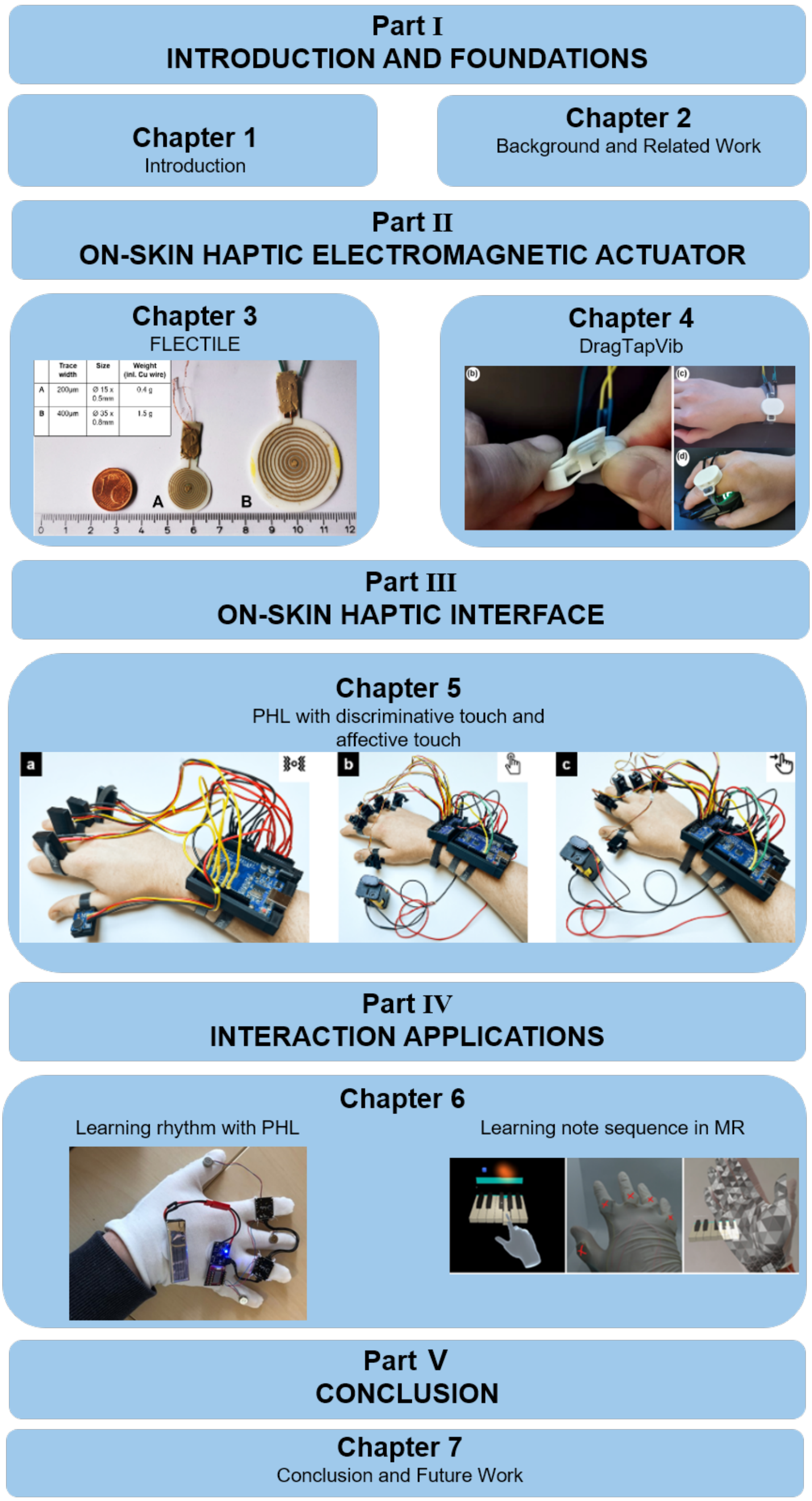


Figure 1.1: Thesis structure.

2 Background and Related Work

This chapter provides a comprehensive review of the literature background and introduces the key concepts that are fundamental to this thesis. First, we describe human skin's basic structure and properties concentrated on the perception of touch, including the receptors, nerve fibers, mechanoreceptive afferent, etc. Also, we present an introduction about affective and discriminative touch and the differences between these two types of touch and potential application scenarios, respectively. Then, we discuss human factor principles that should be taken into account when designing wearables for the human body [47]. Last, we detail on the existing actuation mechanisms employed in haptic interfaces to generate tactile sensations.

2.1 Background on Human Skin

2.1.1 Anatomy of the Skin

The human skin serves as the outer protective covering of the body. It is the largest organ in adult humans, boasting an average surface area of approximately 2 square meters. The thickness of the skin lies at 2.5 mm with a total mass of around 5-6 kg [66]. The skin has three main functions: (1). it plays a significant role in protecting the body against pathogens as the first line of defense from external factors; (2). it regulates various physiological aspects, including temperature, fluid balance, and Vitamins; (3). it interacts with the environment, providing the various sensations with separate receptors (i.e. touch, temperature, and pain) [103]. Human skin can be categorized into two distinct types: hairy and glabrous (hairless) (see Figure 2.1), each of which exhibits differential sensitivity to tactile stimuli since different types of receptors have different densities of innervation. In general, the perception of touch starts at the receptors that are attached to the nerve endings within the skin, which fire upon being triggered. These react to outside stimuli and then relay information about somatic sensations. Somatic sensations are sensations that are related to the physical body or the wall of the body. These are typically classified as tactile, thermal, painful, or pruritic (itch) [44]. Later processing then allows for temporal and spatial discrimination of this information. The human skin comprises three primary layers, namely the epidermis, dermis, and hypodermis (Figure 2.1).

- **Epidermis layer:** The epidermis layer is the top layer of the skin, which could be touched and seen directly. The epidermis layer serves as the boundary between the body and the outer environment, fighting off germs and bacteria to protect the immune system, regulating water balance, and renewing the skin's cells [110]. The epidermis layer also contains melanin, which gives skin, hai r, and eye its color. This substance also absorbs harmful UV (ultraviolet) rays and protects cells from sun damage.

- **Dermis layer:** The dermis layer is the middle layer of the skin, which is held together by a protein called collagen to give skin elasticity and strength [66, 148]. The dermis is a complex combination of blood vessels, hair follicles, and sebaceous (oil) glands, which respectively function to provide blood supply, provide space for hair follicles to grow, produce oil to smooth the skin, and sweat to regulate body temperature. Additionally, it includes pain and touch receptors that enable expressive tactile perception.

- **Hypodermis layer:** The hypodermis or subcutaneous layer is the deepest layer of skin. The majority of human body fat is stored here. It insulates the human body against changing temperatures and protects the muscles and internal organs from impacts and falls.

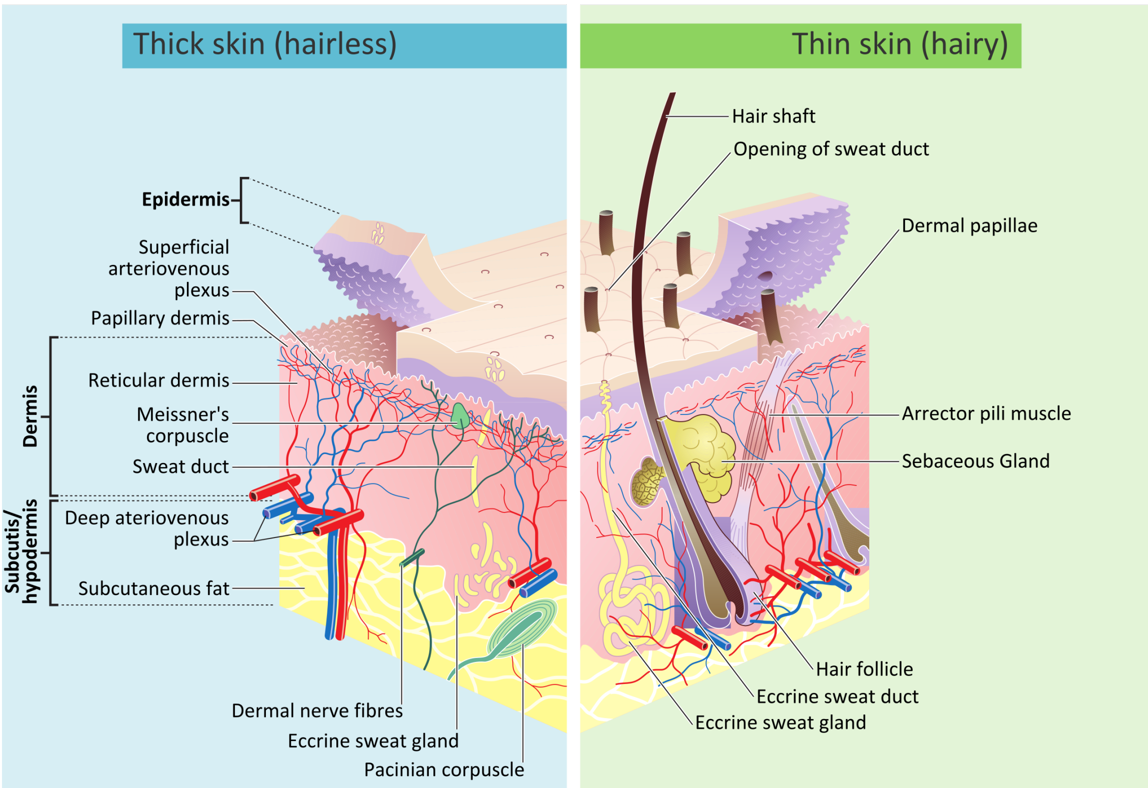


Figure 2.1: Structure of the skin. (Source: [102], under public domain)

2.1.2 Discriminative Touch and Affective Touch

Touch can be divided into two main forms; *discriminative touch* and *affective touch* [109].

Discriminative touch, commonly known as fine touch, plays a crucial role in perceiving, recognizing, and interacting with objects based on their texture, shape, and flexibility. Human hands, specifically the glabrous (hairless) skin on the fingertips and palms, excel in discriminative touch due to the abundant presence of specialized mechanoreceptors. These highly dense receptors are responsible for processing tactile stimuli, contributing to heightened tactile sensitivity and dexterity. The skin contains four main mechanoreceptors that afford discriminative touch: *Merkel cells, Meissner corpuscles, Pacini corpuscles, and Rufini corpuscles* [95]. The mechanoreceptors in human skin are responsible for interpreting tactile, temperature, and pain stimuli [86]. The four mechanoreceptors are illustrated in Figure 2.2.

- **Merkel cells** are closely associated with slowly adapting (SA1) somatosensory nerve fibers. They respond to low-frequency vibrations ranging from 5 to 15 Hz. They are specifically attuned to deep, static touch sensations, enabling the perception of shapes, edges, and other tactile features.
- **Meissner corpuscles** maintain the gentle stimuli and react to moderate vibration (10-50 Hz) and light touch, primarily located in the fingertips and lips [87]. They are rapidly adaptive receptors (RA1).
- **Pacinian corpuscles**, classified as rapidly adapting receptors (RA2), are responsible for detecting significant pressure changes and vibrations in the skin. They react to quick action potentials like vibrations from 40 to over 500 Hz, which are most sensitive but only responsible for sudden stimuli.
- **Ruffini corpuscles** are slowly adapting recptors (SA2). They exhibit sensitivity to skin stretch and contribute significantly to the kinesthetic sense and the precise control of finger position and movement [116].

Affective touch is typically referred to as slowly moving, low-force mechanical stimulation [98, 135], which has a strong emotional component [66]. Affective touch serves a crucial role in fostering social bonding by promoting affiliative, collaborative, and sexual behaviors [155]. Affective touch has been empirically demonstrated to effectively convey positive emotions [8, 61, 85], alleviate feelings of isolation [164], and enhance pain tolerance [115]. The C-Tactile (CT) afferents, located in the non-glossy skin of the body, are unmyelinated low-threshold mechanosensory nerves, which are identified as the primary pathway for affective touch [109, 122]. The CT afferents exhibit optimal responsiveness to gentle and light stroking sensations applied with a force range from 0.3-2.5 mN and with high-frequency responses [2, 21, 161]. Compared with the myelinated fibers (20–80 m/s), the conduction velocities in CT reduce much less ranging from 1-10 cm per second with a mean activation peak at around 3 cm/s [25, 98, 108]. CTs are also temperature tuned [3].

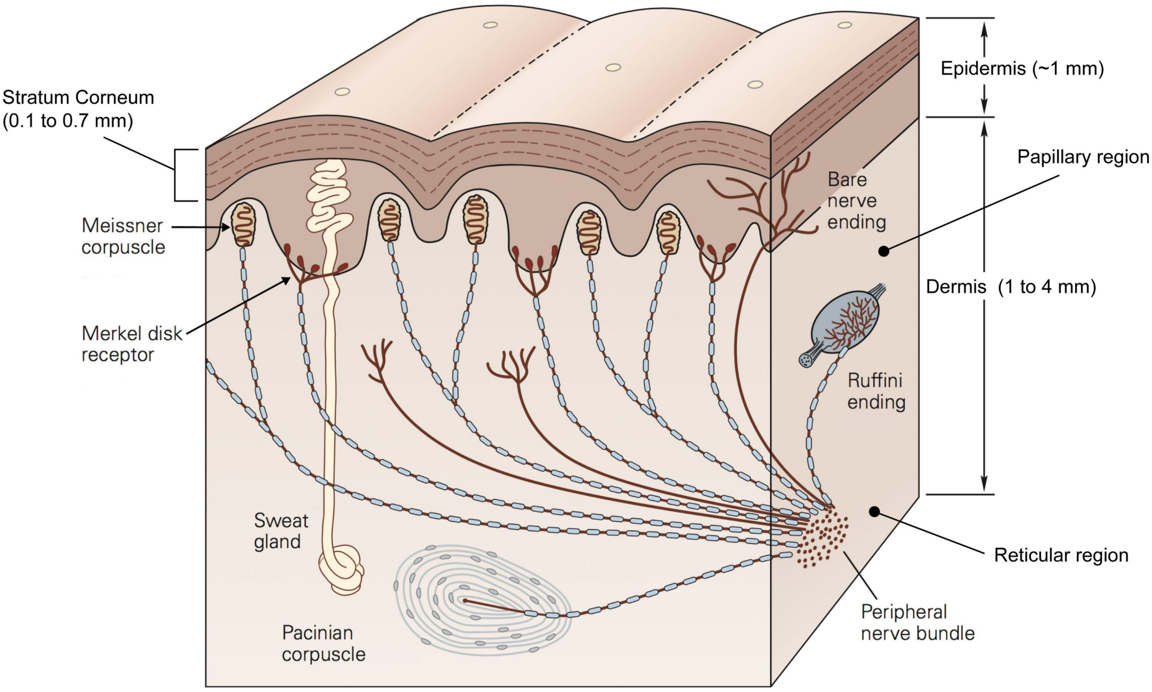


Figure 2.2: A cross-section of the four mechanoreceptors for discriminative touch [25].

Among mechanoreceptive afferents, CT fibers are unique since they preferential response to slowly moving stimuli, specifically at a neutral temperature corresponding to typical skin conditions. Unlike other afferents, CT fibers do not exhibit a preference for cooler or warmer stimulus temperatures. The Cyberball task [164] reported that the participants who feel social exclusion are lessened by the presence of CT-optimal touch (touch that maximally activates CT afferents). Activation of C-Tactile (CT) afferents has consistently demonstrated the ability to elicit pleasurable and positively valenced affective responses [89]. An increasing number of scholarly works have shed light on the significance of affective touch and started exploring this field [109].

2.2 Consideration for Wearable Devices Design

Wearable devices refer to devices or gadgets that can be worn on the body or incorporated into clothing or accessories (see Figure 2.3). The domain of wearable technology encompasses a vast range of devices that are either worn on the body or closely interact with it. This field encompasses a diverse spectrum, spanning from smart glasses and instrumented headphones to smart garments, jewelry, implants, and the ubiquitous smartphones and smartwatches that are prevalent today. Miniaturization of components has enabled wearable and nearly invisible systems, which gives individuals the freedom to interact with their environment in a more flexible and user-customizable way, giving great potential and promise for wearable and ubiquitous computing [104].

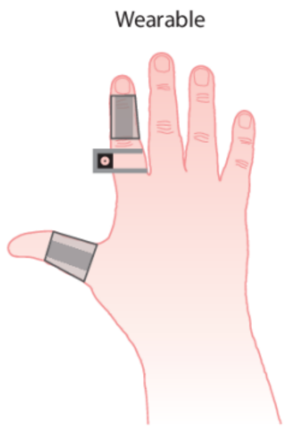


Figure 2.3: Example of wearable devices from Culbertson, Schorr, and Okamura[22]. Users should freely and unhindered interact with the environment with the wearable devices.

Wearable devices are designed to be lightweight, portable, and comfortable, allowing users to carry them or wear them directly on their bodies for extended periods. In the design process of wearable technology, an initial and crucial question that researchers must address is the optimal placement of the device on the human body. Gemperle et al. [47] proposed original guidelines in a predictable order from the simple to the more complex more than 20 years ago, namely: *Placements, Form Languages, Human Movement, Proxemics, Sizing, Attachment, Containment, Weights, Accessibility, Sensory Interaction, Thermal, Aesthetics, and Long-tern Use*. With the advancement of wearable computing, understanding how humans perceive and interact with wearable devices has also grown. Zeagler [176] updated and added information in 2017 with respect to proxemics, weight, accessibility, thermal tolerances, human movement, sensory interaction, and location. For the scope of this thesis, we focus on the following aspects:

- **Placement:** The placement directly impacts user comfort and ergonomics. Wearable devices should be positioned in an unobtrusive manner that minimizes discomfort, irritation, or restriction of movement. The ideal placement is in a large and less flexible area. For versatility, it is also necessary to have relatively identical sizes across the adults [47]. Zeagler [176] reported a body map for the placements based on the work of [47] (see Figure 2.4).

- **Sizing and Weight**: The physical characteristics of wearable devices require careful attention. Sizing and weight can significantly influence user comfort and usability. The devices should be ergonomically designed to ensure that it fits well with the user's body and allows for prolonged use without causing fatigue or discomfort. The dimensions of different parts of the human body vary greatly. Gemperle et al. [47] pointed out that two ways to fit the various body sizes for individuals. The first is the use of static anthropometric data, which details point-to-point distances on different-

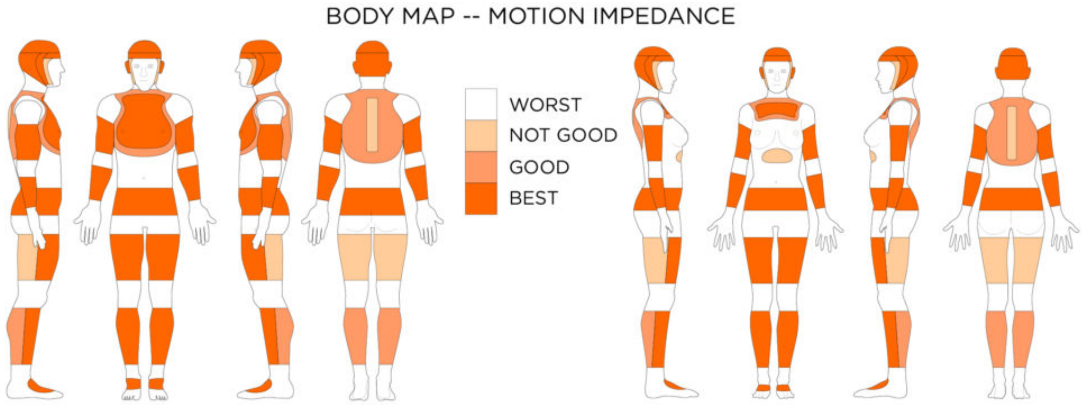


Figure 2.4: This body map shows the best places to place wearable devices on the body in the least obtrusive way. [176].

sized bodies. The second is the consideration of human muscle and fat growth in three dimensions [47]. It is important to place the weight on fleshy, non-sensitive parts of the body while avoiding boney areas. The lower waist area is suitable for heavy loads, and weight should be balanced evenly across the body. Additionally, the placement of batteries should be strategic, considering both functionality and user comfort. See Figure 2.5 for an illustration of weight distribution.

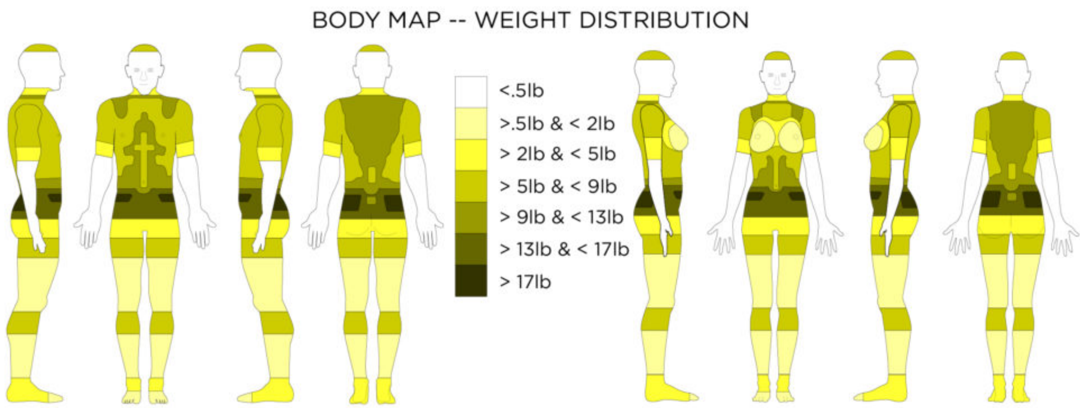


Figure 2.5: The body map illustrates the amount of weight, or pressure that can be placed on the area before the pressure becomes a discomfort [176].

- **Attachment:** Wearable devices need to be securely attached to the user to ensure stability and security. It is also significant that wearable devices should not cause discomfort or hinder the user's mobility. The attachment method should distribute the device's weight evenly and avoid pressure points or excessive tightness (such as single-point fastening systems) [47]. Additionally, the materials used in the attachment should be skin-friendly and breathable. The attachment mechanism should also allow for easy donning and doffing of the device, as well as quick adjustments to accommodate different body sizes or preferences.

- **Tactile Feedback (passive touch):** The stimulation of the skin generated from the outside objects is described as a passive touch [49]. Numerous wearable devices incorporate tangible or haptic feedback mechanisms to provide users with sensory stimuli, often utilizing vibration motors and occasionally employing additional methods, such as electrical stimulation [43, 170]. Understanding the varying levels of sensitivity specific to different areas of the body is of great significance. Two-Point Discrimination Test [119] is a widely used technique for assessing tactile perception. When multiple haptic stimuli are employed to generate a pattern, the ability of the skin to distinguish between closely spaced stimuli and perceive them as separate entities is also imperative [176].

- **Accessibility:** The wearable devices should be intuitive, easy to use, and accessible for individuals with diverse abilities and disabilities [176]. Massive research in the areas of visual, tactile, auditory, or kinesthetic access to the human body provides a great potential [47]. Incorporating appropriate input methods (e.g., touch, voice, gesture) and minimizing the learning curve will enhance usability.

- **Aesthetics:** Wearable devices are not only functional but also could be fashion accessories. The design should consider aesthetics, style, and personal preferences to enhance the user's willingness to wear and showcase the device. Collaboration with fashion designers or incorporating modular components can provide options for personalization and style variations.

- **Social Acceptability:** Social acceptability is vital when designing wearable devices. It influences adoption rates, user comfort and confidence, perception and reputation, etc.. Remland, Jones, and Brinkman [133] reported that people across different cultures, ages, and gender had interconnected influences on touch behaviors and perceptions. The aspects of cultural, social, and ethical need to be taken into account to ensure that wearable devices do not infringe on personal privacy, and social boundaries, or evoke negative connotations.

2.3 Tactile Interface

Chouvardas, Miliou, and Hatalis [18] describe the tactile interface as a human-computer interface that utilizes exclusively tactile signals to present information. It allows users to interact with digital content or virtual objects by simulating the sense of touch through force, vibration, or motion to reproduce the feeling of the objects (e.g., shape, size, and texture.). While vibrotactile stimulation is the most commonly employed method in haptic interfaces, it is worth noting that skin stretching and deformation are also utilized in a significant number of interfaces. This section presents a comprehensive overview of the state-of-art haptic interface. The discussion encompasses the functions of the haptic interfaces, the existing mechanisms employed for generating haptic sensations, and the diverse range of sensations that can be elicited through these interfaces.

2.3.1 Functions

The functions of haptic interfaces revolve around enriching digital interactions by incorporating the sense of touch, including delivering tactile feedback, providing sensory information, enabling object manipulation, and facilitating communication, etc. The functions of haptic interfaces most relevant to the work presented in this dissertation are notification and haptic feedback. The focus primarily centers on these two functions, drawing substantial inspiration and guidance from the relevant literature.

2.3.1.1 Notifications

The notification function of haptic interfaces refers to the capability to deliver tactile feedback or alerts to users. Haptic notifications can be utilized to convey a wide range of information, such as incoming messages, alarms, notifications from applications, or warnings in safety-critical systems. As already described, the skin offers great potential through the receptors. More complex information can be encoded [15, 70] when combining various parameters together (such as frequency, amplitude, duration, etc.). By leveraging tactile sensations, haptic interfaces can be effectively and seamless integrated in the users' daily routine and capture their attention, especially when visual or auditory cues are insufficient or impractical.

In addition to basic daily message notifications, haptics can also be used in some special scenarios when vision and hearing are occupied such as when in control of a vehicle. Tactile information systems installed on the steering wheel have been extensively adopted by automakers for the purpose of driver warnings. These systems are employed to alert drivers regarding the avoidance of fatigued driving and to prompt them to make necessary corrections when the vehicle deviates from the normal driving trajectory. Di Campli San Vito et al. [26] presented two driving simulator studies investigating novel tactile feedback on the steering wheel for navigation. Hwang and Ryu [75] proposed a tactile display on the steering wheel to deliver directional information to the driver.

2.3.1.2 Haptic Feedback

Haptic feedback refers to the tactile or touch-based sensations provided to users through haptic interfaces or devices. It is a form of communication that utilizes the sense of touch to convey information or stimulate sensory experiences. Haptic feedback can take various forms, such as vibrations, forces, textures, or temperature changes, depending on the capabilities of the haptic interface. These sensations could be employed to enhance the user's perception and interaction with virtual or remote environments, providing a more immersive and realistic experience. The implementation and integration of haptic feedback technology into remote surgery permit the operating surgeon on the console to receive haptic information on the type of tissue being operated on [6]. In gaming scenarios, haptic is commonly implemented through vibrating motors or actuators integrated into controllers or gaming peripherals. Haptic feedback can be used to communicate important information or alert the player in virtual reality, mixed reality, or console gaming environments. For instance, it can indicate the direction of an incoming threat through directional vibrations [19], or provide notifications for health points or heat points [128], weapon ammunition interaction [36], or the environment information [178].

2.3.2 Actuation Mechanisms

This section discusses the existing common actuation mechanisms used in haptic interfaces. We also list the advantages and disadvantages of each actuation mechanism. In this thesis, we develop electromagnetic actuation, vibration actuation, and non-vibration actuation, which we will explore in further detail in subsequent chapters.

2.3.2.1 Vibration Motors

The two most common types of vibration actuators used in wearable devices are eccentric rotating mass (ERM) motors and linear resonant actuator (LRA) motors. An ERM motor has a small unbalanced mass attached to the DC motor axle, creating a displacement force when rotating. An LRA motor contains a small internal mass attached to a spring, which vibrates in a reciprocating linear motion. The oscillatory force generated by the alternating displacement of the mass is perceived as vibration in both types of vibration motors. Both types of actuators have the advantage of being small, lightweight, low energy consumption, cheap and portable. They can therefore be flexibly arranged and integrated for designing haptic interface [19, 28, 127, 128, 141].

2.3.2.2 Shape Memory Alloy and Shape Memory Polymer

Shape memory alloys (SMA, most commonly Nickel-Titanium alloy) exhibit the ability to recover their predetermined shape when subjected to certain external stimuli, such as temperature changes or mechanical forces. The unique properties of shape memory alloys, including their high strength, excellent fatigue resistance, and large recoverable strain make them valuable materials for aerospace, biomedical devices, and robotics applications. However, they also come with certain drawbacks, particularly related to their cooling time. One significant drawback is the relatively slow cooling rate of SMAs. As these alloys undergo a phase transformation during the cooling process, the time required for them to return to their original shape can be longer compared to other materials. The slow cooling time of SMAs can limit their applicability in certain dynamic or high-speed applications.

Shape-memory polymers (SMP) possess similar mechanisms as Shape memory alloys. When subjected to external stimuli, such as temperature, electric field, change, light, etc., they can return from their deformed shape to their original state. Due to the advantages of lightweight, low energy consumption, small size, customizability, and biocompatibility of shape memory materials, they continue to drive innovation and research in various fields. Moreover, HCI research is exploring methods to build wearable devices leveraging SMA to generate skin deformation [62, 111]. An increasing body of research has provided insights into the potential applications of shape memory polymers in the field of artificial muscles and tendons [17, 31, 91].

2.3.2.3 Pneumatic

Pneumatic actuators, also known as fluidic actuators, encompass systems where pressurized air is utilized to drive airflow into and out of chambers mostly manufactured from silicone or thin plastic film. Pneumatic actuation has emerged as a widely adopted approach for facilitating tangible and haptic interactions in human-computer interaction (HCI) domains. The prior research in HCI has already explored the pneumatic actuators for multi-sensation interaction [178, 180] and shape-changing interface [83, 157, 172].

Compared to traditional rigid actuators, pneumatic actuators are lightweight and flexible. The actuator's stiffness and compliance can be adjusted by adjusting the pressure inside the chamber to suit different tasks or interaction requirements. The soft material of pneumatic actuators also reduces the potential for hazards during the interaction. Moreover, soft pneumatic actuators can be designed based on bioinspired structures and movements, allowing for applications in assistive devices by providing more intuitive and efficient interaction with the human body.

2.3.2.4 Non-Vibration Motors

Motors are another alternative for designing wearable devices. A servomotor is a rotary actuator or linear actuator that allows for precise control of angular or linear position, velocity, and acceleration. A stepper motor is an electromechanical device that converts digital pulses into distinct mechanical rotations. A complete rotation of the stepper motor is equally divided into steps, each of which corresponds to a fixed angular displacement. The motor can robustly provide high torque and high force output at a low cost. Thus, the motor could be leveraged in designing various on-skin affective sensations such as stroking, rubbing, tapping, and twisting [12, 77, 80, 145]. Motors also exhibit certain drawbacks, including their rigid nature, noise during operation, which limit their use in wearable computing devices.

2.3.2.5 Electromagnetic Actuators

Electromagnetic actuators (EM actuators) transform electrical and mechanical energy into one another using the electromagnetic-mechanical principle [151]. A conductor generates a magnetic field around it once current flows. Previous research have demonstrated the many applications of electromagnetic actuators by controlling induction-generated electromagnetic fields or extrinsic magnetic substances [32, 36, 38, 55, 107, 125, 162, 171]. Duvernoy et al. [32] present a whole-hand tactile display composed of an array of twenty-four actuators, on which users could rest their hands to get expressive haptic information. Guo et al. [55] and Fang et al. [38] successively propose a soft and flexible actuator based on electromagnetic actuation. Yang et al. [171] develop a 3×3 pin-array tactile module for mobile devices using elastic and electromagnetic force. Pece et al. [125] present MagTics, a novel flexible and wearable haptic interface based on magnetically actuated bidirectional tactile pixels. Based on the concept of Magtics[125], Vechev et al. [162] propose a wearable glove including a 15 electromagnetic actuator array to provide real textures in the VR environment. Mazursky et al. [107] report the MagnetIO comprised of two parts: one battery-powered voice-coil worn on the user's fingernail and interactive soft patches made of magnet particles and silicone that can be attached to any surface.

Part II

ON-SKIN HAPTIC ELECTROMAGNETIC ACTUATOR

3 FLECTILE: 3D-Printable Soft Actuators

This chapter presents *FLECTILE*, an approach to producing three-dimensional-printable soft actuators that can be used for a wide range of wearable computing scenarios with the potential to direct interaction, for example, in clothes. The actuator is flexible and bendable and made of soft biocompatible materials at a low cost. The dimension of *FLECTILE* could be customized to fit various body positions.

The human skin, being the largest organ, offers a substantial interactive surface for wearable computing. Extensive research has been conducted on tactile interfaces for human-computer interaction, as demonstrated in prior studies (e.g., [23, 169]). Various driving strategies have been developed, including pneumatic (e.g., [154]), optical (e.g., [175]), and electromagnetic (e.g., [67]) approaches.

Due to its simplicity in controlling and achieving desired functions, electromagnetic actuation has drawn significant attention in recent studies. A soft electromagnetic actuator is an actuator type that employs electromagnetic principles to generate mechanical motion or force. When an electric current passes through a conductor, it generates a circular magnetic field around the conductor. In contrast to traditional electromagnetic actuators, which are often rigid and bulky, soft electromagnetic actuators are designed using flexible and deformable materials. This design enables them to conform to irregular shapes and interact with soft and delicate objects. The main characteristic of soft electromagnetic actuators is their capability to integrate soft and flexible materials with electromagnetic components like coils and magnets. As a result of this combination, the actuator can accomplish diverse types of motion, such as bending, twisting, or stretching, while retaining a compliant and deformable structure. Soft electromagnetic actuators find numerous applications in domains such as robotics, haptic interfaces, medical devices, and soft wearable technologies Li et al. [92] and Zhu et al. [181]. These actuators have been proved to be particularly useful in scenarios requiring interactions with humans or delicate objects due to their soft and compliant nature, which aids in preventing injuries or damage.

The design and fabrication of soft electromagnetic actuators typically involve the integration of conductive materials, such as liquid metals or flexible printed circuits, into soft and elastomeric structures. Liquid metal alloy (LMA) has been widely used in various applications in soft electromagnetic [27, 54, 55]. However, the utilization of both spraying technology and injection methodology during fabrication in related research [27, 54, 55] requires complex process steps, higher costs, and significant effort. Yu et al. [174] proposed a comprehensive and flexible on-skin electromagnetic actuator concept, in which a fixed coil moves a magnet freely in an up-and-down motion. Nevertheless, the coil materials commonly used are copper traces encapsulated in polyamide, which incurs significant manufacturing overhead.

Recent developments in material science have introduced conductive, highly flexible materials based on TPU or PDMS, incorporating silver particles through a *capillary* effect [153]. These materials have been utilized in constructing flexible interactive human on-skin interfaces [134]. We propose in this work that capillary Ag-TPU can be utilized to construct 3D-printable actuators suitable for human wearable devices. To our knowledge, we present the first skin-applicable, fully 3D-printable soft actuator. The content of this chapter was published in Proceedings of the 2020 ACM International Symposium on Wearable Computers [38].

The remainder of this chapter is structured as follows. Section 3.1 discusses related works. Section 3.2 then details on the working principle, design, and fabrication approach of *FLECTILE* respectively. Meanwhile, Section 3.2 illustrates a recipe-style introduction for building *FLECTILE*s in a simple and effective manner. This step-by-step guide provides clear instructions on constructing the actuator, ensuring the process is accessible and straightforward. Following this, Section 3.3 presents the technical evaluation regarding on the possible working frequency and various dimensions and presents a user study on the empirical observations. Section 3.4 presents a set of example applications. To conclude, Section 3.5 discusses the limitations and future work of *FLECTILE*.

3.1 Related Work

Initially, we presented a comprehensive comparison between our research and related studies [27, 54, 55, 174], primarily focusing on various aspects such as materials, manufacturing techniques, flexibility, and application scenarios. This comparative analysis was presented in a detailed and visually accessible manner through Table 3.1, clearly highlighting the distinctions among these works. This comparison facilitated a better understanding of the key differences and nuances that set our work apart. The related study demonstrated more intricate and complex approaches to fabrication, involving multiple steps and techniques. In contrast, our methodology prioritized simplicity and ease of comprehension, significantly reducing production and manufacturing costs.

The design of *FLECTILE* was specifically tailored for the application scenario of a tactile actuator on the skin. Hence, we conducted a thorough comparison between our approach and existing studies aforementioned [27, 55, 174] that shared a similar structure and similar application context. As depicted in Table 3.2, our primary focus revolved around the critical examination and comparison of the fundamental principles driving actuation, which were employed as part of our investigation.

Table 3.1: Comparative analysis [27, 54, 55, 174] of electromagnetic actuators: evaluating materials, manufacturing processes, flexibility, and application scenarios.

Material	Fabrication Method and Process		Stretchability	Application
EGaIn Alloy [27]	Injection	(1). laminate the silicone; (2). cover a micro carbon hollow; (3). cure the micro carbon hollow; (4). inject the LMA into hollow filament; (5). insert the electrodes; (6). form it into the helical shape;	depend on the tube and substrate	Robotics & Vibrotactile Feedback Display
Ga-In Alloy [54]	Injection	(1). wash silicone tubes; (2). inject the LMA into tubes; (3). build electronic connection; (4). seal the metal pins (5). wound tubes into helical shape; (6). cast the silicon; (7). cure the actuator; (8). repeat the process *(6)* and *(7);* (9). trim to desired shape;	depend on the tube and substrate	Robotics
Ga-In Alloy [55]	Spraying	(1). coat a PDMs layer; (2). cure the substrate; (3). cover the film with a mask; (4). print the LM traces; (5). remove the mask; (6). spin to coat a PDMs layer; (7). cure the actuator;	depend on the PDMs substrate	Robotics
Copper Wire [174]	Moulding	(1). place a Cu coil; (2). sub-merge the Cu coil; (3). bake for the first time; (4). seal the coil again; (5). cure the actuator; (6). trim to desired shape;	depend on the silicone substrate	Haptic Interface
Ag-TPU FLECTILE	**Fully 3D Printed**	**(1). print a TPU substrate;** **(2). print traces;** **(3). cure the actuator;**	both coil and substrate are fully elastomer based	**Haptic Interface**

Table 3.2: Diverse driving modes of actuators in related work [27, 55, 174] for inducing vibrations.

Name	Moving Parts
Do et al. [27]	Permanent magnet is triggered by the magnetic field generated from the wound coils to move upward and downward.
Guo et al. [55]	The coil produces an electromagnetic field when stimulated by a statically positioned external magnet, causing it to oscillate laterally.
Yu et al. [174]	Permanent magnet is triggered by the magnetic field generated from the FPCB coils to move upward and downward.
Our work - FLECTILE	**The coil produces an electromagnetic field when stimulated by a statically positioned external magnet, causing it to move upward and downward.**

3.2 FLECTILE: Flexible Tactile Actuator

FLECTILE was designed as a tactile actuator, following the guidelines proposed by Gemperle, Ota, and Siewiorek [46] and Zeagler [176]. The actuator is lightweight, flexible, and available in various configurable scales. Moreover, it can be manufactured using a few entirely 3D-printing-based steps, minimizing the need for manual effort.

3.2.1 Working Principle and Design

FLECTILE operates based on Ampere's law. A conductor generates a magnetic field around it once current flows. The direction of the magnetic field created by a current distribution using Ampere's law is determined by the right-hand rule. First, wrap the right hand around the loop with the fingers in the direction of the current flow. Then, the direction of the thumb represents the direction of the magnetic field produced by that current (see in Figure 3.1). The combination of a state-switching electromagnetic coil by alternating the current direction and a permanent magnet makes up the actuator. Figure 3.2 shows the working principle of *FLECTILE*s. By alternating the direction of the current flowing inside the conductors, the direction of the resulting electromagnetic field could be controlled. Consequently. the actuator could achieve upward and downward motion, depending on the interplay of attraction and repulsion forces induced by external magnets.

We present a novel design where, instead of single-sided coils in related works, the conductive loops are on both sides of the substrate (see Figure 3.2), thanks to the convenience of 3D printing and the flexibility of coil materials. This principle allows current to flow in a clockwise and counterclockwise direction, respectively. According to Ampere's

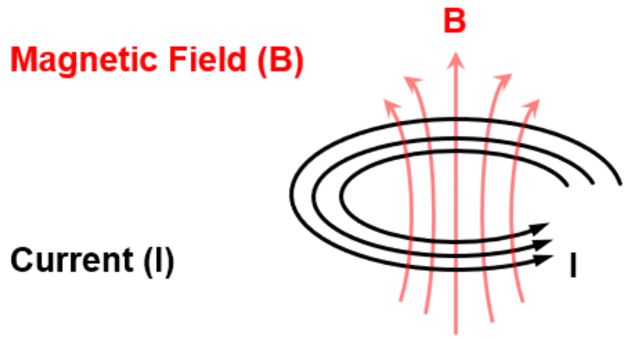


Figure 3.1: Magnetic fields produced by currents flows in the conductor.

Law, when current flows through clockwise and counterclockwise loops, they generate a magnetic field in the same direction. Consequently, the actuator field strength of the Ag-TPU traces improves, bringing it closer to that of single-coil actuators based on the liquid metal alloy. The form language of *FLECTILE* is very simple and could be directly placed on the user's forearm.

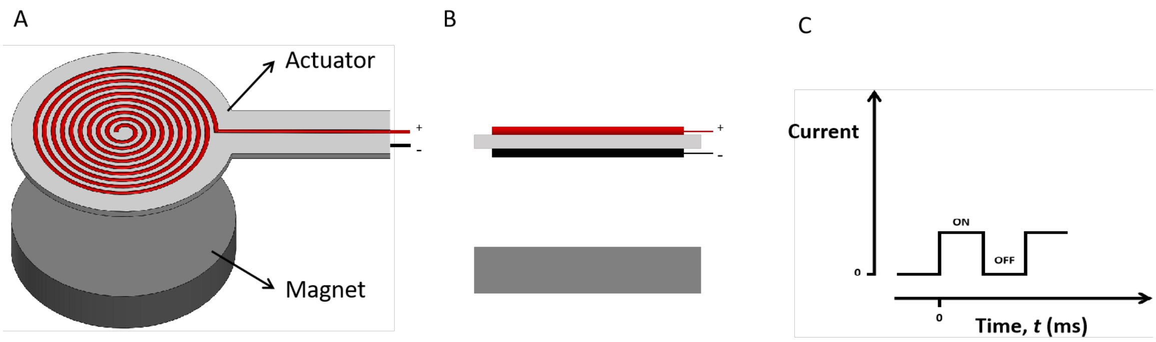


Figure 3.2: (A). 3D view of the *FLECTILE* with printed coils designed in clockwise and counterclockwise on two sides of the substrate; (B). Front view of the placement of *FLECTILE* and the magnet; (C). Utilizing a driving method that involves switching on and off a 5V DC power source.

3.2.2 Manufacturing Process

This section introduces the overall fabrication process of *FLECTILE*. Printing an actuator requires several simple, mostly automated steps. Figure 3.3 shows the fabrication of the electromagnetic soft actuator.

Initially, a 0.8 mm thick Thermoplastic Polyurethane (TPU) substrate with a centrally located all-through hole (1 mm diameter) was produced using a Fused Filament Fabrication (FFF) 3D printer (Model: Ultimaker 3) and semi-flexible filament TPU 95A (Brand: Ultimaker). Subsequently, using a Direct Ink Writing (DIW) 3D printer (Model: Voxel8

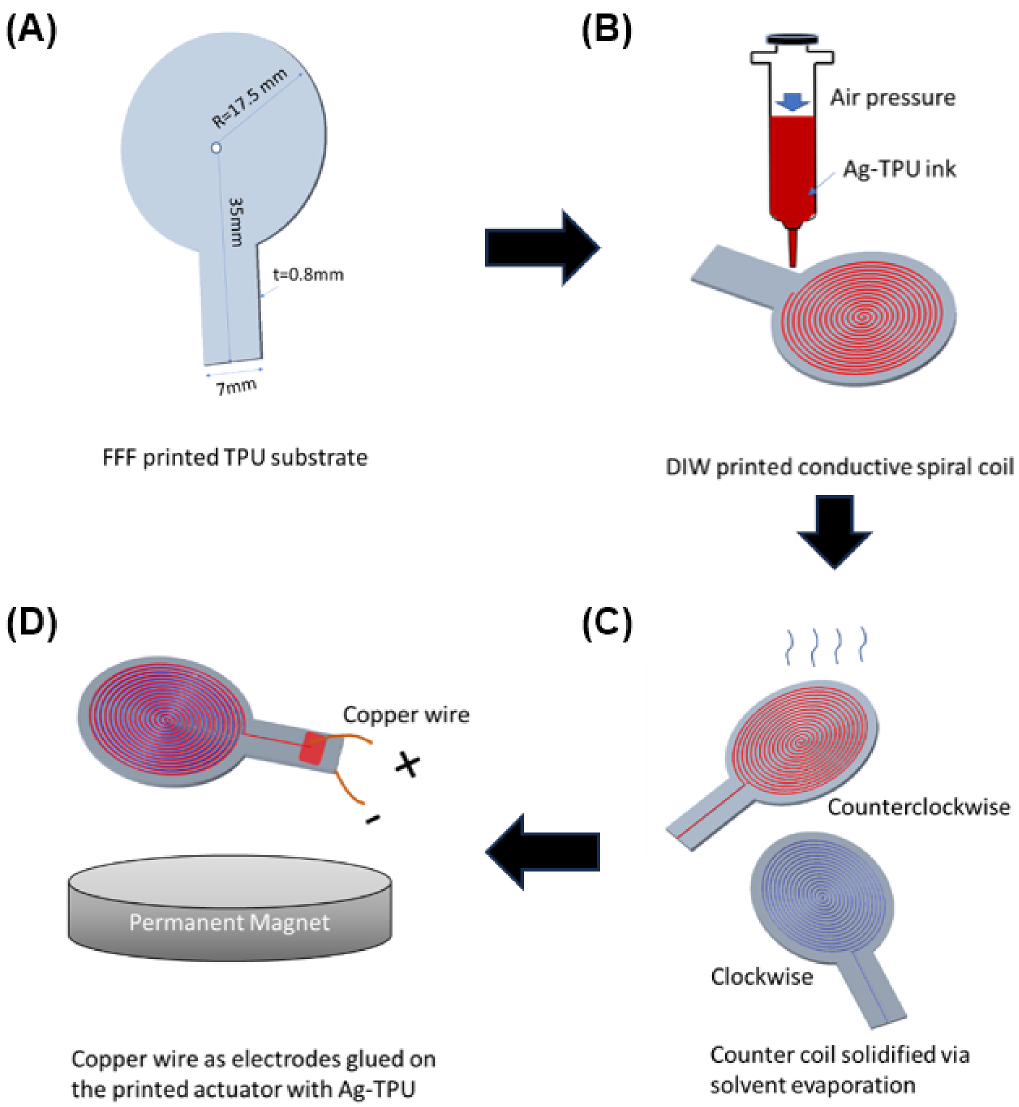


Figure 3.3: The fabrication process involves the following sequential steps: (A). Printing a TPU substrate with a centrally located all-through hole measuring 1mm in diameter; (B). Printing capillary Ag-TPU ink traces on both sides of the substrate; (C). Curing the printed traces to enhance their conductivity and durability; (D). Connecting copper wires and traces using the same Ag-TPU ink to establish electrical connections.

Developer's Kit printer) equipped with a 400 µm nozzle, *capillary* silver TPU ink (Ag-TPU) traces were printed on one side of the TPU substrate, with a silver content of 21 vol%. The actuator was left to dry at room temperature for a period of eight hours. Additional trace was then printed on the other side of the TPU substrate, and a droplet of capillary ink was meticulously inserted into the central hole to establish an interconnection between the two coils. Subsequently, the actuator was left to dry at room temperature for an additional eight-hour period. The fabrication process utilized capillary Ag-TPU ink, which follows the method described in previous research proposed by Sun, Han, and Willenbacher [153]. The capillary Ag-TPU ink contains micro-sized Ag flakes, enabling it to exhibit both high conductivity and stretchability. Its electrical conductivity was measured to be 2884 ± 165 S/cm using a four-point probe method. Therefore, these materials hold tremendous potential for significant advancements in various domains, including wearable devices, soft robotics, and deformable electronics.

In order to enhance accessibility, we have compiled a concise and user-friendly set of recipe-style instructions for creating do-it-yourself (DIY) actuators tailored to specific individual applications. This approach simplifies the process by breaking it down into step-by-step instructions (shown below), allowing individuals to easily fabricate actuators according to their unique needs and desired applications.

Ingredients

- Ultimaker 3 TPU 95A filament (2.85 mm, 750 g, white);
- Capillary silver TPU ink (Ag-TPU, including 21 vol% Ag [153]);

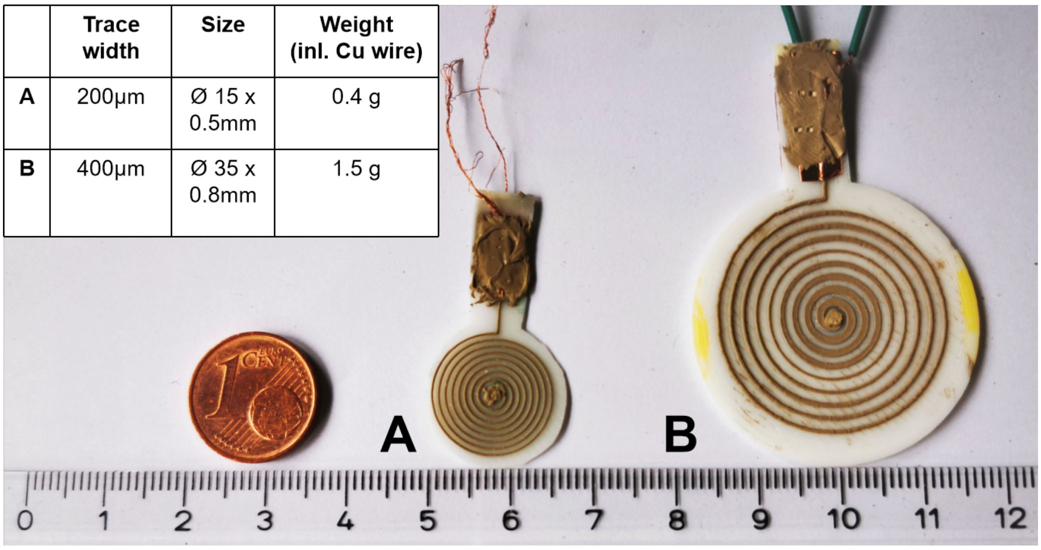
Apparatuses

- Fused Filament Fabrication (FFF) 3D printer;
- Direct InkWriting (DIW) type 3D printer;
- A needle (1 mm in diameter);

Instructions

- Design the mold for substrate with CAD software (parameter of the sample actuator is shown in Figure 3.3 (A));
- Print substrate using TPU 95A filament from FFF 3D printer;
- Print a trace on one side of the substrate firstly using Ag-TPU ink and DIW printer;
- Use the Ag-TPU ink to fill the hole in the center of the substrate;
- After 30 minutes of cure, print the trace on the other substrate side;
- Let actuator sit at room temperature for 8 hours until cured;
- Connect the copper wires with the printed traces with the Ag-TPU ink;

Moreover, *FLECTILE* actuators can be printed freely in varying sizes. The print width of the trace can be adjusted by modifying the size of the nozzle in the Direct Ink Writing (DIW) 3D printer. By employing different nozzle sizes, variations in the width of the printed trace can be achieved. According to wearability constraints by Zeagler [176], the weight and size limits of the area on the forearm are 226g and much less than 40mm. Figure 3.4 shows different actuators in dimension, both of which are far below the limitations (including, e.g., a 100 g magnet). The smallest actuator we have manufactured exhibits dimensions comparable to that of a one euro cent coin, with a weight of merely 0.4g (see Figure 3.4 Example A).



	Trace width	Size	Weight (inl. Cu wire)
A	200µm	Ø 15 x 0.5mm	0.4 g
B	400µm	Ø 35 x 0.8mm	1.5 g

Figure 3.4: Various diameters and trace width/distance configurations.

3.3 Evaluation

In order to assess the applicability of *FLECTILE*s, we first investigated their general actuator properties, then we conducted a user study. We employed an actuator with a trace width of 400 µm, a diameter of 35 mm, and a thickness of 0.8 mm. The choice of diameter size was informed by previous work on soft actuators conducted by Guo et al. [55]. The magnet had dimensions of Ø 42x9 mm and a holding force of 55 kilograms. Initially, the distance between the permanent magnet and the actuator was set to 1 mm. The technical foundation involved an *Arduino Duemilanove* microcontroller board (ATmega328) operating at 5 V. The connection between the copper wires on the soft actuators and the microcontroller was established using crocodile clips and jumpers via Digital I/O Pins.

3.3.1 Actuator Properties

In order to characterize the actuator under various conditions, we conducted three experiments to determine the most stable working frequency, the maximum working distance, and the impact of different magnetic fields.

3.3.1.1 Working Frequency

The first experiment aimed to determine the robust working frequency range of the actuators. A slow-motion camera (240 fps) was positioned to capture the actuator's performance, specifically defined as stable and continuous actuation. The working performance was characterized by varying the electric actuation frequency in the range of 1-80 Hz. This frequency range aligns with the consensus on the limits of human exposure to vibration [52, 147]. Within the frequency range of 1 to 10 Hz, we used a step-size of 2 Hz, while for the range of 10 to 80 Hz, we used a step-size of 10 Hz. Additionally, we investigated the upper-frequency limit using a step-size of ten. No visible vibration was observed above 200 Hz.

Figure 3.5 illustrates the changes in normalized amplitude with respect to actuation frequency, extracted frame-by-frame from a video. The actuator demonstrates robust performance within the frequency range of 1 Hz to 30 Hz. However, an unexpected continuous small pulse emerges above 40 Hz. We propose that the insufficient strength of the magnetic field causes the actuator to be pulled in the opposite direction before changing its motion, resulting in the observed behavior. The actuator exhibits the most stable performance within the frequency range of approximately 20 Hz to 30 Hz. Therefore, we utilized a frequency of 20 Hz in the subsequent user study. *FLECTILE* exhibits compatibility with a wide range of frequencies, making it suitable for diverse applications.

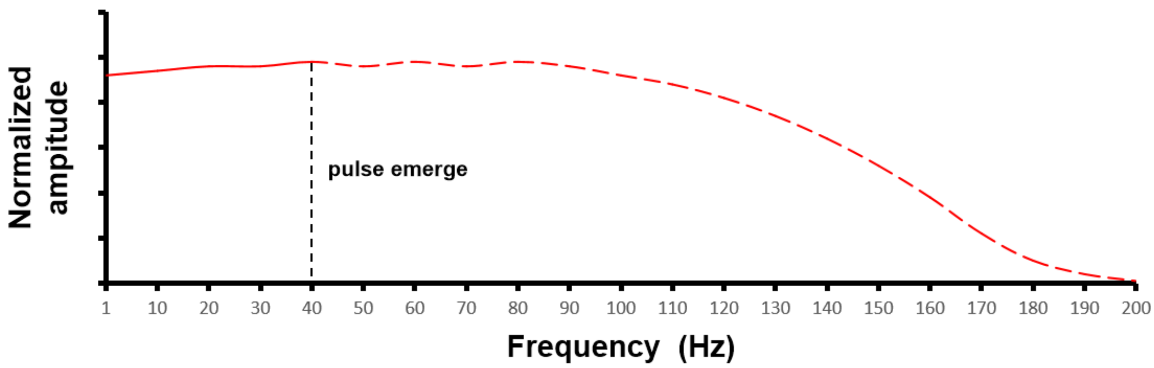


Figure 3.5: Experiment 1 results, Actuator response frequency: 1-200Hz.

3.3.1.2 Working Distance Range

The second experiment was conducted with the objective of determining the maximum operational range of the actuator. To achieve this, we employed 3D printing technology to create cubes with varying heights ranging from 10 to 20 mm, corresponding to working distances spanning from 1 to 11 mm. These cubes were printed in one-millimeter increments. Subsequently, we securely attached the actuator to each cube and established a connection to the AC power source. Employing a methodical approach involving gradual height adjustments of the cube, we meticulously defined the actuator's effective operational range. The experimental configuration is visually depicted in Figure 3.6.

Upon analyzing our observations, which are summarized in Table 3.3, it became evident that no perceptible vibrations occurred once the working distance surpassed 7 mm. This significant finding implies that beyond this critical threshold, the interaction between the permanent magnet and the actuator was effectively suppressed, resulting in stable performance.

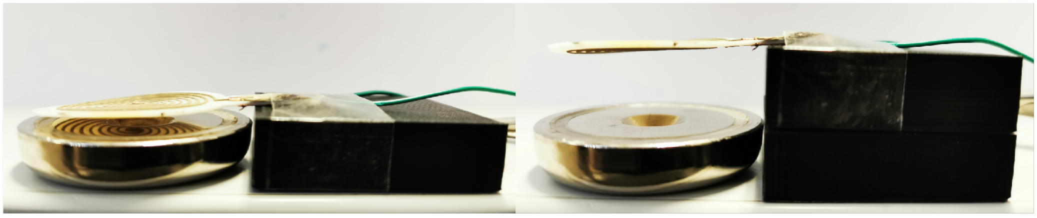


Figure 3.6: Experiment 2 set up: 3D-printed cubes for varying distance.

3.3.1.3 Impact of Magnetic Field

The operational performance of the actuator is contingent upon two critical factors: the separation distance between the actuator and the magnet, and the magnetic field strength generated by the magnet. The interplay of these factors collectively contributes to the overall effectiveness of the actuator. In pursuit of comprehending the impact of varying magnetic field strengths on the performance of *FLECTILE* actuators, our third experiment was designed. In this investigation, we utilized four separate Neodymium disk magnets, each characterized by a different holding force, spanning from 4.5 kg to 18 kg.

The results, as detailed in Table 3.3, reveal a noteworthy finding - a less powerful magnetic field is also capable of activating the actuator, in contrast to the robust magnet with a holding force of 55 kg used in our initial experiments. The magnetic disks with dimensions of Ø30x5 mm and Ø20x3 mm exhibited the capability to produce discernible actuation. Remarkably, both of these magnets fall well below the size constraints proposed by Zeagler [176]. Consequently, the utilization of smaller magnets with comparatively weaker magnetic fields offers the potential to optimize *FLECTILE* actuators, rendering them more compatible with realistic application scenarios and more wearable.

3.3.2 User Study

In order to examine the perception of pleasant vibrations generated by the actuator at 20 Hz, we recruited six participants using a convenience sampling method. The participants' age ranged from 19 to 40 years, with a mean age of 27.8. The sample consisted of 4 males

Table 3.3: Results of Experiment 2 and 3.

Design Parameter	Set Up	Result
Distance (Exp.2)	Fix *FLECTILE* on the cubes with different height	Actuation visible from 1-7 mm distance
Magnetic field (Exp.3)	Magnet sizes and corres-ponding holding forces: Ø15x3 mm (4.5 kg) Ø15x5 mm(8 kg) Ø20x3 mm(12 kg) Ø30x5 mm(18 kg)	Actuation visible with Ø30x5 mm and Ø20x3 mm

and 2 females. Based on the two-point discrimination sensitivity test conducted on various body locations, the finger was determined to be the most sensitive area [176]. Therefore, participants were instructed to test *FLECTILE* using their fingers. Participants were recruited from our laboratory and did not receive any incentives for their participation.

Procedure: The actuator was tested in four different scenarios, and participants were requested to test three times in each scenario and provide feedback at the end of each scenario.

In the first experiment, participants were instructed to *observe* the movement of the actuator. Participants were presented with the actuator in a controlled environment. They were asked to focus on the actuator's motion and *observe* how it operates. No physical interaction with the actuator was required (see in Figure 3.7 A).

The second experiment involved participants *hovering* their fingers over the actuator without making contact before it initiated motion. They were instructed to position their fingers close to but not in contact with the actuator (see in Figure 3.7 B).

In the third experiment, a 3D-printed case incorporating the actuator and magnet was utilized, allowing it to be applied to the participant's finger. Participants were instructed on how to apply the case to their fingers. The actuator was activated within the case, and participants experienced the actuator's motion with their fingers *resting* on the case. Subsequently, we asked the participants to lightly *press* the actuator for the fourth scenario (see in Figure 3.7 C).

Result: The study's results revealed that all participants universally *observed* a distinct vibration, which they could readily and clearly detect during both the "*hover*" and "*rest*" conditions. However, it is noteworthy that in the "*press*" condition, a subset of participants, specifically three out of the six, did not perceive any sensation. This observation suggests that the perceptibility of the vibration may be contingent upon the magnitude of applied force.

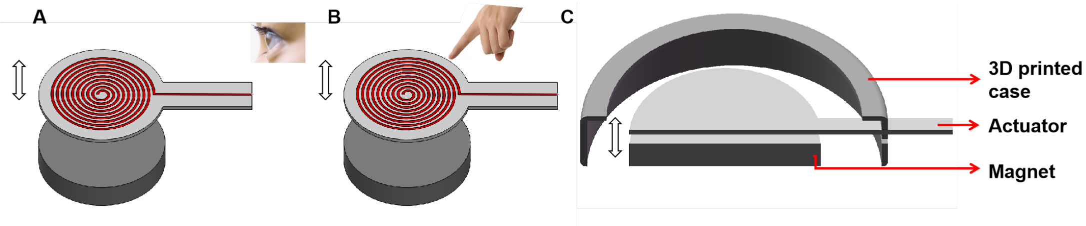


Figure 3.7: (A). *Observe*; (B). *Hover*; (C). Section view of 3D printed case to place the finger used in the *Rest* scenario.

In terms of user experience, all participants consistently reported a high level of comfort and expressed that the actuator did not pose any discernible intrusion or disruption during the course of the experimental sessions. These findings underscore the promising potential of the actuator for delivering subtle tactile feedback while ensuring user comfort and non-intrusiveness.

3.4 Demo Wearable Applications

To show the applicability of *FLECTILEs* in a wearable context, we built two prototypes of applications as shown in Figure 3.8. Given its thin form factor and flexibility, *FLECTILE* can be used to render haptic feedback. To illustrate this, we prototyped two functional on-body notification scenarios.

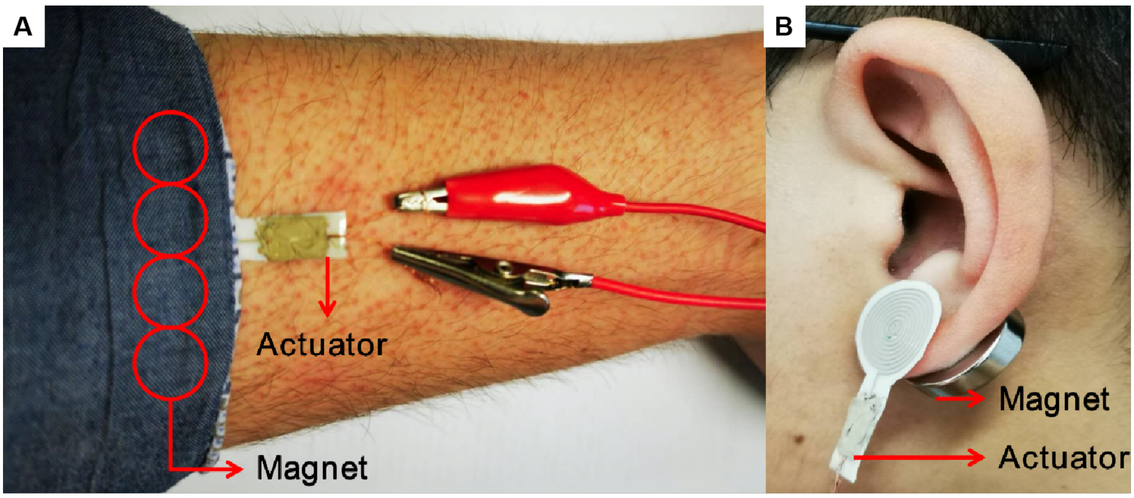


Figure 3.8: Application: (A). Vibration sleeves; (B). Earring-shaped haptic feedback system.

Application 1: In Figure 3.8 (A), the illustration depicts an application scenario involving the integration of a magnet within a textile sleeve. In this configuration, the red circles signify potential magnet placement locations. Furthermore, the *FLECTILE* actuator is strategically positioned directly on the forearm. The primary objective of this setup is to facilitate on-body notifications.

This innovative approach serves the crucial purpose of enabling users to receive information without relying solely on visual cues, thereby reducing the likelihood of missing important details. In addition to its informative function, the actuator also imparts a subtle and gentle patting sensation directly onto the user's skin. This application scenario demonstrates the potential for wearable devices to enhance user interaction and provide discreet, tactile notifications, underscoring their significance in augmenting information dissemination and user experience.

Application 2: In the application scenario presented in Figure 3.8, a novel utilization of the *FLECTILE* actuator is depicted. In this context, the actuator is strategically placed on the user's earlobe. The magnet, an integral component of this setup, is securely affixed to the posterior side of the user's ear using double-sided tape. To ensure the stability and positioning of the *FLECTILE* actuator, a flexible wire is employed to encircle and grip the earlobe.

This particular configuration serves a parallel purpose to the on-skin notification previously described, emphasizing its potential for discreet information dissemination and user interaction. The placement of the actuator on the earlobe underscores the versatility of wearable devices, showcasing their ability to offer unobtrusive, tactile notifications that extend beyond traditional on-skin applications. This scenario also highlights the growing potential for wearable devices to become widely adopted as popular gadgets. Moreover, it underscores the emerging field of ear computing, which unveils the possibilities of integrating vibrating actuators into ear-based positions.

3.5 Conclusion

Within this chapter, we present a comprehensive guide detailing the fabrication process of a wearable electromagnetic actuator that can be attached to the skin. The primary innovation of our actuator lies in the novel design of the 3D-printable soft electromagnetic inductor, which features 3D-planar helical coils made from soft and stretchable materials. An important advantage of our actuator, *FLECTILE*s, is its rapid manufacturability in single-unit batches, made possible using readily available DIY equipment. Furthermore, our actuator distinguishes itself by being entirely elastomer-based, cost-effective due to minimal silver usage, and remarkably lightweight, ranging in weight from 0.4 g to 1.5 g depending on its size.

Previous studies conducted by Sun, Han, and Willenbacher [153] have demonstrated the material's high durability and repeatability. These findings provide additional support for the reliability and longevity of our actuator, making it suitable for extended and repetitive use. Additionally, the distinctive characteristics of this material open up new avenues for design exploration and offer numerous possibilities in the field of soft electronics design and manufacturing.

In our evaluation, we comprehensively assessed *FLECTILE* from both material and user perspectives, considering its performance and user experience. The findings of our evaluation indicate that *FLECTILE* exhibits a broad frequency range of operation and is capable of generating and transmitting vibrotactile sensations. All participants consistently reported being able to visually perceive and tactilely sense the vibrations produced by the actuator. It is noteworthy that three out of the six participants reported an inability to perceive vibrations when pressing the actuator. This observation can be attributed to the excessive force applied, which restricts the available space for the actuator to generate vibrations.

The strength of the magnetic field generated by the traces in *FLECTILE*s is influenced by multiple key factors. Firstly, the density of the coil plays a significant role in determining the magnetic field strength. A higher coil density results in a denser magnetic field, while a lower density may lead to a weaker magnetic field. Secondly, the applied current flowing through the coil has a direct impact on the magnetic field strength. Increasing the applied current generally leads to a stronger magnetic field, while decreasing the current reduces the field strength accordingly. Additionally, the conductivity of the trace material in *FLECTILE*s, which is regulated by the silver fraction, is another crucial factor affecting the magnetic field. The higher the silver fraction, the greater the conductivity of the trace material, resulting in a more efficient flow of current and subsequently a stronger magnetic field. By adjusting and optimizing these factors, *FLECTILE*s can be created in various shapes and sizes. The flexibility in modifying coil density, applied current, and silver fraction allows for the customization of *FLECTILE*s to suit specific application requirements. This adaptability enables the principle underlying *FLECTILE*s to be employed in a wide range of promising applications, where diverse form factors and functionalities are desired. From wearable technologies to soft robotics and haptic interfaces, *FLECTILE*s offer the potential for innovative solutions that can be tailored to specific needs and contexts.

4 DragTapVib: On-Skin Electromagnetic Multi-Stimuli Actuator

Chapter 3 introduced a flexible electromagnetic (EM) haptic actuator, demonstrating significant promise and feasibility in the context of designing and prototyping EM-based haptic actuators. This prompts an essential inquiry: how can the inherent characteristics of electromagnetism be harnessed to devise haptic sensations capable of eliciting and communicating a more extensive array of tactile experiences to the people? Inspired by this insight, this chapter presents *DragTapVib*, a minimal scale electromagnetic actuator that renders dragging, tapping, and vibrating sensations on the user's skin with a simple device. The approach is based on the effective electromagnetic system [38, 125], and it is an easy-to-manufacture, low-cost wearable device. The *DragTapVib* (see Figure 4.1) works by driving a tactor that drags or taps the skin consistently, which potentially excels in wearable multimodal haptic interfaces and extends the possibilities of electromagnetic wearable actuators.

The skin, being the oldest sensory system, provides the sense of touch, which is elicited by mechanical, thermal, chemical, or electrical stimulation, resulting in sensations such as pressure, vibration, temperature, or pain [79]. The skin serves as a constant companion to individuals, creating an opportunity for immediate, subtle, and discreet feedback. Different types of skin cells respond to specific stimuli. For instance, Merkel, Meissner, and Pacinian cells in the hands respond to very-low, low, and high frequencies (approximately 5 Hz, 5-40 Hz, and 40-400 Hz) to detect vibrations [97]. Cells such as Merkel and Meissner cells are sensitive to low-frequency tapping, while Ruffini cells perceive skin stretching. The spatial and temporal resolution of skin sensations is achieved through cutaneous receptors, including Pacinian corpuscles, which are distributed across the body at varying densities [163]. Given the diverse array of sensations that can be perceived on the skin, previous research has explored various actuation principles to provide tactile feedback, including vibrotactile stimulation [38], dragging or sliding sensations [76], stretching or deformation of the skin [165], temperature changes [126], and even airflow [160]. Combining multiple types of stimuli in a single device is highly desirable as it maximizes the variety of outputs that can be presented to the user while occupying minimal space on the skin surface.

Overall, the human skin's remarkable capabilities for sensing and its continuous presence on the body offer immense potential for developing novel and versatile tactile feedback systems that can enhance human-machine interactions across numerous domains. The content of this chapter was published in Proceedings of the ACM International Augmented

Humans Conference 2022 [36] and Proceedings of the 15th ACM International Conference on Pervasive Technologies Related to Assistive Environments in 2022 [40].

The remainder of this chapter is organized as follows: Section 4.1 provides an overview of related works in the field to support the context for our research. Next, Section 4.2 presents a comprehensive overview of *DragTapVib*, including its working principle, design, and fabrication process. The technical evaluation to assess the mechanical properties of *DragTapVib* is detailed in Section 4.3. Then, Section 4.4 presents the findings from our first user study, which focuses on exploring the sensibility and distinguishability among the three stimuli generated by the actuator. Section 4.5 describes another user study conducted to investigate the actuator's potential in providing directional cues. Following this, Section 4.6 presents two wearable applications to demonstrate the utility of the actuator. Finally, Section 4.7 concludes the chapter by discussing the limitations of *DragTapVib* and outlining potential areas for future research.

4.1 Related Work

Our research builds upon prior work in the field of wearable actuators within the Human-Computer Interaction (HCI) community. Tactile interaction has been well investigated in past decades [46, 53]. Many haptic feedback mechanisms providing not only kinesthetic but also static tactile stimuli [63, 69] have been reported. Prior work has proven that vibrotactile displays can be beneficial in many aspects, such as for notifications [38, 127, 180] and medical navigation [132]. In our work, we begin by providing a comprehensive summary of relevant publications that explore actuators capable of integrating multiple stimuli. Subsequently, we introduce wearable tactile devices that have been designed to deform the skin, drawing upon previous research in the HCI domain.

4.1.1 Multi-Stimuli Actuators

In past decades there has been a dramatic increase in unified devices that can provide multiple stimuli. Wang, Ohnishi, and Xu [166] proposed the definition of multimodal haptic devices: " be able to produce multimodal haptic stimuli, including forces, vibration, thermal stimuli, and shape". Thanks to the combination of multimodal natures, these devices have greatly enriched the applications and potential of haptic perceptions [146]. Zhu et al. [180] presented a pneumatic forearm actuator that can produce multiple haptic stimuli, including compression, skin stretch, and vibration. Preechayasomboon, Israr, and Samad [130] reported *Chasm* which could render low-frequency skin-stretch and high-frequency vibrations, simultaneously and independently. Shim, Lee, and Lee [144] combines wind and vibration together around the wrist as a multimodal tactile display. Hamdan et al. [57] developed an on-skin interface to deform the skin directly based on shape memory alloy (SMA) springs. He, Wang, and Xu [64] presented a wearable device, which generates light presses and drags to assist blind and visually impaired (BVI) people to search for the correct objects in unfamiliar surroundings. Multi-stimuli devices have yielded good results gradually and drawn a growing trend. However, all the above-listed devices need to combine multiple different actuators or multiple adoptions of the same actuator (e.g., one with a tactor, one without ,etc.) to provide multiple sensations. In contrast, *DragTapVib* we contributed in this chapter leverages one simple mechanism to implement all its three sensations.

4.1.2 Skin Drag Display

The application scenarios of wearable actuators depend heavily on the type of output the actuator rendering on the human skin. In general, actuators generate tactile feedback by deforming the human skin. Therefore, previous works have used intuitive terminology to describe the output of the actuators, such as vibrotactile feedback, vibrating, tapping, pressing, squeezing, compressing, dragging, and stretching [76, 78, 117, 165] etc. Our device integrates the pressure force and shear force to render multiply sensations. There are two typical ways to apply shear force on the human skin. One method involves fixing the endpoints of the actuator to the skin with tape or plaster, and the actuator deforms the skin by applying force directly to the attachment points. The other way is to drag a tactor on the skin. Therefore, we highlighted these two closest relevant methods to our work.

4.1.2.1 Attachment Points

Ito et al. [78] introduced a skin-stretcher worn around the users' neck for gently urging head rotation using servo motors to push / pull the skin. Muthukumarana et al. [117] embedded shape memory alloy (SMA) wires in a lightweight actuator to stretch the skin. Springlet [57], which is attached to the skin by means of self-adhesive tape made of silicone rubber, deforms the skin by applying force to the attachment points and supports six non-vibrating tactile primitives. SCWEES reported by Haynes et al. [62] is a lightweight 3D-printed semi-flexible actuator that attaches to the inner forearm skin at two points using two adhesive pads, stretching and squeezing the skin's surface gently. All these works have attachment points that is always in contact with the skin and through which the force is transmitted to the skin for perception.

4.1.2.2 Tactor

Skin displacements have also been proven to be useful in interaction and have the potential for several applications[51]. It is worth noting that the shear force is able to provide information about directions. Thus, related work has explored using the small shear stimuli to communicate direction cues via skin stretch. Most frequently various forms of shear force actuation are leveraged on the users' hand [51, 76, 80, 152], considering the practicality and light form factor. Gleeson, Horschel, and Provancher [50] reported a fingertip-mounted tactile device to convey direction information, which is served as initial design guidelines for future devices. Je et al. [80] presented The tactoRing that drags a small tactor on the skin around the finger, preciously indicating qualitative and quantitative information. Skin Drag Display reported by Ion, Wang, and Baudisch [76] drags a physical tactor across the user's wrist to produce a stronger tactile stimulus than vibrotactile, which allows users to recognize tactile shapes significantly. These works inspired our prototype design, and we also leveraged a flexible tactor driven by the magnetic repulsion to induce the on-skin sensations: drag / tap / vibrate as a novel mechanism.

4.2 DragTapVib: Tri-Stimulus Actuator System Overview

To facilitate the construction and replication of our design, we begin by providing an introduction to the fundamental components and structure of *DragTapVib*. This actuator incorporates an overlapping electromagnetic coil design housed within a 3D-printed enclosure. Moreover, in the spirit of open-source collaboration, we make available all the necessary 3D files, schematics, and a comprehensive fabrication guide for our implementation, accessible at the following repository: [1]. By employing our approach, we successfully generate robust electromagnetic fields capable of displacing a static magnet affixed to a tactor, thereby enabling the delivery of diverse tactile sensations through the utilization of various activation patterns.

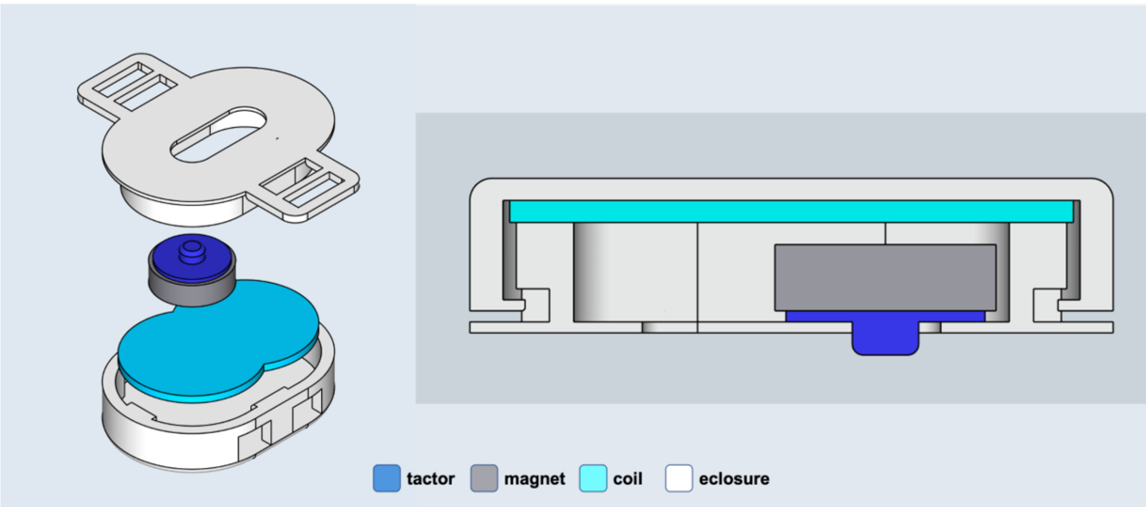


Figure 4.1: Overview of the of *DragTapVib*.

[1] https://github.com/teco-kit/DragTapVib

4.2.1 Hardware Implementation

The key component of our design is the electromagnetic (EM) actuator responsible for driving the tactor, which provides tactile feedback to the users. As depicted in Figure 4.2, the core elements of *DragTapVib* consist of commercially available, two-layer flexible PCBs obtained from Flexar.io [2], along with a permanent magnet and 3D-printed tactor and housings, all of which have a low cost (less than 3 Euros for a complete actuator).

Each flexible PCB coil is constructed with 70 turns of copper trace, distributed across two layers, on a 17 mm diameter, resulting in a resistance of 22.5 Ohms per coil. The thickness of each PCB is 0.1 mm, with a weight of 0.066 grams. The neodymium magnet employed measures Ø 10 mm x 3 mm and possesses a maximum holding force of 2 kg. Both coils are connected to an *Arduino Nano* microcontroller, operating at a voltage of either 3.3V or 5V.

The actuator's total mass amounts to 4.3 grams, and its external dimensions are 6.5 mm (height) x 28.6 mm (width) x 20 mm (depth). To enable the rendering of stimuli to the user through the vertical and horizontal movement of the static magnet and tactor, we allocate 1.5 mm and 8.5 mm of space within the case, respectively.

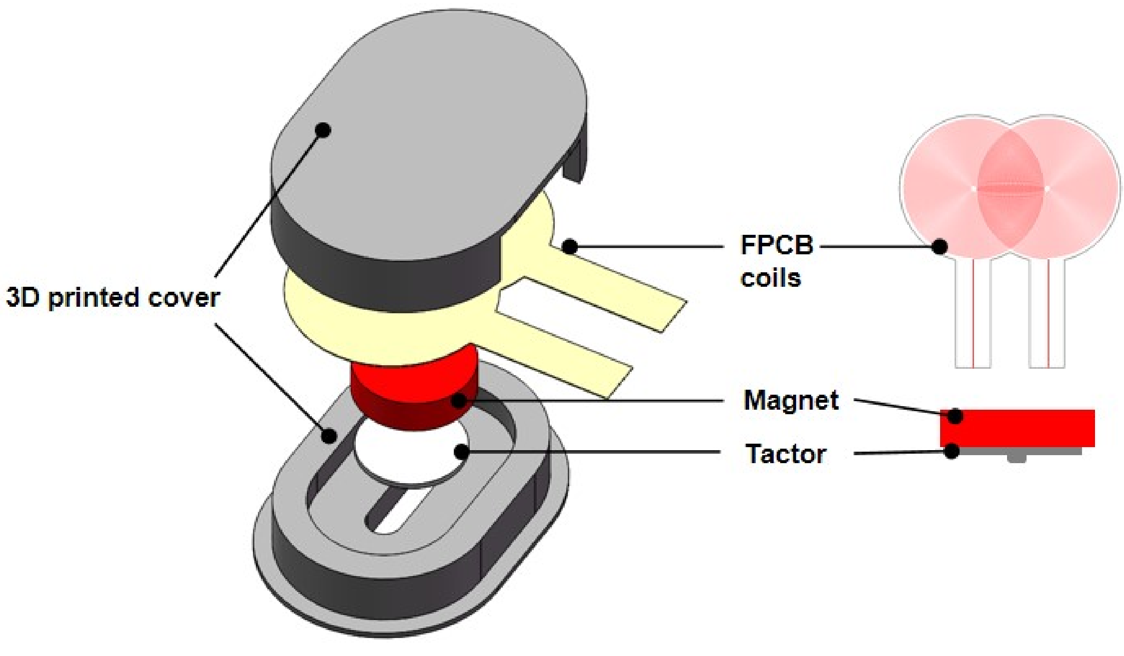


Figure 4.2: Explosion view of the *DragTapVib*.

[2] https://flexar.io/

4.2.2 Fabrication and Assembly

In this section, we provide a comprehensive demonstration of the step-by-step assembly process for the main components of the actuator, resulting in a lightweight wearable haptic feedback device. By presenting a "cook-style" instruction, readers can easily replicate and construct their own *DragTapVib*s with simplicity and effectiveness. The assembly process is visually depicted in Figure 4.3.

Ingredients

- 1 Magnet (Ø 10 mm x 3 mm);
- 4 Flex PCBs;
- Ultimaker 3 TPU 95A filament (2.85 mm, 750 g, white);
- Ultimaker 3 PLA filament (2.85 mm, 750 g, white);
- Double-sided tape;

Apparatus

- Ultimaker 3 3D printer;

Instruction

- Print housing using TPU 95A filament from the 3D printer;
- Print tactor using PLA filament from the 3D printer;
- Glue the tactor on the bottom of magnetic with double-sided tape;
- Superimpose and paste the two flex PCBs together and connect them in parallel;
- Insert the flex PCBs into the bottom part of the housing;
- Place the magnet with tactor on top of the flex PCBs;
- Assemble the upper and lower parts of the housing;

4.2.3 Electronics and Schematics

We developed and constructed two distinct versions of our actuator to cater to specific requirements: a USB version primarily employed for characterizing the actuator's properties, and a wireless version designed to facilitate more realistic application scenarios.

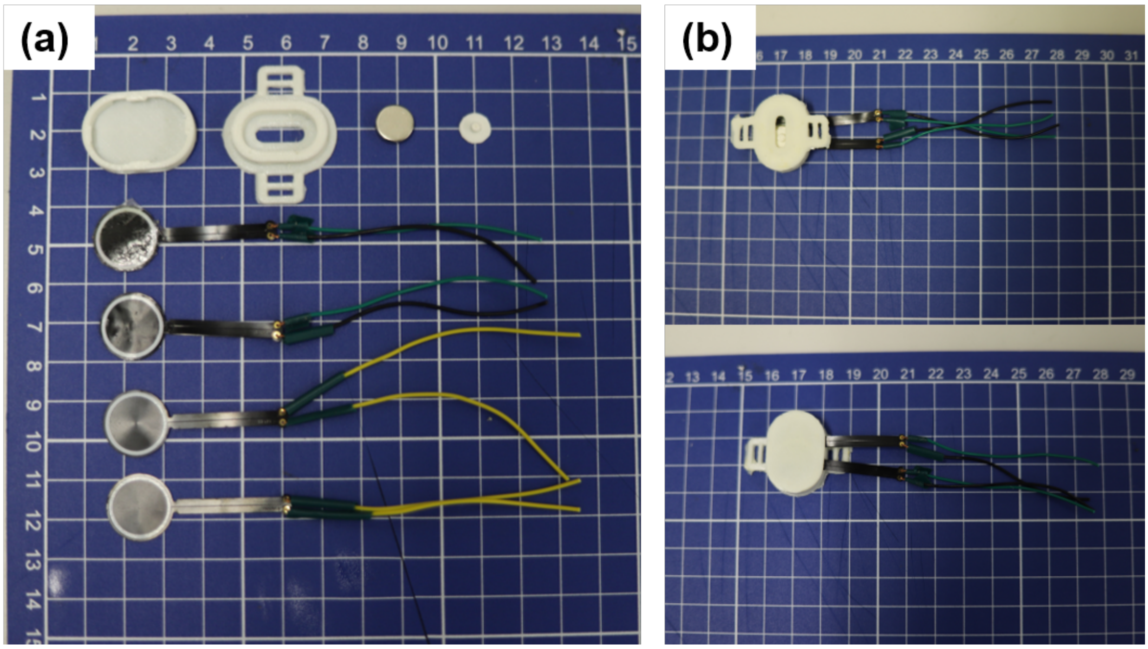


Figure 4.3: *DragTapVib*'s components and assembly. (a). All components before assembly; (b). A completed device.

For the wireless variant, we utilized the *ESP32* microcontroller, which integrates Wi-Fi and dual-mode Bluetooth capabilities. This integration, along with a low-level library developed in Python, enables seamless connectivity between the actuator and mobile devices, enhancing portability and versatility in usage.

All evaluation interfaces presented in the following evaluation part were implemented using the Arduino Integrated Development Environment (IDE), ensuring a standardized and reliable platform for conducting the evaluations.

The electronics schematic of our USB prototype, controlled by an *Arduino Nano* microcontroller is illustrated in Figure 4.4. The prototype is connected to wires approximately 0.5 meters in length, allowing for convenient positioning during experimentation. Both coils of the actuator are connected to an H-bridge (*L9110 Dual-Channel H-Bridge Motor Driver Module*), which serves to control the direction and intensity of the electrical current. The H-bridge, in turn, is connected to the *Arduino Nano* microcontroller, which operates at either 3.3V or 5V, providing the necessary power supply for the actuator.

4.2.4 Working Principle

DragTapVib operates on the principle of Ampere's Law, wherein an electromagnetic field is generated by a conductor when an electric current passes through it. By systematically controlling the direction and intensity of the electric currents flowing through the two

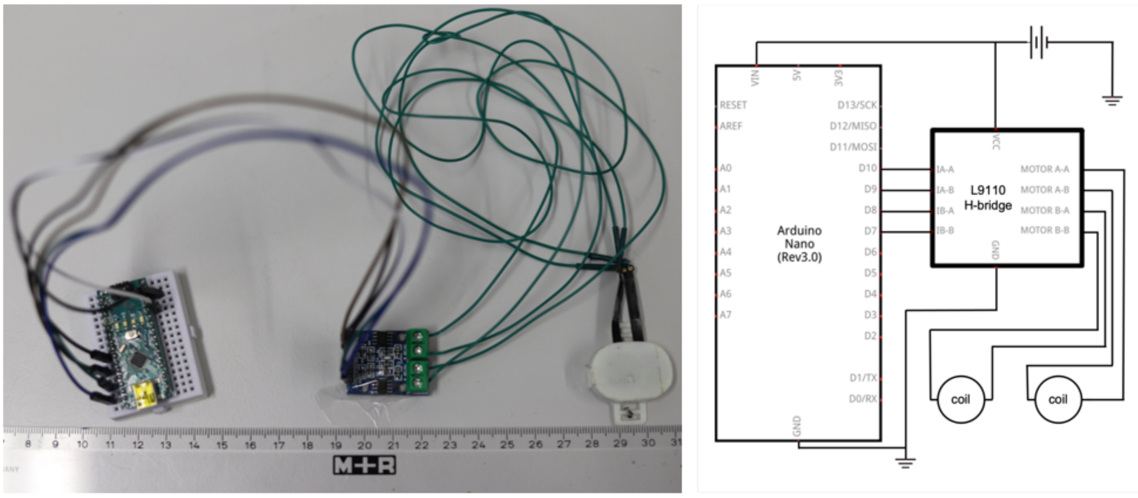


Figure 4.4: Electronics schematic of the USB version actuator.

electromagnetic coils in *DragTapVib*, it becomes possible to manipulate the position of a static magnet. This allows for the generation of various tactile sensations on the users' skin. Through the coordinated repulsion and attraction forces produced by the coils, the tactor's motions can be precisely controlled, resulting in the delivery of distinct stimuli to the user.

In addition, we investigated the impact of coil arrangement on the resulting magnetic field. Figure 4.5 provides a simulation of two different coil arrangements (software: *COMSOL Multiphysics*). When the two coils are situated side-by-side, the induced electromagnetic field's distribution along the axis defined by the centers of the two coils is primarily concentrated at the central region of each coil. However, this configuration yields a relatively weak magnetic field, which is insufficient to firmly attract the magnet. Conversely, when the two coils are overlapped, the magnetic field along the direction of the two coil centers becomes strengthened. This overlapping design generates a stable and more uniform magnetic field, resulting in improved actuation performance during tapping and vibration. Additionally, the overlapping configuration minimizes the horizontal movement of the magnet and tactor. Based on these findings, we adopted the overlapping coil design to achieve a more robust electromagnetic field and enhance the actuator's performance.

4.2.5 Rendering Three Haptic Sensations

To generate a range of haptic sensations, we manipulate the electromagnetic field based on the aforementioned actuation principle. The motion of the tactor under different magnetic field conditions, resulting from changing current flows within the FPCBs, is illustrated in Figure 4.6. The *Dragging* mode operates by alternately attracting and repelling the tactor through the coordinated action of the two coils. This motion causes the tactor to move

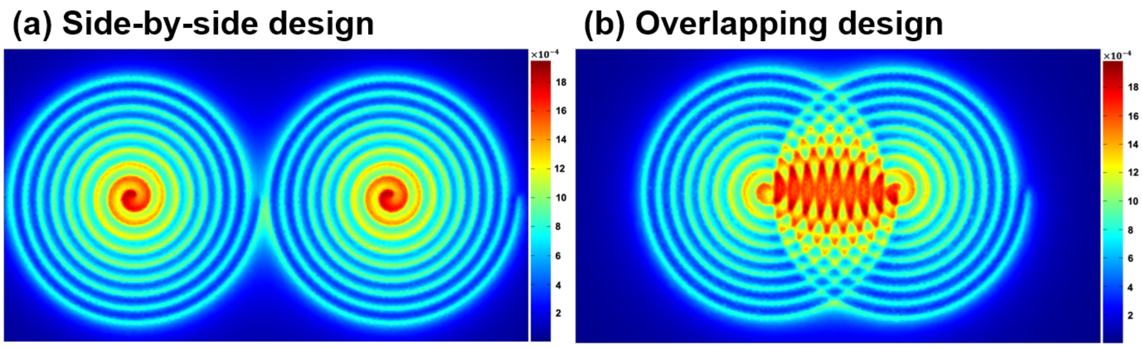


Figure 4.5: Simulation of the magnetic field: (a). side-by-side coil design; (b). overlapping coil design.

back and forth along the surface of the user's skin. The *Tapping* mode delivers gentle taps to the user by retracting and extending the tactor pin inside and outside the case, respectively. The *Vibrating* mode involves maintaining the tactor in constant contact with the user's skin while rapidly moving it up and down. This rapid movement produces a vibration sensation, primarily due to the magnet's quick retraction. By employing these different modes of operation, we could provide users with a versatile range of haptic feedback experiences.

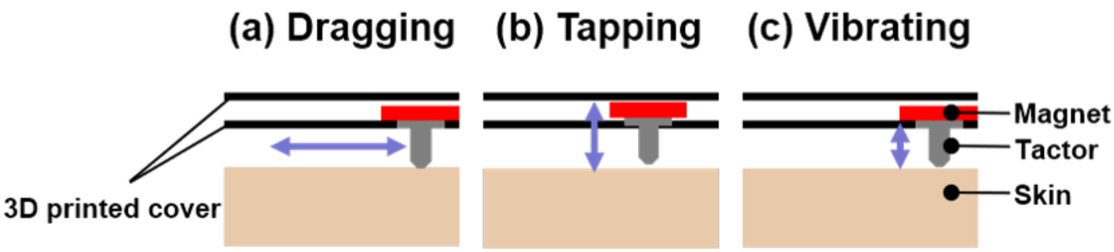


Figure 4.6: Schematic cross-section of the motions of the tactor: (a). dragging; (b). tapping; (c). vibrating.

Subsequently, we introduced three haptic sensations in detail:

1. **Dragging**: This sensation is generated from the horizontal movement of the tactor, which contact and stretch the skin laterally to produce on the shear force directly [165]. We alternately activated the magnetic field to drive the magnet and tactor. Then, the mechanism keeps dragging the users' skin directly at a predetermined speed. The maximum tactor movement distance in our device is 8.5 mm, which is far higher than the small amount of skin stretch could be easily detected (0.27 mm) [131].

2. **Tapping**: Tapping consisted of applying and removing contact to the same region, maintaining approximately equal force at the same rate [89]. We controlled the magnetic field to attract the repel the magnet periodically to manage the vertical

movement of tactor. Thus, the tactor could contact and leave the skin at a specific rate.

3. **Vibrating**: This sensation is also generated from the vertical movement of the tactor. However, we leveraged a higher frequency to control the alternation of the current. Thus, the user feels the vibration of the whole actuator more than the movement of the tactor.

4.3 Technical Characterization

In order to investigate and understand the technical properties of *DragTapVib*, we performed a series of experiments. The initial characterization involved measuring the actuation speed and noise level of our device. Subsequently, we conducted experiments to examine the relationship between magnet movement and the corresponding maximum force generated during t*Dragging*, *Tapping*, and *Vibrating*, respectively. Throughout the calculations, we considered a standard gravity value of g = 9.80 m/s^2. These experiments aimed to provide insights into the performance and capabilities of *DragTapVib*, allowing for a better understanding of its technical characteristics.

4.3.1 Measuring Speed & Noise

Latency: The system exhibits an actuation time of 25 ms, which refers to the duration between the activation of power and the initiation of the mechanism's operation. This actuation time was measured using a slow-motion camera capturing footage at a rate of 240 frames per second (fps) [158]. This relatively fast speed is thanks to the effective electromagnetic system, which enables us to create seamless real-time interactions by directly rendering multiple sensations on the skin. This capability allows for an enhanced user experience, as the actuator can deliver tactile feedback instantly and in a responsive manner. We conducted a comparison of the rise-up time between commonly used actuators in haptics and our prototypes. For reference, the rise-up time of an ERM actuator typically ranges from 40 to 100 ms (Model: Texas Instruments DRV2605, data-sheet, p. 15, Table 1) and LRA actuator: 12.9 ms [130].

Operational noise: We further assessed the operational noise of our device using a microphone, employing a similar method described in [158]. The measurements were recorded at arm's length from the device and in comparison to a quiet background. Our device registered an operational noise level of approximately 35 dB SPL (Sound Pressure Level). As a reference, a normal conversation at 4 feet produces around 60 dB SPL.

4.3.2 Dragging

Frequency: We positioned a slow-motion camera with a frame rate of 240 fps to capture the movements of the tactor from a bottom-view perspective. In order to understand the relationship between the frequency of electric actuation and the corresponding magnet movement, we conducted experiments by incrementally varying the actuation frequency from 1Hz to 30Hz with a step size of 1Hz. Figure 4.7 indicates how the tactor's movement varies with different actuation frequencies.

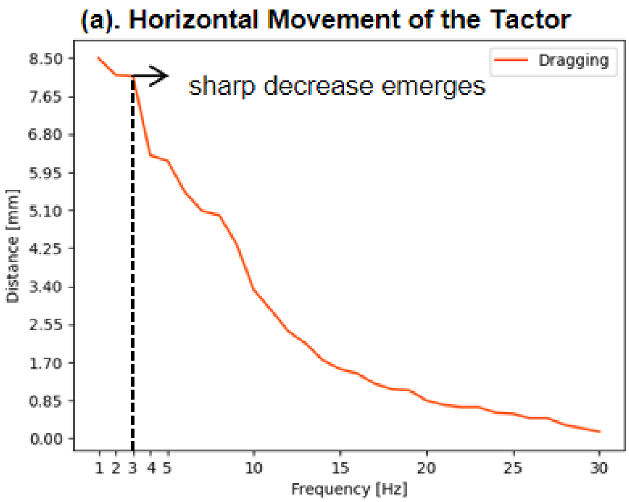


Figure 4.7: Evaluation results for the horizontal movements of the tactor.

As the actuation frequency increased, the range of motion for the tactor gradually decreased. The actuator demonstrated its most reliable performance within the frequency range of approximately 1 Hz to 3 Hz. However, the results obtained from the frequency response characterization revealed a significant decay in the actuator's output starting from 4 Hz and beyond. At frequencies exceeding 30 Hz, the motion of the magnet approached zero, indicating diminishing effectiveness and reduced functionality.

Force: In our initial investigation, we examined the maximum dragging force generated during the linear reciprocating motion of the actuator. To measure this force, we connected the tactor, attached to the magnet, to a weight using a thread and pulley system (see Figure 4.8 (a)). We gradually added weight until the tactor reached its maximum capacity and could no longer lift the weight. The maximum weight that the actuator could sustain was determined to be 1.9 grams, equivalent to a force of 18.6 mN.

Additionally, we investigated the dragging force exerted when the magnet was positioned at the center of one coil. Using the same experimental setup as previously described, we gradually added weight until the electromagnet could no longer securely hold the magnet in place at the coil's center. The maximum weight that the electromagnet could support under these conditions was measured to be 4.9 grams, corresponding to a force of 48.0 mN.

4.3.3 Tapping

Force: We investigated the maximum mechanical *tapping* force generated by the actuator for user interaction. To assess this, we attached a plate on top of the tactor to support the weight (see Figure 4.8 (b)). We continued adding weight until the tactor could no longer extend fully beyond the 3D-printed cover. The results revealed a maximum weight of 5.2 grams, which included the weight of the magnet and connection mechanism (totaling 1.7 grams). Consequently, the maximum static tapping force achieved by our prototype reached 51.0 mN. Comparing these results to previous works such as those by King, Donlin, and Hannaford [84], Dosher and Hannaford [30], and Louw, Kappers, and Koenderink [100], which reported detection thresholds ranging from 25 to 40 mN for static tactile displays, our actuator demonstrates the ability to generate higher forces within shorter actuation periods, resulting in more perceptible stimuli [68]. Furthermore, Pece et al. [125] reported forces up to 160-200 mN using a four-layer coil mechanism operating at 24 V. It is worth noting that our prototype operates at a lower voltage range (3.3 V - 5 V) with fewer layer of coils, yet still achieves considerable force output.

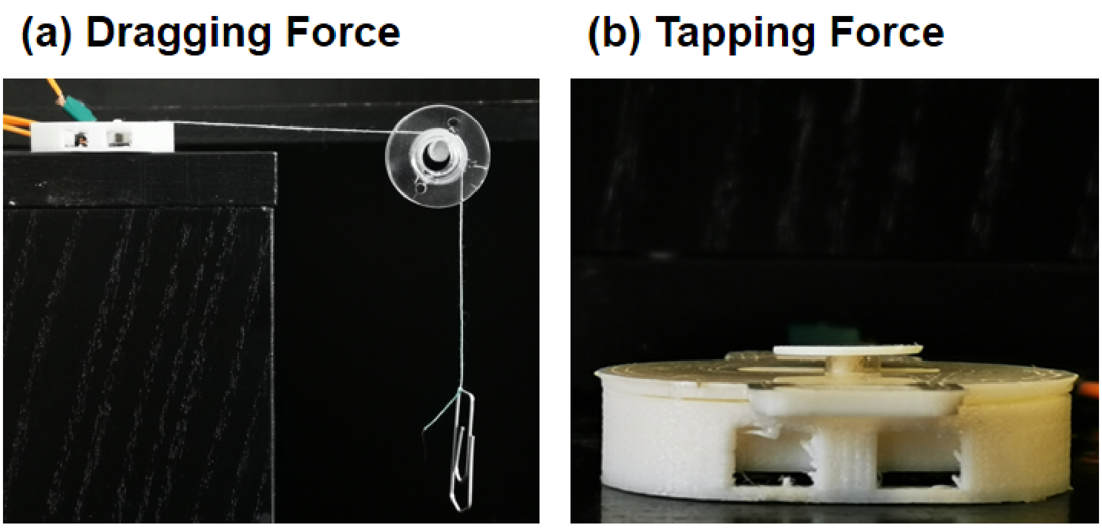


Figure 4.8: Force test setup: (a). dragging; (b). tapping.

4.3.4 Vibration

As depicted in Figure 4.9, the horizontal movement of the tactor exhibits a sharp decline within the 20-30 Hz range. This indicates that the tactor is unable to fully extend beyond the cover, resulting in a limited generation of strong mechanical force beyond this frequency range. To further investigate the relationship between frequency and the magnet's movement, we attached a 9-axis IMU (Brand: Sparkfun; Model: ICM-20948) to record changes in the Z-axis acceleration. The actuation frequency was adjusted from 30 Hz to 250 Hz with a step size of 10 Hz, and then from 250 Hz to 1000 Hz with a step size of 50 Hz. The Z-axis accelerometer readings were utilized to characterize the relationship between the actuation frequency and the actuator's amplitude during vibration. As shown in Figure 4.10, the normalized acceleration values exhibit a downward trend, with a significant decrease observed beyond 50 Hz. Furthermore, the readings approach zero from approximately 130 Hz onward. These findings demonstrate the limitations of the actuator's amplitude at higher frequencies and suggest the reduced effectiveness of the actuation beyond certain frequency thresholds.

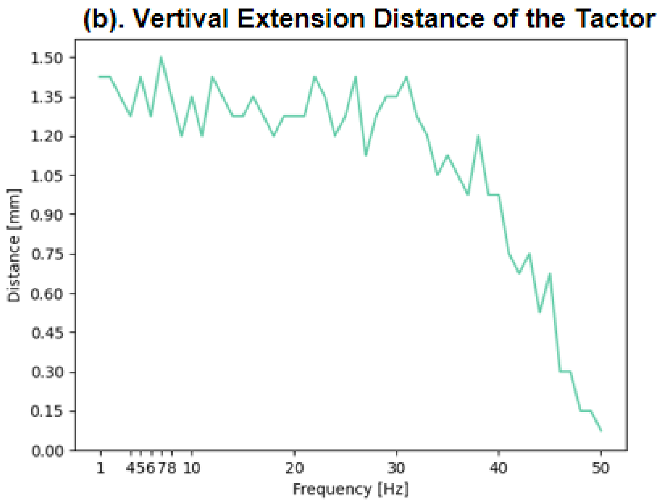


Figure 4.9: Evaluation results for vertical extension distance of the tactor.

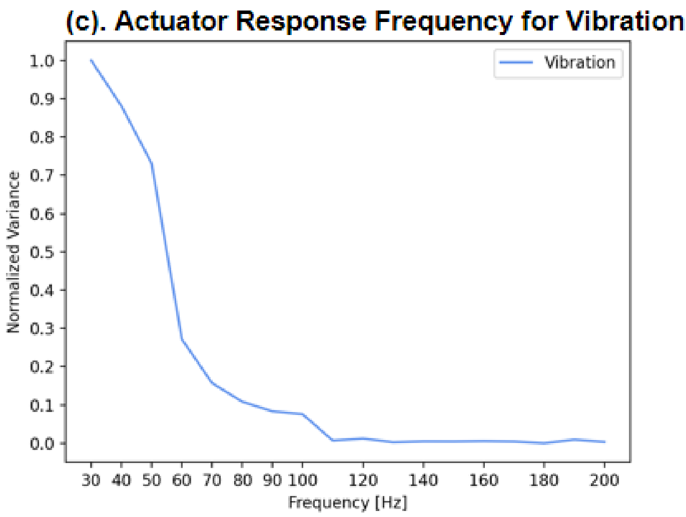


Figure 4.10: Evaluation results for actuator response frequency for vibration.

4.4 User Evaluation for Evaluating Perceived Tri-Stimuli

To comprehensively evaluate and explore the potential application scenarios of *DragTapVib*, we conducted a series of user evaluations using our prototype. The lightweight and compact design of *DragTapVib*, coupled with its ability to provide three distinct sensations (*Drag*, *Tap*, and *Vibration*), enhances the potential for diverse application scenarios. These evaluations aimed to investigate the tactile acuity [167] across different body locations, as well as to advance the development of wearable haptic displays capable of delivering more than just vibrations to the skin. Notably, our prototype offers the opportunity to program and deliver rich information to the skin through these three main sensations, as depicted in Figure 4.6.

Location	Sensitivity			Comfort			Distinguishability		
	D	T	V	D	T	V	D	T	V
Proximal Phalanx	**6.5 (6.25-7.00)**	**7 (6.25-7.00)**	7.00	6 (6.00-6.75)	**6.5 (6.00-7.00)**	**6 (6.00-6.75)**	**7 (6.25-7.00)**	**6.5 (5.25-7.00)**	**6 (4.25-7.00)**
Middle Phalanx	**6.5 (6.25-7.00)**	6.5 (6.00-7.00)	7.00	6 (6.00-6.75)	6 (5.25-6.00)	5.5 (5.00-6.00)	6 (5.25-6.75)	5.5 (4.25-6.75)	5.5 (3.25-7.00)
Inner Wrist	6.25 (6.00-7.00)	6.5 (6.00-7.00)	7.00	5 (4.25-5.00)	5.5 (5.00-6.00)	5.5 (5.00-6.00)	5 (5.00-6.50)	5 (5.00-5.75)	5.5 (4.00-7.00)
Outer Wrist	6.25 (6.00-7.00)	**7 (6.25-7.00)**	7.00	**7 (6.25-7.00)**	6.5 (6.00-7.00)	**6 (6.00-6.75)**	**6.5 (5.00-6.75)**	**5.5 (4.25-6.75)**	**6 (3.5-7.00)**

Figure 4.11: Exploratory study results. The median and interquartile range from 7-point Likert scale ((1 = strongly disagree and 7 = strongly agree).

Furthermore, the effective electromagnetic system employed in our device allows for activation across a wide range of actuation periods. While the results from previous technical evaluations have provided insights into the actuator's response to different frequencies, further investigation is needed to scale this scope down further to filter out the parameters that are perceived and distinguished clearly by users. Consequently, we aim to address the following research questions based on our user evaluations:

- **RQ1**: How the varying locations of the body could influence perception in terms of (A) *sensation sensitivity*, (B) *comfort*, (C) *distinguishability*?
- **RQ2**: How could the actuation period ranges affect while perceiving and discerning sensations well?
- **RQ3**: How to assess participants' ability to tell the three stimuli apart?

4.4.1 Exploratory Study

To address our research questions, we conducted an exploratory study aimed at identifying the optimal placements (RQ1) and determining the most effective actuation period (RQ2) for our device. Previous studies have highlighted six potential body locations for haptic actuators, namely the outer wrist, index finger, palm, center chest, ankle, and upper-arm [101, 125]. Considering that our prototype operates based on the Lorentz force and functions optimally when placed in a horizontal orientation, we took into account the sensitivity of different locations on the arm [176]. As a result, we selected four specific positions: *Index Finger Proximal Phalanges*, *Index Finger Intermediate Phalanges*, *Outer Wrist* and *Inner Wrist* for our exploratory study, which were determined to be the most suitable for our objectives (see Figure 4.12).

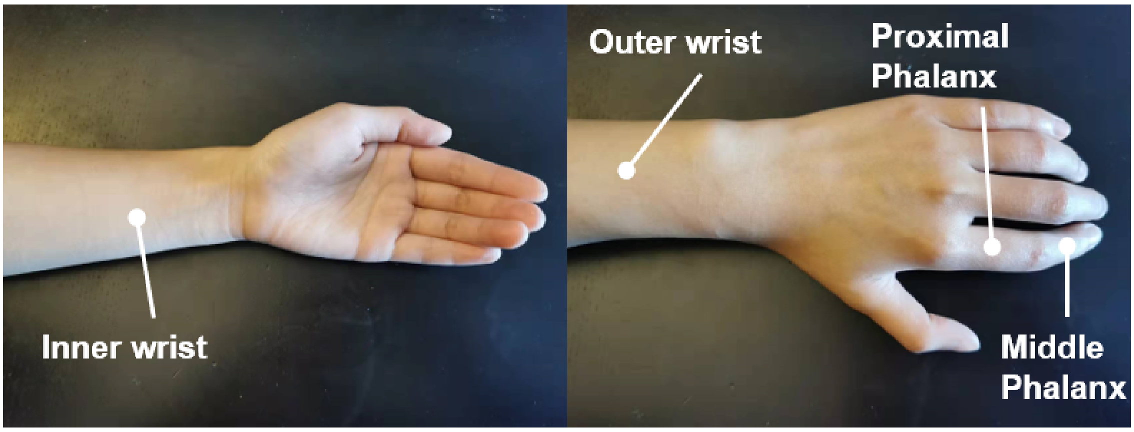


Figure 4.12: Schematics of the locations in our tests.

We tested actuation frequencies for *Dragging* of 1, 2 and 3 Hz and for *Vibration* of 30, 40, and 50 Hz following the above results. *Tapping* [89] is composed of applying and removing contact with the skin with the same rate. Previous work reported [10, 125] reported a best actuation period of 0.25 and 0.5 seconds respectively. Thus, we tested the actuation interval for *Tapping* of 0.25, 0.5, 0.75 and 1 seconds.

A total of six healthy participants (Mean Age = 27.7; Standard Deviation = 3.6 years; five males; one female) were recruited to participate in the study. The participants were seated in a standard office chair, and their dominant arm was positioned on a table. To secure the actuator onto the participants' forearms, an elastic strap was used. Prior to the main exploratory study, participants were familiarized with a pattern comprising three distinct sensations delivered by the actuator. To minimize any potential auditory distractions, participants were instructed to wear noise-canceling headphones, effectively eliminating any noise generated by the actuator.

During each test, the tactor was actuated for a duration of five seconds using a randomly selected parameter from the testing ranges. This procedure was repeated for all the testing periods, with a 20-second pause between trials. To ensure a balanced experimental design, the test orders for wearing locations were counterbalanced among the participants. After testing each type of stimulus, participants were required to provide two responses: (a) identify the perceived sensation and (b) assess the appropriateness of the stimulus speed, considering whether it was neither too slow nor too fast. Subsequently, participants were asked to answer a series of questions from three different perspectives: (A) sensitivity, involving the statement "I could easily and clearly feel the exact movement of the tactor on my skin"; (B) comfort, involving the statement "I would use the device to receive notifications at this location"; and (C) distinguishability, involving the statement "It was easy to tell which type of stimulus was activated and what I felt." Participants were requested to rate their responses on a 7-point Likert scale. To ensure participant comfort and minimize potential fatigue, a five-minute break was provided between each location test.

The findings from the exploratory study are summarized in Figure 4.11. The **Index Finger Proximal Phalanx** and **Outer-Wrist** emerged as the trade-off locations, ranking highest in terms of sensitivity, comfort, and distinguishability. Participant feedback revealed that wearing the actuator on the **Index Finger Middle Phalanx**, although it conveyed stronger sensations at times, was perceived as uncomfortable and inconvenient due to the need for frequent bending of the finger. Participants P1 and P5 specifically expressed their discomfort with this placement, with P1 stating, "It is weird and uncomfortable to wear the actuator on the Index Finger Middle Phalanx where needs to be bent often, though this part conveyed stronger sensations sometimes," and P5 mentioning that "Notifications could be easily missed when the finger is bending, for instance, typing with the keyboard." On the other hand, participants expressed positive feedback for the **Outer Wrist** location, which is commonly used in wearable computing. P2 described the sensation of "Dragging" as similar to someone scratching them, expressing surprise and enjoyment. Based on the results, the optimal actuation frequencies for *Dragging* and *Vibration* were determined to be **2 Hz** and **40 Hz**, respectively, while the most effective actuation interval for *Tapping* was **0.5** seconds across all tested locations.

4.4.2 Main Study

The objective of our main study was to validate the capability of our prototype to deliver three distinct sensations that could be both perceived and distinguished by users. Building upon the narrowed-down results from the exploratory study, the main study was divided into two parts: *Perception* and *Distinction*. These two parts aimed to further investigate the users' perception of the sensations generated by the actuator and their ability to differentiate between the three types of stimuli.

4.4.2.1 Participants

A total of 12 participants were recruited from our campus (Mean Age = 28.2; Standard Deviation = 3.3; ten males; two females), none of whom had participated in the previous exploratory study. All participants were seated in office chairs equipped with noise-canceling headphones to minimize auditory distractions during the study.

4.4.2.2 Study Design

In our study, we employed a within-subject design featuring two independent variables, namely, "Location" (with options for **Index Finger Proximal Phalanx** and **Outer-Wrist**) and "Stimuli" (including *Drag*, *Tap*, and *Vibration*).

Perception: Participants were instructed to perceive all three stimuli at two different locations. The order of stimulus presentation and location assignment was counterbalanced among the participants. During each trial, a single stimulus was rendered by the actuator. Each stimulus was activated three times, with each activation lasting for five seconds, followed by a five-second pause. To assess their perception and recognition of the stimuli, participants were instructed to press a button as quickly as possible once they recognized and identified the stimulus, allowing their response time to be logged. After each trial, participants were asked to classify the type of stimulus they perceived and rate their recognition performance using a 5-point Likert scale. To ensure participant comfort and reduce fatigue, a 30-second break was provided between trials, while a 50-second break was given between location blocks for rest and recording participant feedback.

Distinction: We conducted an absolute identification study to evaluate participants' ability to distinguish between the three different signals (*Dragging*, *Tapping*, and *Vibration*). Participants were informed that they would experience a total of 12 stimuli, consisting of 4 instances of each stimulus type. The order of presentation for the stimuli was randomized, and participants were unaware of the specific number of each stimulus type. During the study, each stimulus was played once and lasted for three seconds, with a 10-second pause between subsequent stimuli. Participants were instructed to press a button corresponding to the stimulus they perceived after each presentation. Upon completion of the entire experiment, we conducted a brief conversation with the participants, encouraging them to provide feedback on potential applications and share their comments regarding our device and the three stimuli.

The overall experiment is comprised of *Perception*: 12 participants * 2 body locations * 3 stimuli * 3 repetitions; *Distinction*: 12 participants * 12 random stimulus * 2 body locations. The duration of the test took approximately 40 minutes per participant.

4.4.3 Results

4.4.3.1 Response Time

The data analysis encompassed the evaluation of participants' response times, measuring the duration between the initiation of a stimulus and their subsequent action (see in Figure 4.13). The outcomes of this analysis revealed a consistent trend: participants consistently exhibited quicker response times when the stimulus was applied to the finger as opposed to the wrist, regardless of the nature of the stimulus employed [176].

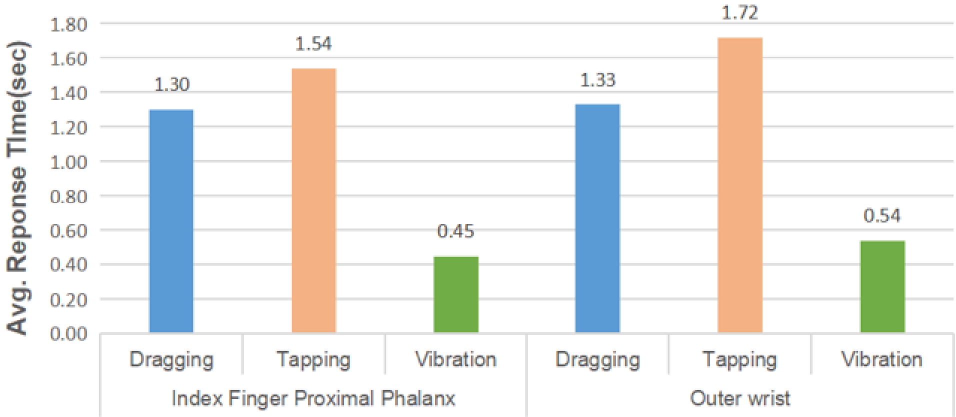


Figure 4.13: Average response time grouped by type of stimuli and location.

4.4.3.2 Accuracy

The overall accuracy of perception reached 87.5%, indicating a high level of accuracy in distinguishing the three stimuli. Upon reviewing the experimental data, we identified errors predominantly occurring in the *Dragging* and *Tapping* stimuli, with the *Vibration* stimulus being perceived flawlessly. Additionally, the location of the stimulus presentation had a significant impact on perception accuracy, with the finger location yielding significantly higher accuracy compared to the wrist location.

Regarding the distinction accuracy, the overall accuracy reached 97.9%, with a distinction accuracy of 98.6% for the **Proximal Phalanx** location and 97.2% for the **Outer Wrist** location, respectively. Figure 4.14 displays the results of the distinction study, clearly indicating that errors primarily occurred when distinguishing between the *Tapping* and *Dragging* sensations. Furthermore, the experimental results demonstrate that the *Finger Phalanx* location achieved higher accuracy compared to the *Outer Wrist* location.

4.4.4 Discussion

The purpose of this evaluation was to address the research questions we formulated earlier. Regarding **RQ1**, we successfully narrowed down the potential locations for the actuator to the *Proximal Phalanx* and *Outer Wrist*, which are widely utilized in the HCI community. Throughout our main study, we observed minimal differences between these two locations. However, the *Proximal Phalanx* exhibited shorter response times and higher accuracy compared to the *Outer Wrist*. These findings align with previous literature, which suggests that the tactile acuity of the index finger surpasses that of the outer wrist [167]. Regarding **RQ2**, we successfully determined the optimal actuation parameters. By integrating the results from the technical evaluations and considering previous research on skin perception frequencies [79, 97], we identified the optimal actuation period for *Tapping*. Remarkably,

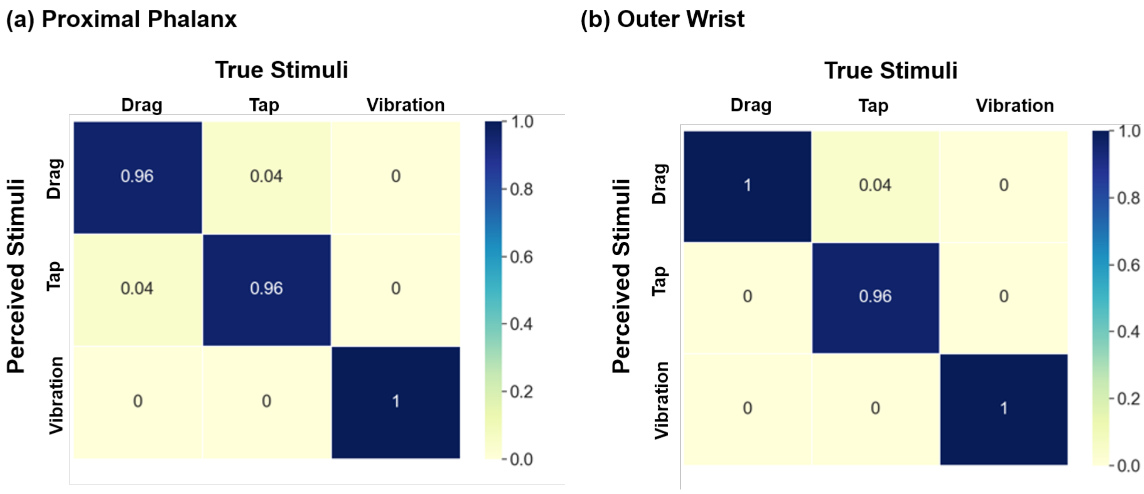


Figure 4.14: Left: Confusion matrix for Proximal phalanx; Right: Confusion matrix for Outer wrist.

our findings align with previous literature [5, 10, 93], further supporting the validity of our approach. In conclusion, when addressing **RQ3**, the outcomes of our evaluation decisively confirm the outstanding performance and practicality of our prototype. These results not only underscore the potential utilization of our device in various application scenarios but also emphasize its viability for real-world applications.

The lightweight design of the actuator garnered substantial acclaim from a significant majority of the participants in our study. Specifically, nine out of twelve participants expressed their willingness to consider the actuator for notification purposes, with one participant even suggesting its potential for enhancing immersive gaming experiences. However, it is important to note that one participant reported a minor concern regarding the actuator's tendency to generate slight warmth toward the conclusion of the experiment.

Additionally, one participant experienced occasional discomfort and mild discomfort when the actuator was applied to the **Outer Wrist**. Furthermore, our observations indicate that not all stimuli were perceived with the same level of intensity. Following in-depth discussions with the participants, we discerned that the vibration sensation was notably more intense in comparison to the other stimuli (with a total of six participants making this observation). This insight provides valuable direction for future investigations aimed at understanding the perceived intensity of distinct stimuli.

In terms of preference, a majority of users favored the *Tapping* and *Dragging* stimuli, finding them more comfortable and less intrusive in contrast to the *Vibration* stimulus. Collectively, the feedback from the participants underscores the actuator's potential for diverse applications, particularly in the context of notifications. It also highlights areas for potential improvement, such as addressing issues related to heat generation and considering potential discomfort associated with specific actuator placements.

4.5 Preliminary User Study for Signalling Direction Cues

The above sections introduced the feasibility of the *DragTapVib*. In the following sections, we aim to explore further how could the different sensations could be leveraged to provide the directional cues. The utilization of haptic signals for communicating directional cues has garnered increasing attention in recent years. This growing interest is fueled by the potential to provide users with non-visual feedback across a broad spectrum of applications. Haptic feedback, which involves the use of touch or tactile sensations, has proven to be an effective and intuitive means of conveying information, particularly in situations where relying on visual or auditory cues might be impractical or unwanted. In numerous real-world scenarios, individuals often require awareness of directional information without diverting their attention from their primary tasks, for example users may need to receive directional cues without having to glance at a screen or listen to audible instructions [14, 51, 65, 82]. Haptic feedback serves as a promising solution to this challenge, as it allows users to remain engaged in their activities while still receiving essential directional information. Prior research has provided evidence of successful implementations of haptic feedback in various domains, including navigation, gaming, and motion guidance. Through the use of tactile cues, users can intuitively and efficiently perceive directional information, thereby enhancing their overall experience and performance in a wide array of tasks.

Passive haptic learning (PHL) is a method where users acquire motor skills through tactile stimulation without active attention. In typical PHL scenarios, haptic cues are presented sequentially and not in response to the user's lateral movements. This means that learning sequences involving lateral movements, such as those required for playing the piano, can be challenging within a passive framework. Passive haptic learning aims to streamline the learning process by presenting a predefined sequence of haptic cues while the user performs corresponding motor actions. However, introducing lateral movements can potentially complicate the training [138], as it may become more challenging for users to associate haptic cues with specific actions. In contrast, other haptic learning approaches or interactive haptic systems may include lateral feedback and responses. For instance, active haptic learning can provide real-time feedback on the user's movements, allowing for lateral motion integration. In our study, we developed a hypothesis to explore the potential benefits of incorporating additional haptic cues to convey lateral movements while learning a new piano sequence. Our research question specifically examines this aspect:

- **RQ:** Can the introduction of supplementary haptic cues for lateral movements enhance learning a new piano sequence?

4.5.1 Pattern Design

DragTapVib demonstrates the ability to generate both discriminative touch (vibration) and affective touch (touch and drag). We utilized the combination of these affective touches to convey directional signals. The complete motion of the actuator comprises two distinct parts: Firstly, the tactor initiates a dragging motion from the initial position (left/right) to the end position (right / left), which solely serves to position the tactor accurately. Subsequently, the tactor performs a series of 8 taps (see Figure 4.15) to convey the tactile cue during our experiments. The entire stimulus duration lasts approximately 1 second.

Figure 4.15: Exemplary stimulus illustrating the presentation of tactile cues in the form of the combination affective touch (*dragging* and *tapping*) generated by the *DragTapVib* actuator.

4.5.2 Study Design

The primary goal of our study was to assess the feasibility and effectiveness of using tactile cues to support a direction-sensing task, while also validating the practicality of the actuator for everyday work scenarios. In this context, we designed the experiment to investigate the following aspects: (1). Location Preference; (2). distinguishability of the directional cues.

We conducted a study involving 16 participants (two of whom did not test with the third location had been excluded) recruited through a sample of convenience. During the experiment, all participants were seated in an office chair, and they placed their dominant arms on the desk while holding a mouse in their hands. The actuator was then attached to each participant's arm using an elastic band. Employing a within-subject design, we evaluated three body locations for actuator placement: (1) the underside of the wrist, (2) the top side of the wrist, and (3) the underside of the arm closer to the elbow (illustrated in Figure 4.16). The order of locations was randomized for each participant.

The study procedure, depicted in Figure 4.17, commenced with familiarizing each participant with a predefined pattern. Subsequently, participants calibrated the actuator until they felt confident in differentiating taps. Each participant was then tested with a random sequence of 20 stimuli. Following the test, participants were requested to rate their comfort level and their subjective ability to distinguish stimuli in order of preference, and they were encouraged to provide additional remarks and feedback.

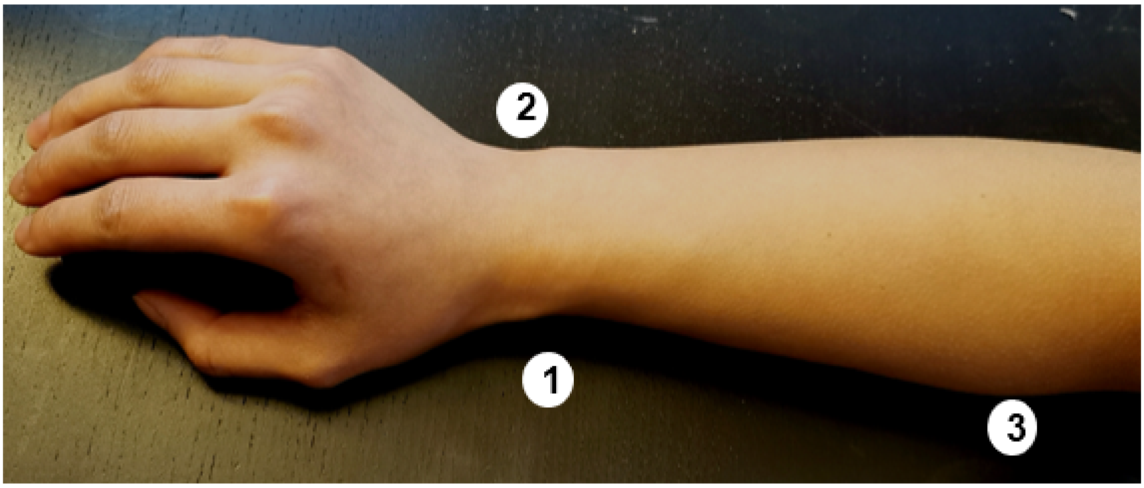


Figure 4.16: Three potential locations to place the *DragTapVib* actuator.

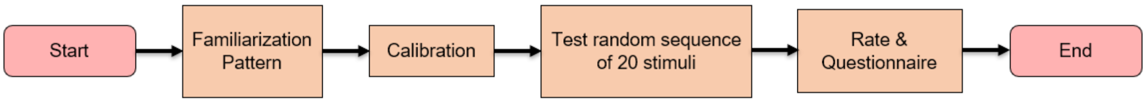


Figure 4.17: The flow chart of the study design.

4.5.3 Results and Discussion

Location Preference: Participants were asked to rank the three locations after completing all the tests, without prior knowledge of their own results. The position on the underside of the arm was ranked the highest, with 11 participants reporting feeling most confident with this placement. In contrast, the preference for the top side of the wrist and the underside of the arm close to the elbow was not as pronounced as with the first position.

Accuracy: We inspected the data of the recognition accuracy from the participants. The underside of the wrist yielded the highest accuracy, with the majority of participants correctly identifying 18-20 out of the 20 stimuli. There were only two outliers who guessed 17 or 16 correctly. In comparison, the other two positions performed less effectively in recognizing the stimuli. The results for the underside of the arm exhibited a wider range, with the highest score being 20 correct responses, while the lowest score was only 13 correct responses.

We carefully reviewed the participants' remarks and observations. Many participants mentioned that correctly identifying the stimuli was not a straightforward task, requiring their full concentration to perceive the tactile cues accurately. Interestingly, the ability to distinguish the stimuli seemed to be more related to learned associations rather than the innate perception of the stimuli. Participants reported recognizing the left or right direction based on their previous experiences with the tapping patterns, rather than relying solely on the immediate sensory feedback.

The effectiveness of stimulus classification also appeared to be influenced by the precise placement of the actuator on the participants' arms. During the calibration session, participants had the opportunity to find the optimal position, and once they achieved this, they were better able to distinguish the stimuli. It is important to note that the ideal placement varied significantly among participants due to the different sizes and thicknesses of their arms. Consequently, the size of the contact area emerged as a potential influencing factor. Participants who had larger and flatter contact surfaces on their arms seemed to find it easier to discern the stimuli accurately.

Overall, these findings suggest that successful perception and discrimination of the stimuli are influenced by both learned associations and the precise positioning of the actuator on the individual's arm. The size and shape of the contact area also play a significant role in facilitating the differentiation of tactile cues.

4.6 Demo Application Scenarios

To demonstrate the feasibility of our actuator in realistic daily life, we employed a wireless prototype of *DragTapVib*. This prototype utilized an ESP32 module that established a connection with a smartphone through Bluetooth Low Energy (BLE) technology. In the following, we introduce two demo application scenarios to underscore the adaptability and potential use cases of our actuator.

Application 1: On-body Notifications

The design of the *DragTapVib* is tailored to harmoniously integrate with conventional wearable form factors, as exemplified in Figure 4.18 (left). Users can conveniently wear the device on their outer wrists to avail themselves of tactile feedback. To enhance the overall user experience, we have developed an Android application that emulates a range of notifications, encompassing incoming calls, new messages, and alarms. Each notification type is conveyed to the user through distinct tactile stimuli: *dragging* for incoming calls, *tapping* for new messages, and *vibrating* for alarms. This innovative approach empowers users to receive critical information without being dependent on visual cues, enabling them to remain engrossed in their primary activities without disruptions.

Application 2: Game Play

As depicted in Figure 4.18 (right), the *DragTapVib* device offers the convenience of being worn not only on the outer wrist but also on the index finger's proximal phalanx. Leveraging its flexibility and lightweight design, *DragTapVib* introduces novel opportunities for enriching immersive gameplay experiences. We apply our device to shooting games. For

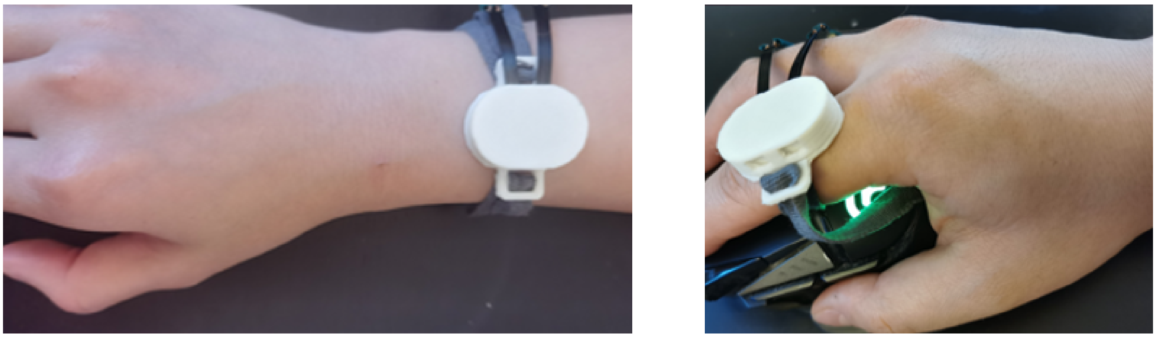


Figure 4.18: Left: Notification application. Right: Gameplay application.

instance, when engaged in a shooting game while using a computer mouse, *DragTapVib* can replicate various tactile sensations to create a more interactive gaming environment. As the user reloads a firearm within the game, the actuator of *DragTapVib* simulates a dragging sensation on the user's skin. Moreover, when a single shot is fired in the game, *DragTapVib* delivers a tactile tap to heighten the user's physical awareness. Similarly, during sustained firing, the actuator generates vibrations to augment the overall gaming experience. This demonstrates the device's versatility in enhancing gameplay through tactile feedback.

4.7 Conclusion

This chapter presents *DragTapVib*, an innovative and lightweight electromagnetic wearable haptic actuator that can deliver three haptic and tactile feedbacks (*Dragging*, *Tapping*, and *Vibration*) individually. We have presented the design, fabrication, and actuation mechanisms of our device. Given its ease of replication, we have introduced a novel approach to wearable actuators for the benefit of the broader research community. Technical evaluation results validated the performance of the actuators and demonstrated their inherent mechanical properties. User study results revealed the quantitative perceptibility and distinguishability of each haptic stimulus. Both the technical evaluation results and user studies suggest *DragTapVib* is an innovative wearable haptic interface and greatly extends the possibilities of electromagnetic wearable actuators. As wearable devices integrated with richer haptic feedback become mainstream, *DragTapVib* is a step towards this goal. We are working on the next version of our device and hoping that our work could foster further research in that direction.

One of the challenges we identified in our experiments is the generation of small amounts of Joule heat within the coil resulting from the reversal of the current direction. Notably, this issue was reported by only one participant and occurred during prolonged usage without breaks, exceeding 30 minutes. To address this concern in future iterations of our device, we intend to implement solutions such as silicone molding and the inclusion of a heat insulation layer. These measures aim to mitigate heat-related issues and enhance the overall user experience.

A long-term objective in our research involves further exploration of the tactor's movement space, with potential adjustments to the range for dragging or tapping. Additionally, we envision the possibility of expanding the tactor's mobility along a 2D space positioned above the skin by increasing the number of coils in two directions. This development holds particular promise, especially in the context of virtual reality (VR) applications.

Part III

ON-SKIN HAPTIC INTERFACE

5 Investigating Passive Haptic Learning of Piano Songs Using Affective and Discriminative Touch

As demonstrated in Chapter 4, leveraging the utilization of diverse tactile senses among individuals holds the promise of establishing multiple interaction modes. This, in turn, unlocks plenty of potential applications in the field of wearable multimodal haptic interfaces. Building upon this foundational understanding, our research endeavors to delve deeper into two fundamental categories of touch: *discriminative touch* and *affective touch*. We aim to do so within specific interactive contexts, such as Passive Haptic Learning.

Learning new skills can be a time-consuming and challenging endeavor. One approach to lowering the barriers and costs of skill acquisition is through Passive Haptic Learning (PHL). In PHL, users can acquire skills by receiving tactile stimulation without requiring their explicit attention [138]. This method utilizes tactile feedback generated by motors to convey specific information on how to perform tasks while users are engaged in other activities. Passive haptic learning has demonstrated success in teaching individuals various skills, such as simple piano songs [138], Morse code [140], and braille typing [141]. Moreover, it has been applied in the field of Passive Haptic Rehabilitation to assist patients recovering from strokes or incomplete spinal cord injuries in rehabilitating upper extremity functionality and body motion control [106, 142]. The research on PHL gained momentum in the mid-2010s and has witnessed significant progress over the past decade. It offers a promising and potentially more efficient approach to learning certain information. Recent research efforts in this area have focused on improving the robustness and comfort of the learning experience.

Passive haptic learning, focusing on its impact on learning musical instruments, has been a popular research area, and significant advancements have been made. However, previous studies predominantly emphasized the use of discriminative input, primarily through vibration, as the tactile simulation [74, 138, 141]. The potential of utilizing affective touch, encompassing actions like stroking and tapping, remains largely unexplored within the domain of passive haptic learning (PHL). According to Kress et al. [89], somatosensory areas and the insula in the human brain will thus show different responses to stroking vs. tapping. Facing this finding, this chapter contributes the work to explore tapping and stroking as effective alternatives to vibration in passive haptic learning by suggesting a wearable solution including the three self-built wearable systems corresponding to three tactile- sensations. Furthermore, our research is designed to assess the viability of alternative approaches, particularly the use of affective touch, in comparison to the conventional method of discriminative touch. To summarize, we aimed to explore the following research questions in this chapter:

RQ1: Is a passive haptic learning system that uses affective sensation as effective as one that uses a discriminative sensation due to the possibility of activating certain nerve cells in the skin carries a positive effective value [124]?

RQ2: Are there significant differences such as learning rate, user perception, etc., when using different affective sensations such as a tapping sensation or a stroking sensation for passive haptic learning?

This investigation provides insights into the comparative efficacy and potential benefits of affective touch within diverse interactive scenarios. The content of this chapter was published in the Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies, Vol. 7, No. 3 [41].

The remainder of this chapter is organized as follows: Section 5.1 furnishes a comprehensive overview of relevant literature within the field, serving as a foundation to contextualize and support the rationale behind our research. Next, Section 5.2 presents a thorough and detailed overview of the three self-built wearable systems, incorporating their design intricacies, the fabrication process, and the technical evaluation to assess the mechanical properties. Then, Section 5.3 presents the details of the user study. Section 5.4 demonstrates the result of the user study. Following this, Section 5.5 discusses the limitations of our work. Finally, Section 5.6 concludes the chapter and outlines the prospective avenues for future research in this domain, highlighting areas ripe for exploration and development.

5.1 Related Work

Our research contributes to the exploration of how different types of tactile signals can influence learning performances in passive haptic learning. We begin by reviewing existing literature in the field of passive haptic learning, emphasizing its feasibility and the achievements made over the past decades. We also delve into the previous works on tactile signals that have been applied, drawing inspiration from their findings. Additionally, we discuss the fundamental aspects of touch perception, including the receptors, nerve fibers, and mechanoreceptive afferents involved. Lastly, we explore relevant previous studies that have focused on haptic devices to create various types of tactile sensations, with a particular focus on tapping and stroking, which aligns with the scope of this thesis.

5.1.1 Passive Haptic Learning (PHL)

In 1970, Krugman and Hartley [90] proposed the concept of two distinct types of learning: active learning, characterized by purposeful behavior, motivation, practice, and achievement; and passive learning, characterized by effortless receptivity to animated stimuli, amenable to relaxation aids, and an absence of resistance to what is learned. Subsequent studies have explored the existence and efficacy of passive learning in various domains. For instance, Zukin and Snyder [182]demonstrated passive learning in election events, while Eisenman et al. [35] presented a case study of a 71-year-old female who successfully performed CPR on her husband despite lacking formal training. In the context of music, Huang, Do, and Starner [71] introduced the potential for passive learning of physical skills through haptic cues and found that passive haptic learning enhanced participants' understanding of piano music pieces. Building on these findings, Huang et al. [74] developed the "Mobile Music Touch" system, conducting two studies that revealed participants' ability to learn note sequences through repeated skin stimulation without active attention. Expanding beyond piano playing, Seim, Quigley, and Starner [141]taught typing skills on an unfamiliar keyboard using passive haptic learning. Participants not only learned the typing phrase but also the letter-to-key mapping. Additionally, Seim et al. [140]showed the effectiveness of passive haptic learning in teaching participants Morse code for letters of the English alphabet, with significantly higher accuracy compared to a control group. The exploration of passive haptic learning continues to offer valuable insights into its potential application across diverse learning scenarios. However, without exception, the PHL systems in previous studies have chosen vibration as the tactile signal. Questions remaining are: (1). whether other tactile signals are as effective as the vibration; (2). whether the vibration could be replaced by other more natural and pleasant tactile sensations [62]? Hence, we explore the answers to the above questions in this work.

5.1.2 Discriminative and Affective Touch

Skin serves multiple essential functions, including protection, excretion, regulation of body temperature, and sensory reception of external stimuli [87]. Research on the perception of touch has been active for over a century, with a focus on somatic sensations that encompass tactile, thermal, painful, and pruritic (itch) sensations [44]. The perception of touch begins with specialized receptors attached to nerve endings within the skin. When these receptors are triggered by external stimuli, they send signals that relay information about somatic sensations. Further processing allows for temporal and spatial discrimination of this tactile information. In this context, we concentrate solely on the tactile sensations, omitting discussions of thermal, painful, and pruritic sensations. It is essential to note that differences exist between glabrous (non-hairy) and hairy skin regions concerning receptor types, nerve fibers, and emotional responses. Hairy skin regions tend to evoke more pleasant sensations, while glabrous regions are more associated with discriminative sensations and less related to pleasantness [2, 3].

Nerve fibers can be classified into myelinated and non-myelinated types. Myelinated fibers are wrapped in a substance called myelin, which acts as an insulator and increases the conduction velocity of nerve signals. These myelinated nerve fibers are known as Aβ fibers [2, 11, 45]. On the other hand, non-myelinated fibers are referred to as C-fibers [2]. Aβ fibers project to the primary somatosensory cortex (area SI), while unmyelinated CT (C-tactile) fibers project to the posterior insula [13, 120, 122]. Generally, Aβ fibers predominantly convey discriminative touch signals, which are used for localization. In contrast, CT fibers are particularly relevant to the perception of affective touch [89, 98, 108, 121, 168]. Tactile stimuli on the skin are processed by four distinct low-threshold mechanoreceptors (LTMs): Pacinian units, quickly adapting (RA), slowly adapting type 2 (SA2), and slowly adapting type 1 (SA1) receptors [2, 109]. Each of these LTMs serves a specific function in converting different mechanical stimuli into nerve impulses in Aβ large-diameter afferents, with conduction velocities ranging from 20 to 80 meters per second [109]. In comparison, CT fibers have much lower conduction velocities, ranging from 0.5 to 2 meters per second [109]. The force activation thresholds and optimal frequencies (ranging from 0.5 to 4000 Hz) for activation of the mechanoreceptive afferents on hairy skin, as reported by Ackerley, Wasling, and McGlone [2] and Deflorio, Di Luca, and Wing [25], provided valuable information for the design and development of the systems in our study.

5.1.3 Skin Stimulation Devices

Haynes et al. [62] introduced a lightweight 3D-printed device that utilizes shape memory coils to actuate the skin at two points. The device gently stretches and squeezes the skin surface as the memory spring contracts and reverts. Their findings suggested that the "stretch" produced by their device could offer rich information and provide more emotionally stimulating feedback compared to traditional vibrotactile stimulation during task performance. In another study, Ion, Wang, and Baudisch [76] proposed a device that drags a physical tactor along a 2D path across the user's skin (referred to as stroking in our work). They evaluated 12 different shapes on the user's forearm and concluded that skin stroking was more effective at conveying the meaning of certain movements compared to using vibration stimuli. Furthermore, Fang et al. [36] presented a novel and compact actuator capable of generating sensations of skin stroking, tapping, and vibration robustly. The device provides a versatile and efficient solution for delivering multiple tactile sensations. Over the past few decades, there has been a significant increase in research efforts toward wearable systems capable of providing various tactile stimuli. Single tactile sensations are no longer deemed sufficient, and researchers are striving to strike a balance between delivering rich and clear information through tactile signals while ensuring the user experience remains unobtrusive and pleasant.

5.2 Passive Haptic Learning Systems Design

In this section, we present the core components and assembly details of three self-built wearable systems designed to produce three distinct sensations: vibration, tapping, and stroking. Each system was engineered for simplicity and efficiency, allowing for easy component replacement in case of failure without the need for complex soldering. Moreover, we have made all 3D files, schematics of our implementation, and a comprehensive fabrication guide freely available to the public[1], encouraging others to replicate our systems. The overview of the three systems attached to an user's forearm are depicted in Figure 5.1, Figure 5.2, and Figure 5.3.

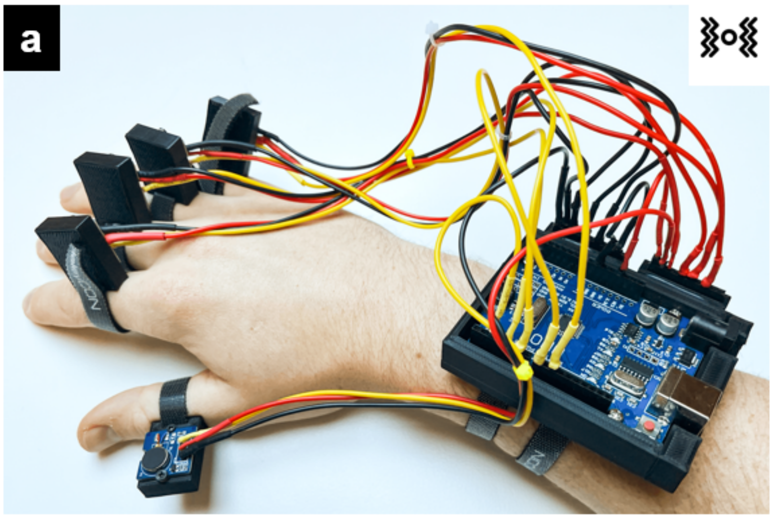


Figure 5.1: Vibration system attached to an user's forearm.

5.2.1 Vibration System

The vibration system comprises an Arduino Uno microcontroller, five vibration motors (Brand: Grove Seed; Model ANDA-B1020), electrical wirings, a 3D-printed case (Material: Black PLA), and velcro bands. These motors have an approximate vibration frequency of 200Hz and were effectively controlled using the Arduino UNO. Unlike previous approaches that embedded vibration motors directly on users' fingers within a glove [28, 129, 140, 141, 142], we opted to attach the vibration motors in a 3D-printed case, as illustrated in Figure 5.4. The case features a curved bottom, offering a larger contact area and the flexibility to be conveniently adjusted to individual comfort. Figure 5.4 (b) depicts one element of the vibration system as mounted on an user's finger.

[1] `https://github.com/teco-kit/discriminative_touch_and_affective_touch_actuators`

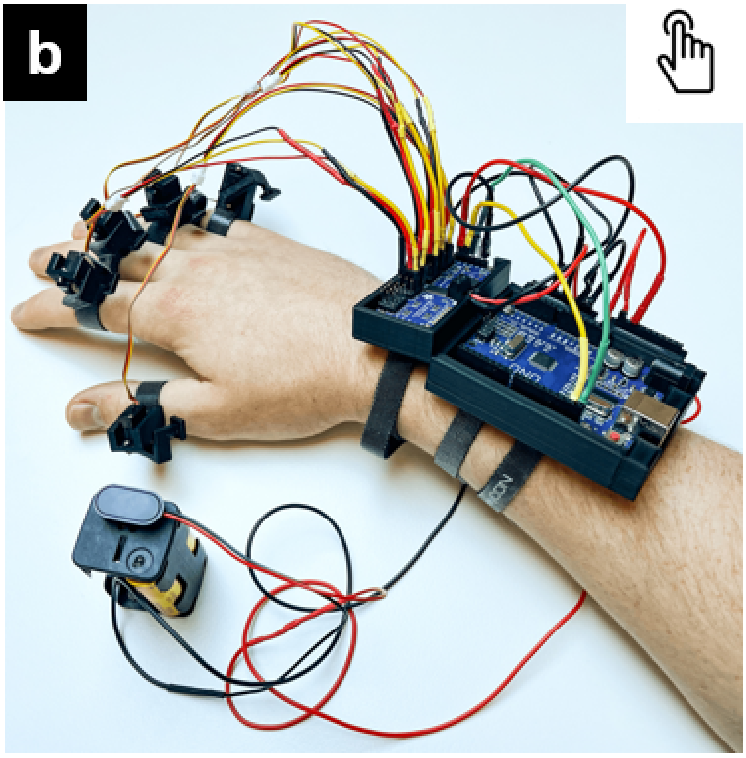


Figure 5.2: Tapping system attached to an user's forearm.

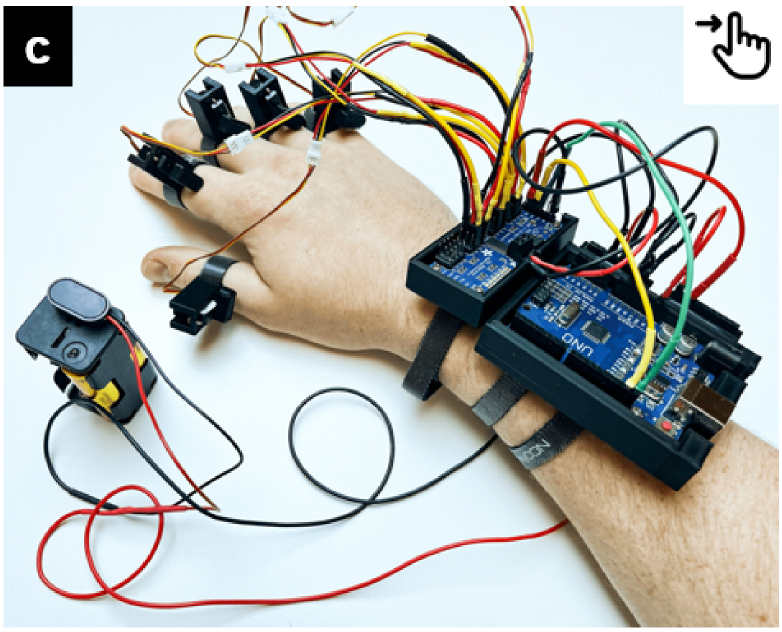
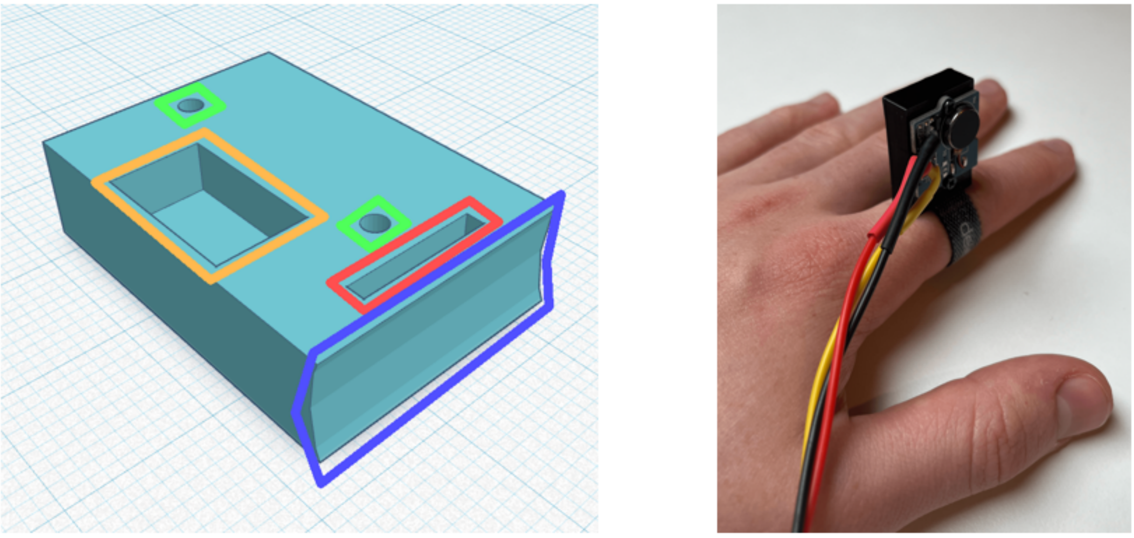


Figure 5.3: Stroking system attached to an user's forearm.



(a). Case for the vibration motor used in the vibration system. Red: bottom, space for the velcro bands. Green: Screw holes for fixing the vibration motor. Orange: Space for the back end of the pins. Blue: curved bottom as a contact to finger.

(b). Vibration motor and case fixed on the index finger of a user using a velcro band.

Figure 5.4: 3D model, and the implementation on an user's finger of one element of the vibration system.

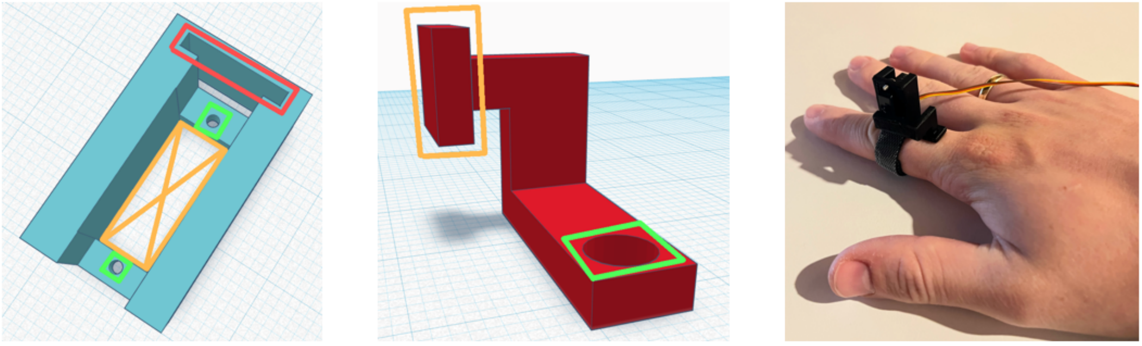
5.2.2 Tapping System and Stroking System

5.2.2.1 Electronics and Schematics

The tapping and stroking systems utilized the same microcontroller as the vibration system. For both systems, we employed ten mini-servo motors (Master DS208) in total, with five motors allocated for each system. These mini-servo motors delivered an actuating force of approximately 0.1-0.2 kg and achieved a 45° movement in about 0.1 seconds. To ensure the Arduino board's safety and prevent potential damage when drawing power directly for the servo motors, we implemented a separate power supply for the motors. This power supply consisted of three AA batteries, providing a maximum voltage of 4.5V. Additionally, we integrated a Pulse Width Modulation (PWM) board (Model: Adafruit PCA9685) with the Arduino Uno board, simplifying the control of the servo motors through a pulse width modulated signal. This arrangement allowed for precise control and efficient actuation of the servo motors in both the tapping and stroking systems.

5.2.2.2 3D Printed Cases and Contactors

Tapping System Tapping, as defined in previous research, involves the application and removal of contact to the same region on the user's skin with nearly equal force at a consistent rate [89]. In our design, we developed a tapping system comprising a servo motor case and a contactor. The contactor is designed in a hammer-like configuration, featuring an 8×8 mm square plate that directly applies pressure against the skin. This plate is connected to the output shaft of the servo motor through an L-shaped support, which is linked to the plate via a hole situated near the end of the support. For visual reference, Figure 5.5 displays a 3D printed model and demonstrates the implementation of one element of the tapping system on an user's finger.



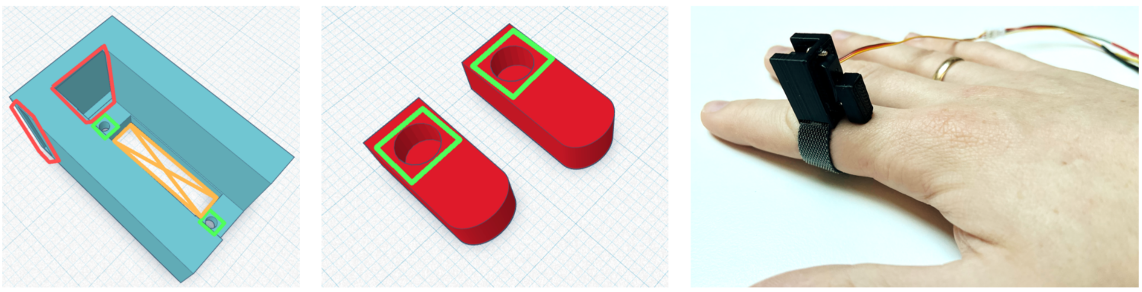
(a). Case for the servo motor used in the tapping system. Red: bottom, space for the Velcro band. Green: Screw holes for fixing the servo motor. Orange: Space for the servo motor.

(b). 3D model of the contactor for the tapping system. Orange: hammerhead that touches the skin. Green: cutout for the counterpart to the output shaft of the servo motor.

(c). Servo motor and case fixed on a user's index finger using a velcro band with a contactor attached. Contactor in "down" position.

Figure 5.5: 3D models for the case and hammer-shaped contactor, and the implementation on an user's finger of one element of the tapping system.

Stroking System: The stroking system involves the movement of the contactor over the user's skin, gently indenting it. Similar to the tapping system, the stroking system also comprises a case and a contactor. The 3D model of the case for the servo motor closely resembles that of the tapping system. However, for the stroking contactor, we adopted a distinct design: a $15 \times 7 \times 5$mm square with a rounded bottom end. Additionally, a hole was incorporated to ensure compatibility with the servo output shaft (refer to Figure 5.6). The contactor effectively conveys stroking sensations to the user's fingers when the servo motor is in motion. For placement, the output shaft of the motor is situated near the interphalangeal joint of the finger (as depicted in Figure 5.6).



(a). Case for the servo motor used in the stroking system. Red: bottom space for the velcro band. Green: Screw holes for fixing the servo motor. Orange: Space for the servo motor itself.

(b). 3D model of the contactor used in the stroking system. Green: Cutout for the servo output shaft.

(c). Servo motor and case fixed on a user's index finger using velcro band. Contactor is placed in the center of the total movement range.

Figure 5.6: 3D models for the case and the contactor, and the implementation on an user's finger of one element of the stroking system.

5.2.3 Three Wearable System Technical Characterization

For the reproducibility of the three systems we built, we hereby characterized the mechanical factors of the three systems.

5.2.3.1 Vibration System

We measured the vibration amplitude by attaching a 9-axis accelerometer (Brand: Spark Fun; Model: LSM9DS1) to the back of the vibration system case using double-sided tape (see Figure 5.7). The accelerometer readings were recorded, and the average amplitude value during the operation was found to be approximately 1.03 G. This value is slightly smaller than that reported in a previous study [28], which also used vibration motors in passive haptic learning and reported an amplitude of 1.34 G. The weight of a single vibration actuator worn on each finger is 6.6 grams.

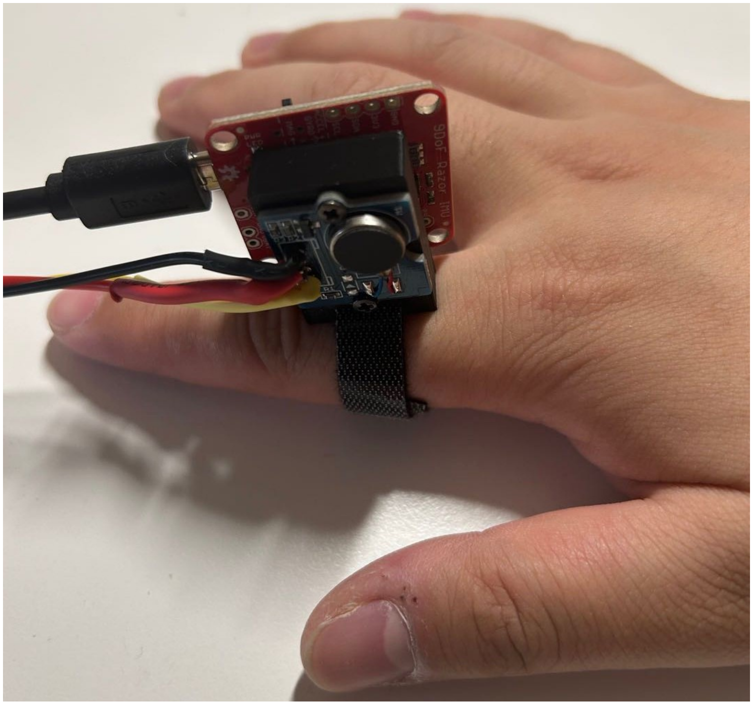


Figure 5.7: Experiment setup: An accelerometer is mounted on the back side of the vibration actuator.

5.2.3.2 Tapping System

We utilized a force sensor (Brand: Interlink Electronics; Model: FSR 400) to measure the tapping force. The force sensor has a diameter of 5 mm and a measuring range from 0.2 N to 20 N. Placed between the human skin and the contactor of the tapping system (see

Figure 5.8), we conducted measurements on each finger on the palm. Due to variations in finger size, the contactor drop distance ranged between 8mm and 10mm. Our device exerted an average force of 0.42N against the finger, with a maximum force of 0.53N. The total mass of a single tapping actuator worn on each finger is 3.9 grams.

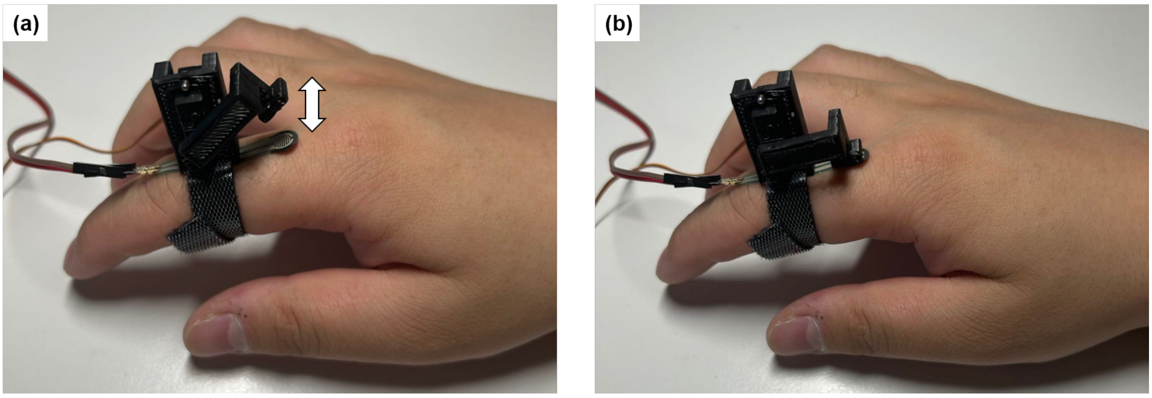


Figure 5.8: The tapping actuator pushes against the user's finger. (a). The contactor lifts up; (b). The contactor falls.

5.2.3.3 Stroking System

To measure the stroking distance of the stroking system on the user's finger, we employed an ink contact test between the actuator and each finger on the palm (see Figure 5.9). Given the rounded bottom of the contactor (see Figure 5.6 (b)), the actuator creates a line contact with the finger when activated. For the test, we coated the contactor of the stroking system with washable green ink. Upon actuation of the actuator, it leaves an ink mark on the finger, allowing us to determine the stroking distance. Measurements were taken on each finger on the palm, resulting in stroking distances ranging from 4mm to 6mm due to variations in finger sizes. The stroking actuator worn on each finger weighs 4.7 grams.

5.2.4 MIDI Keyboard

For the subsequent user study, we utilized the same keyboard (Brand: Casio; Model: Casio CT-S100) as previously employed in the study conducted by Donchev, Pescara, and Beigl [28]. This keyboard not only serves as a regular piano keyboard but also incorporates a MIDI interface that enables recording of various parameters associated with each note played, such as duration and keyboard settings. Additionally, we affixed an LED strip (Model: WS2812B) on top of the keys (see Figure 5.10). The LED strip consists of 144 LEDs per meter, facilitating the mapping of one individual LED to each key.

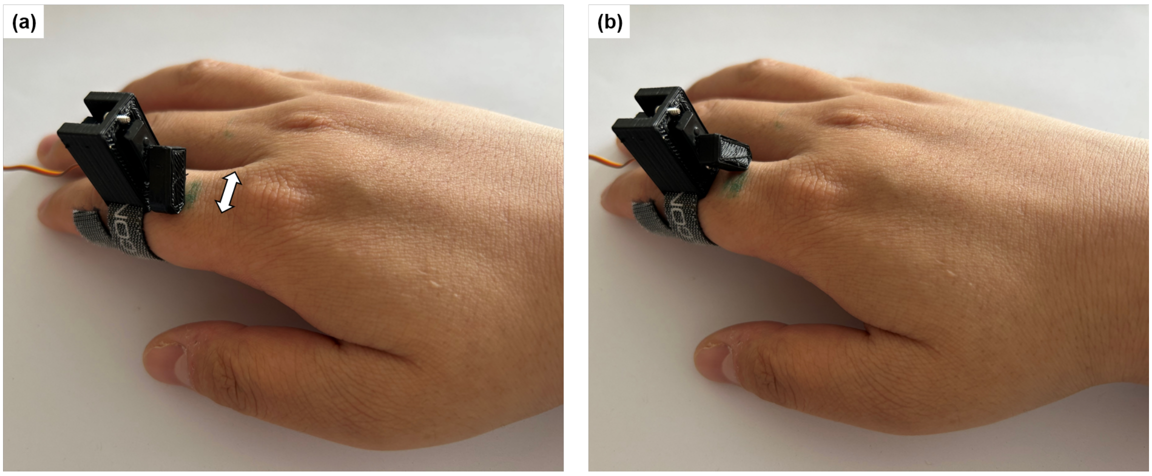


Figure 5.9: The stroking distance of the actuator on the hand. The green ink shows the result of a contact test. (a). The schematic diagram of the movement of the contactor; (b). The movement distance of the contactor.

Figure 5.10: Keyboard with attached LED strip with the connector of the LED strip on the left side.

5.3 User Study

5.3.1 Participants

We recruited a total of 17 participants (7 males, 10 females) with an average age of 28 years and an age range of 15 to 57 years, through convenience sampling. None of the participants were left-hand dominant. All participants were comfortably seated in an office chair with their arms resting on the desk during the study. The musical experience of the participants was assessed and summarized in Table 5.1: Four participants had prior piano experience, while the remaining 13 participants had no previous experience with the piano. In addition to piano experience, we considered the participants' musical experience with other instruments as well. During the data analysis, two participants were excluded due to data loss and overwriting. Therefore, the final dataset comprised 15 participants (6 males, 9 females) with an average age of 26.7 years and an age range of 15 to 57 years.

Table 5.1: Participants and their musical experience.

Subject	Piano Experience	Other Musical Experience
1	No	No
2	No	No
3	< 1 year	2-5 years (guitar)
4	No	No
5	No	No
6	No	2-5 years (flute)
7	No	> 4 years (flute)
8	No	No
9	No	No
10	< 1 year (rarely played)	4 years (flute), 7 years (violin)
11	No	6 years (saxophone), 5 years (guitar)
12	No	3 years (flute)
13	No	< 2 years (guitar, rarely played)
14	No	No
15	No	3 years (flute)
16	> 4 years (2-4 times per week)	8 years (accordion), 6 years (guitar), 1 year (harmonica)
17	1-3 years (2-4 times per week)	4 years (flute), 40 years (guitar),18 years (trombone)

5.3.2 Study Design

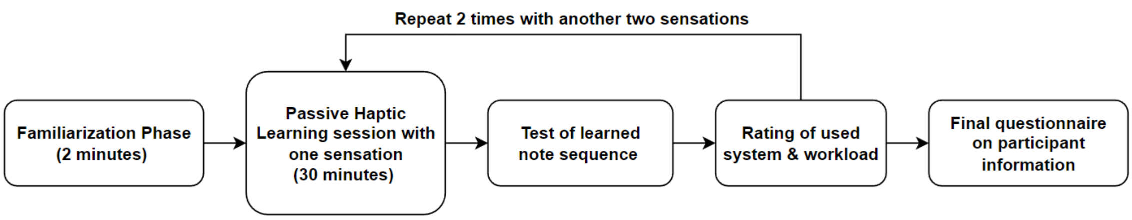


Figure 5.11: Study design of the user study (each PHL session uses a different device and a different note sequence).

We adopted a within-subject study design to investigate the differences among the tapping, stroking, and vibration systems when used for passive haptic learning. To maintain consistency with previous studies in the field of passive haptic learning, we used note sequences (Note A and Note B) from the studies by Donchev, Pescara, and Beigl [28] and Huang et al. [74] (see Figure 5.12). Additionally, we created a new note sequence, Note C, which was designed in a manner similar to Notes A and B in terms of speed and tone.

The note sequences exclusively utilized the keys C through G to ensure that participants did not need to perform lateral movements on the keyboard. Figure 5.12 illustrates the note sequences used in the user study. The mapping between the notes and the fingers can be seen in Figure 5.13 (left), and it remained consistent with the mappings used in previous studies [28, 74]. All note sequences were composed with a speed of 70 beats, as validated by Donchev, Pescara, and Beigl [28], representing a moderate tempo. For the distraction task during the learning sessions, we employed the open-source game Gweled [56] (see Figure 5.13 right). The participants' mouse clicks during the learning sessions were recorded for subsequent analysis, to ascertain whether participants were focused on the game or on the learning task.

Figure 5.12: Note sequences taught to the participants in the study.

The main user study comprised four main parts: one warm-up session and three Passive Haptic Learning (PHL) sessions. In each PHL session, a different wearable system was utilized to provide three distinct haptic sensations: tapping, stroking, and vibration. Prior to the warm-up phase, participants were introduced to a familiarization pattern containing all relevant information. At the beginning of the study, all participants signed a consent form granting permission for the use of their private data.

During the warm-up phase, the participants were provided with two minutes to familiarize themselves with the keyboard, guided by the LED strip attached to it. The LEDs on the keyboard cycled in the sequence: C - G - F - E - D - C - G. Each LED was illuminated for 500ms before turning off, followed by the next LED signal. Participants were instructed to follow the highlighted LED strip and press the corresponding keys. None of the wearable systems we constructed were worn during this phase. Furthermore, participants were not given any information about the note sequence they were to learn later passively, nor had they heard or seen the note sequence before this warm-up phase.

The user study was designed to ensure counterbalancing against the three note sequences and the three wearable systems, thereby eliminating any potential order effect. Each passive haptic learning session lasted approximately 30 minutes, including both a learning phase and a testing phase. During the learning phase, participants wore the respective wearable system on their finger and forearm for the entire duration. While

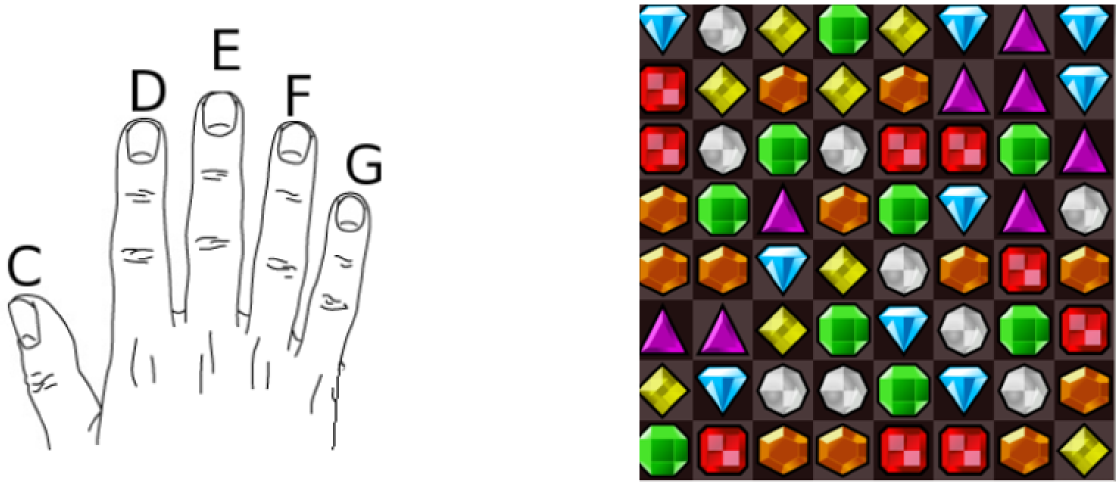


Figure 5.13: Left: Mapping of fingers to notes on the MIDI keyboard, same as [28, 74]. Right: Distraction task: Gweled [56]

wearing the system, they engaged in playing the game Gweled [56] (see Figure 5.13 right) while simultaneously receiving passive haptic stimuli through the wearable system on their fingers. The game involved horizontally or vertically exchanging seven types of gems on an 8×8 playing field. Successful placement of three or more gems of the same type in a row or column resulted in the gems disappearing and an increase in the score. New gems were subsequently added from the top. Participants could play in the "endless" mode, allowing continuous play for the entire learning session.

The duration of the stimuli provided by the wearable system matched that of the taught notes, ranging from 431ms (for an eighth note) to 1065ms (for a quarter note), followed by a 50ms pause. Participants were granted a 30-second break between trials for rest. During the testing phase, participants were not provided with any recall aids: the lights on the keyboard were not lit, and the sound of the keyboard was muted. Participants were given three attempts to play the melody they were supposed to learn, and the MIDI interface of the keyboard recorded the played notes. Following the testing phase, participants were given a questionnaire to assess their subjective evaluation of the device's comfort and effectiveness. They were asked to rate their experiences using a 4-point Likert scale, aiming to capture essential opinions without invoking a neutral response. Additionally, participants were asked to complete a one-stage NASA Task Load Index [60] questionnaire to gauge the workload they experienced while using the passive haptic learning system.

After completing the experiments with all three systems, a brief conversation was conducted with the participants, encouraging them to express their views and opinions regarding the entire learning process, as well as their feedback and suggestions concerning the three sensations (tapping, stroking, and vibration) and our wearable systems. The entire test duration per participant ranged from 2 to 2.5 hours, depending on individual experimental set-ups and participation.

5.4 Results

5.4.1 Game Engagement

The primary focus of our study centers on passive learning, where users learn a sequence aided by various tactile signals: vibration, stroking, and tapping. To assess whether participants' attention shifted from the game to the stimulation, we monitored their engagement with the game during the learning phase. We considered participants as disengaged if there was a drop in the click rate of over 15%. The results showed that none of the participants exhibited a click rate drop exceeding 15%, with the largest observed drop being 13.59%. Furthermore, we observed that the click rate values were relatively consistent among the three systems. This indicates that participants remained engaged with the game while receiving passive haptic stimuli, regardless of the specific tactile sensation used.

5.4.2 Passive Learning Effect

5.4.2.1 Effectiveness among Three sensations

We employed two evaluation methods to assess the effectiveness of piano learning passively with three different sensations (tapping, stroking, and vibration): dynamic time warping (DTW) and a simple comparative algorithm (SCA). DTW, proposed by Sakoe and Chiba [136], is well-suited for measuring time-series similarity by allowing flexible "elastic" transformations of time series [143]. It enables the determination of an optimal global alignment between two time series, making it particularly useful when comparing the duration of notes played. As it has been used in previous studies [28, 74, 141, 140], we adopted DTW for our analysis. However, DTW has some limitations, such as not registering an error if a key is accidentally pressed twice instead of once, as per the correct note sequence. Given this, our focus was on comparing the number of correct notes rather than the duration of each note. To ensure potential comparability with existing studies and for consistency, we retained DTW as one of our evaluation methods. To ensure the accuracy of participants' performance, we adopted a similar algorithm as proposed by Pescara et al. [129] called the simple comparative algorithm (SCA). This algorithm compares two lists of integers, one being the recorded notes and the other representing the correct notes. During the comparison, the algorithm keeps track of errors using an error counter.

The SCA first compares the elements at index i in both lists. If the elements are identical, no error is recorded. However, if they differ, the algorithm tests whether switching the next element at index $i + 1$ with the current element would result in a list where both elements are now identical to the corresponding elements in the correct note list at indices i and $i + 1$. In such a case, the error counter is incremented by $1/3$. On the other hand, if the switch does not produce matching elements, the error counter is incremented by 1 to indicate a more significant error where both notes are incorrect. To account for cases where the number of notes played is different from the correct number, the SCA assigns a weighted error value. If the number of played notes is fewer than the correct notes, each missing note is counted as an error of 2/3. Conversely, if the number of played notes exceeds the correct number, each additional note is also counted as an error of 2/3. This approach allows for a fair evaluation of participants' performance, emphasizing both note accuracy and sequence length. In this chapter, we consider the SCA as the preferred evaluation method due to its ability to provide a comprehensive assessment of participants' performances in passive haptic learning sessions.

A one-way ANOVA was conducted to assess the statistical significance of the differences in DTW error amounts among the vibration, tapping, and stroking systems. The results indicated that there was no statistically significant difference in error amounts when using DTW ($p = 0.693$, $\alpha = 0.05$, see Table 5.2). Similarly, no statistically significant difference was observed among the three systems when employing the SCA method ($p = 0.580$, $\alpha = 0.05$, see Table 5.2). Based on these findings, we can conclude that passive haptic learning is equally effective when using the stroking or tapping systems compared to the widely used vibration system.

Table 5.2: ANOVA results for DTW and SCA.

	df	F	***p***
Dynamic Time Warping (DTW)	2	0.37	0.69
Simple Comparative Algorithm (SCA)	2	0.55	0.58

5.4.2.2 Novice and Experienced Participants

The study by Huang et al. [74] previously proposed that participants with prior piano experience did not perform as well as those without experience. Our own experiments yielded similar findings, as we observed that individuals without prior piano experience outperformed those with experience across all three systems (vibration, stroking, and tapping). The results indicated that experienced participants made more errors compared to novices on the vibration, stroking, and tapping systems. Specifically, the analysis using DTW revealed that experienced users made 0.19, 0.23, and 0.47 more errors than novices on the vibration, stroking, and tapping systems, respectively. Similarly, the analysis using SAC showed that experienced users made 0.25, 0.59, and 0.60 more errors than novices on the same systems. These findings suggest that prior piano experience may not necessarily provide an advantage when using the different tactile systems in the context of passive haptic learning.

5.4.2.3 Learning Error

Our findings revealed that the utilization of tapping and stroking systems led to more accurate note sequence performances in passive haptic learning, as measured by SCA, when compared to the vibration system. Specifically, we observed a reduction of 0.86 and 1.26 errors (see Table 5.3) in the average number of errors for users when using the tapping and stroking systems, respectively. This indicates that the tapping and stroking systems yielded better results with an average error reduction of 1.06 compared to the vibration system.

Table 5.3: Mean and standard deviation of error numbers for the stroking, tapping, and vibration system analyzed by SCA (the preferred method in our work)

Sensations	Mean	St. Dev.	Max	Min
Stroking	4.66	3.72	13.33	0
Tapping	5.06	4.35	20.00	0
Vibration	5.92	2.51	11.33	0

However, when we evaluated the same data using DTW, the difference in error rates between the tapping and stroking systems and the vibration system was not as pronounced. The difference in error amounts was only 0.54 and -0.25 (see Table 5.4) when comparing the averages of the stroking and tapping systems to the vibration system. This discrepancy might be attributed to the tendency of DTW to miscount actual errors (see Section 5.4.2.1). Given that SCA offers a more intuitive and real-world approach to measuring errors, we conclude that the tapping and stroking systems are likely to facilitate higher learning rates compared to the vibration system.

Table 5.4: Mean and standard deviation of error numbers for the stroking, tapping, and vibration system analyzed by DTW

Sensations	Mean	St. Dev.	Max	Min
Stroking	4.89	3.14	10.49	0
Tapping	4.07	2.71	11..27	0
Vibration	4.61	2.54	15.72	0

5.4.3 Comfort

In terms of comfort, unanimous agreement was observed among all participants, indicating that none of the sensations induced by the three systems were perceived as uncomfortable. Notably, our study uncovered a noteworthy preference among participants, with the stroking system being consistently rated as the most pleasant sensation by over 50% of the participants. In contrast, only 11% of participants favored vibration as the most enjoyable sensation. On average, vibration received the lowest pleasantness rating among the three Passive Haptic Learning (PHL) systems in our investigation. These findings are in line with existing research on affective and discriminative touch. Stroking is considered a form of affective touch [2], and studies by Pawling et al. [124] have shown that humans find it pleasant to be stroked by inanimate objects. On the other hand, vibration, with its high frequencies of around 200Hz, is typically associated with discriminative touch, which is not commonly perceived as pleasant [2].

Notably, several participants reported a prolonged perception of tapping and stroking sensations even after a 30-minute duration, whereas discerning the positions of the vibration became challenging towards the conclusion of the Passive Haptic Learning (PHL) session. Participants expressed difficulty in distinguishing the locations of the vibrations, with feedback indicating a sense of uniformity, such as "*it all felt the same*" and "*just could not feel where the vibration was occurring from anymore.*"

Notably, more than five participants articulated a distinct sensation akin to "*the fingers being pushed down, just like if somebody taught you to play the piano*" with the tapping system. Simultaneously, participants conveyed that the positions of sensations provided by the tapping and stroking systems were more readily discernible than those produced by the vibration system.

5.4.4 Workload

The standard deviations of the averages for each of the NASA TLX domains are relatively low, with the majority of them below 0.71. Considering that the granularity of the NASA TLX questionnaire is 21 points, graded from 0 to 20, a standard deviation of 0.9 represents a negligible difference, amounting to less than one point out of a possible 21-point difference. From this observation, we can confidently conclude that neither the tapping nor the stroking systems were perceived to be more mentally taxing than the vibration system across any of the domains evaluated. Furthermore, in conjunction with the findings on learning rates, we can deduce that none of the systems impose a higher cognitive demand on the user compared to the vibration system. This indicates that using a tapping or stroking system is, at the very least, as effective, if not more, as a vibration system, while maintaining a comparable level of user demand.

5.5 Discussion

In this chapter, we conducted an investigation to assess the effectiveness of three different tactile sensations (vibration, tapping, and stroking) in passive haptic learning for teaching piano notes. The evaluation aimed to address the research questions formulated earlier.

The results revealed that there were no significant differences among the three sensation systems (vibration, tapping, and stroking) in terms of their effectiveness in passive haptic learning (**RQ1**). This suggests that using stroking or tapping as a signal can be just as effective as using vibration, indicating that vibration may not be the sole practical signal for passive haptic learning.

Furthermore, we observed that both tapping and stroking systems were capable of teaching more notes to participants compared to the conventional vibration system in passive haptic learning (**RQ2**). Additionally, the study found that participants perceived the tapping and stroking systems to be more pleasant and less noisy compared to the vibration system, making them a more natural and unobtrusive way of conveying information to users. Specifically, the stroking system was rated as the most pleasant sensation, aligning with existing research on affective and discriminative touch (**RQ2**).

Meanwhile, our study suggests that passive haptic learning may yield greater benefits for individuals lacking prior experience, a trend consistent with prior research [74]. This discovery reinforces the potential utility of passive haptic learning as an effective tool for music education, particularly among novice learners.

It is crucial to highlight that our study's accuracy rate per note sequence stood at approximately 50%, a value lower than the reported accuracy in the Mobile Music Touch study [74]. This variance may be attributed to a notable distinction in the test phase conditions between our research and that of Huang et al. [74]. Unlike their study, our participants did not have access to a recall aid during the test phase, wherein they could hear the note sequence played from the keyboard and observe the corresponding keys lighting up before the testing session.

Further investigation is warranted to gain a more nuanced understanding of the accuracy of different tactile sensations in passive haptic learning. We aim to replicate the protocol employed by Huang et al. [74] in future research endeavors, specifically delving into the accuracy aspect of passive haptic learning.

5.6 Conclusion

This chapter aimed to compare the effectiveness of three tactile sensations, namely vibration, tapping, and light stroking, within the context of Passive Haptic Learning (PHL). The results from the user study indicated that both the tapping and stroking systems are equally effective as the vibration system in teaching note sequences through PHL on a piano. This finding provides valuable insights and serves as a reference for future exploration of different sensations in passive haptic learning. Furthermore, participants using the tapping and stroking systems showed a significant improvement, making up to 1.06 fewer errors on average compared to when using the vibration system. Additionally, our findings align with previous research, demonstrating that PHL is more effective for participants without prior piano experience, regardless of which system is employed. Notably, our statistics revealed that novices comprehend the note sequences better when using the tapping and stroking approach.

Given that there has been limited prior research investigating the three sensations in the manner of this thesis, further investigation is needed to expand our understanding of their potential applications and benefits. We believe that our work not only provides new insights for the development of passive haptic learning systems but also facilitates their practical implementation in various scenarios. The results presented in this chapter contribute to advancing the field of haptic learning and provide a basis for exploring innovative and effective ways to utilize tactile sensations in educational contexts.

While it is plausible to consider that the force differences of the sensations provided to the participants could potentially impact the learning rate in the study, it is essential to note that the vibration method employed in our study aligns with previous research. This consistency allows for meaningful comparisons of our results with those reported in other studies [28, 129, 139]. Additionally, the design of the sensations of light stroking and tapping drew inspiration from a study by Kress et al. [89].

During the user study, we gathered valuable feedback from participants regarding their perceptions of the stroking and tapping sensations. Participants described stroking as "*feeling like something tickling the skin, but not quite the same*", while tapping was described as "*feeling like a person letting their fingers fall on the skin in cycles from a distance of about 4-5 cm*". Since there was no prior research utilizing stroking and tapping for passive haptic learning, we lacked a basis to directly compare and adjust the sensations generated by the tapping and stroking system based on previous research. Nonetheless, these sensations were well-received by the participants and demonstrated promising potential as effective alternatives to traditional vibration-based methods in passive haptic learning.

An additional limitation of our study is the lack of high integration among the individual parts mounted on each finger. As a result, the installation process proved to be somewhat tedious, and the wires were scattered, potentially impacting user comfort and ease of use. To address this limitation, we intend to rectify the existing system by developing a more streamlined and integrated device. By transforming the system into one embedded device, we aim to enhance convenience, wearability, and user experience during passive haptic learning sessions. This improvement will make the system more user-friendly and facilitate a smoother overall user experience.

The effectiveness of tapping and stroking for passive haptic learning has been demonstrated in our study. However, the potential impact of various tactile sensations in other application areas of PHL remains uncertain. We postulate that teaching motor skills, such as braille typing or Morse code, through tapping and stroking, is likely feasible, as previous studies have already shown with vibration. Nevertheless, further research is required to validate our assumptions. Moreover, Passive Haptic Rehabilitation is gaining attention as a potential therapeutic approach. The effects of stroking and tapping on this field are largely unexplored and warrant investigation. Additionally, the wide array of sensations that can be perceived by the human body, coupled with the increasing availability of wearable tactile devices, opens up numerous possibilities for extending human reality perception and enhancing user experiences. We intend to investigate how these stimuli can be seamlessly integrated during users' movement to augment their overall experience.

Another intriguing avenue for future exploration lies in studying human perception. The different mechanoreceptors in human skin play a vital role in interpreting various tactile, temperature, and pain stimuli. For example, Merkel cell neurite complexes respond to low vibrations (5-15 Hz) and deep static touch, while Meissner corpuscles detect gentle stimuli and react to moderate vibrations (10-50 Hz) and light touch. Pacinian corpuscles, on the other hand, respond to a wide range of vibrations (40-500 Hz), making them highly sensitive but only responsive to sudden stimuli. Skin stretching is perceived by Ruffini corpuscles, which have a slower reaction time [86]. We wonder whether using different sensations, other than vibration, could influence the retention rate of information in passive haptic learning. Could sensations like skin stretching or twisting be employed for PHL effectively? Moreover, are there differences in the levels of cognitive demand imposed on participants during passive haptic learning sessions when using different sensations? These fascinating questions demand further investigation.

Part IV

INTERACTION APPLICATIONS

6 Integration of Haptic Interfaces with Complementary Interaction Techniques

The last three chapters discussed and explored mainly the design and development of haptic actuators and interfaces. Starting with this chapter, the integration of comprehensive haptic interfaces with other interactive technologies is explored, aiming to enhance the overall immersive and efficiency aspects of the experience. This chapter delineates and investigates the potentialities arising from the convergence of wearable haptic interfaces with diverse interaction technologies, encompassing visual and auditory feedback, as well as mixed reality. The chapter endeavors to propel the evolution of haptic user interfaces by exploring and amalgamating these convergences. Its overarching goal is to unveil novel approaches for augmenting human-technology interaction through the strategic application of haptic interfaces. In the subsequent sections, a systematic unpacking of the multifaceted contributions and inherent implications of these integrated approaches will be unfolded.

6.1 Investigating Three Learning Signals for Passive Haptic Learning in Different Contexts

This section explored 3 different learning signals: haptic, auditory, and haptic & auditory during the learning phase for passive haptic learning. This chapter presents an user study with 24 participants to investigate the influence of different learning signals on users' ability to learn rhythms. Learning the rhythm of a piano note is equally important as mastering the correct note sequence. While focusing on playing the right notes is crucial for accuracy, understanding and internalizing the rhythm enhances the musicality and overall quality of performance. Rhythm is the temporal arrangement of musical sounds and rests, and it provides the framework that gives music its groove, feel, and flow. When learning a piano piece, grasping the rhythm ensures that you not only play the correct notes but also capture the intended expression, emotion, and dynamics of the composition. This chapter focused on the following aspects: (1). how these learning signals would influence the ability to learn a rhythm passively in terms of the duration and timing the participants reproduced; (2). how would the different contexts would have an impact on the performance of the participants? The content of this chapter was published in

Proceedings of the 16th ACM International Conference on Pervasive Technologies Related to Assistive Environments in 2023 [39].

6.1.1 Related Work

Learning a new musical instrument is becoming a challenging and time-consuming task. In today's busy and fast-paced urban life, people are gradually losing sufficient time to learn musical instruments. Passive haptic learning (PHL), as defined by Seim, Estes, and Starner [138], is an emerging learning method, where the acquisition of sensorimotor skills doesn't need active attention to learn. PHL has been well investigated in the past decade among the HCI community. There have been many studies concerned with applying PHL to a variety of actions, for example, learning Morse code [140], Braille [141], and playing the piano [138]. Great progress has been made in teaching users how to learn skills. Most of the PHL studies have concerned themselves with inspecting whether the learned movement itself is correct, such as moving the right finger when recalling a piano song [28, 40] or correctly associating patterns with the haptic feedback, for instance, Braille [141] or Morse code [129]. However, a key component when people start learning music is the understanding of rhythm. Previous works had concluded promising results about the effect that the haptic signals had on learning rhythms. Ebisu et al. [34], Ebisu, Hashizume, and Ochiai [34] and Kanke, Terada, and Tsukamoto [81] proposed the method of teaching rhythms using electrical muscle stimulation. Miura and Sugimoto [113] reported an armband that vibrates for the specified time and strength to teach the rhythms. Takano and Sasaki [156] and Stanley and Calvo [149] combined auditory and visual cues to teach the rhythms.

6.1.2 System Design

The glove utilized in this study was crafted from soft and stretchy cotton material. Vibration motors were strategically mounted on each finger, encircling the intermediate phalanges, with the exception of the thumb, which lacks this particular phalanx. Therefore, the motor was positioned on the underside of the distal phalanx of the thumb. Two of the vibration motors were connected to TLC boards (Model: TLC59711), which were sewn onto the index and ring fingers of the glove, facing downward. The remaining three vibration motors were attached magnetically to the glove using small integrated magnets (see Figure 6.1 (a)). These motors had a frequency of approximately 200 Hz and were controlled through a BLE Nano v2 chip. Special care was taken to ensure that the connections between cables and the vibration motors were not taut to avoid any vibration carry-over between fingers. The PHL glove was powered by a Li-Po battery, with a total weight of 49 grams.

The Ukulele used in this experiment was constructed from wood and had a Soprano size, measuring 53 centimeters in length. It was tuned to the standard gCEA ukulele tuning (see Figure 6.1 (b)). As for the keyboard employed in the study, it was a mechanical keyboard featuring Cherry MX Red switches. These switches require minimal force to press down

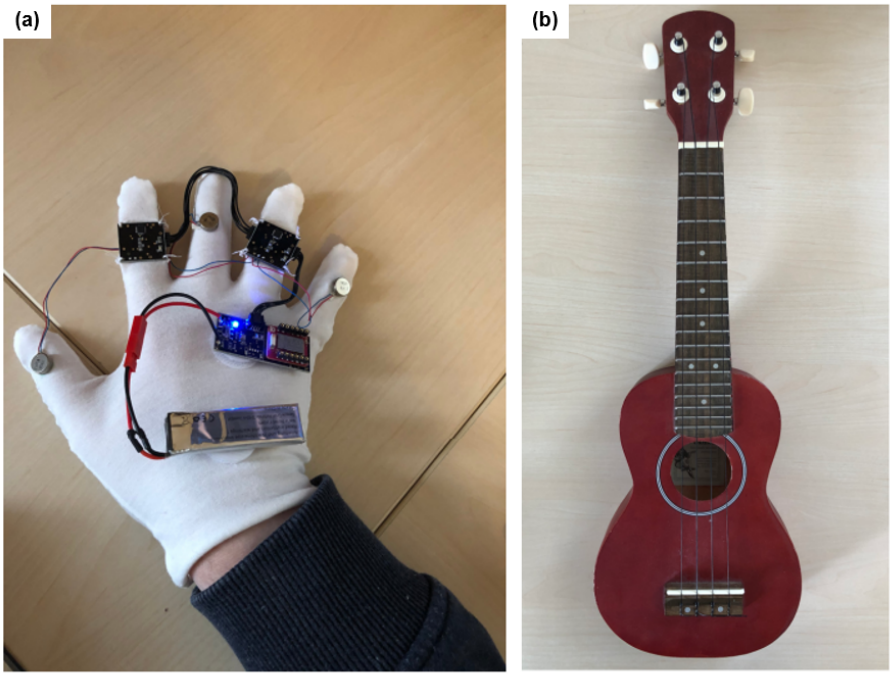


Figure 6.1: Passive Haptic Learning glove and Ukulele: (a). Glove and electronics position on the hand; (b) Ukulele used in the experiment.

and produce no "clicking" sound when actuated, while also lacking a tactile bump upon registering the key press. The keys had a travel distance of 4 millimeters, registering the keypress after traveling 2 millimeters.

6.1.3 Methods

6.1.3.1 Participants

The study utilized a within-subject design, and we recruited 24 participants (16 males, 8 females) through convenience sampling to participate in our studies. The participants were evenly divided into three groups based on the signals they received.

- *Group Hap (G1)* received only passive haptic cues;
- *Group Hap & Aud (G2)* received both passive haptic cues and auditory signals;
- *Group Aud (G3)* received only auditory signals;

To ensure a balanced representation, each group was counterbalanced according to participants' musical experience before the study. An overview of all the participants is provided in Table 6.1.

Table 6.1: Participants and their musical experiences.

Subject	Musical Experience	Instrument	Duration of Musical Exp.
G11	Yes	Guitar/ French Horn	14 Years
G12	No		
G13	Yes	Piano	2 Months
G14	Yes	Piano	10 Years
G15	Yes	Violin	9 Years
G16	No		
G17	Yes	Piano	5 Years
G18	Yes	Piano	8 Years
G21	Yes	Guitar	1 Year
G22	Yes	Piano	3 Months
G23	Yes	Piano	6 Years
G24	Yes	Violin	14 Years
G25	No		
G26	Yes	Drums	4 Years
G27	No		
G28	Yes	Flute/Piano	5 Years
G31	Yes	Piano	5 Years
G32	No		
G33	Yes	Piano accordion	5 Years
G34	Yes	Guitar/Recorder	8 Years
G35	No		
G36	Yes	Piano	3 Years
G37	Yes	Piano accordion	3 Years
G38	No		

Figure 6.2: (a). Note sequence used in this study, using a total of four different notes and pause lengths; (b). Each finger's correlation with the notes.

6.1.3.2 Study Design

The design of our studies draws inspiration from previous works [28, 74]. To ensure consistency and comparability with these studies, we used a similar length of taught rhythm based on their note sequences. However, we made certain modifications to the note sequences used in previous studies. In contrast to the note sequences employed in those studies, which lacked a diverse range of note lengths and pauses between notes, we designed our note sequence to include notes and pauses of varying lengths. This allowed us to assess participants' ability to distinguish between different note duration. The tempo of the note sequence was set to 150 beats per minute.

To minimize potential bias from participants' prior knowledge or familiarity with specific songs, the note sequence used in our study was not taken from any commonly known piece. Figure 6.2 (a) illustrates the designed note sequence, with each line representing a different finger (from the thumb to the pinkie), and Figure 6.2 (b) shows the mapping of fingers to tones.

As a distraction task during the learning sessions, we provided participants with the option to play the same video game used in a previous study [28]: *Tetris*[1]. This allowed us to assess participants' engagement levels during the learning sessions and ensure that they remained focused on the passive haptic learning task.

6.1.3.3 Procedure

At the beginning of the study, participants began by providing demographic information and signing a consent form. They were then given an overview of the study, which included a brief explanation of Passive Haptic Learning, a summary of related research, and the objectives of our specific study. Next, participants were introduced to the PHL glove we developed, and the functionality of the glove was explained to them.

Following this, participants received detailed instructions about the distraction task, including the controls and rules of the game. To assess participants' engagement with the distraction task, we recorded and analyzed their scores during the game to determine whether they were actively focused on playing.

Subsequently, we proceeded to the learning phase of the study, where participants engaged with the Passive Haptic Learning task using the designated learning signals.

Learning Phase: Participants in *G1* and *G3* were instructed to wear the glove and received tactile signals or auditory signals every 10 seconds during the learning session. For participants in *G2*, who were exposed to both haptic and auditory signals, the signals were also presented every 10 seconds. However, to prevent cognitive overload from

[1]https://tetris.com/play-tetris

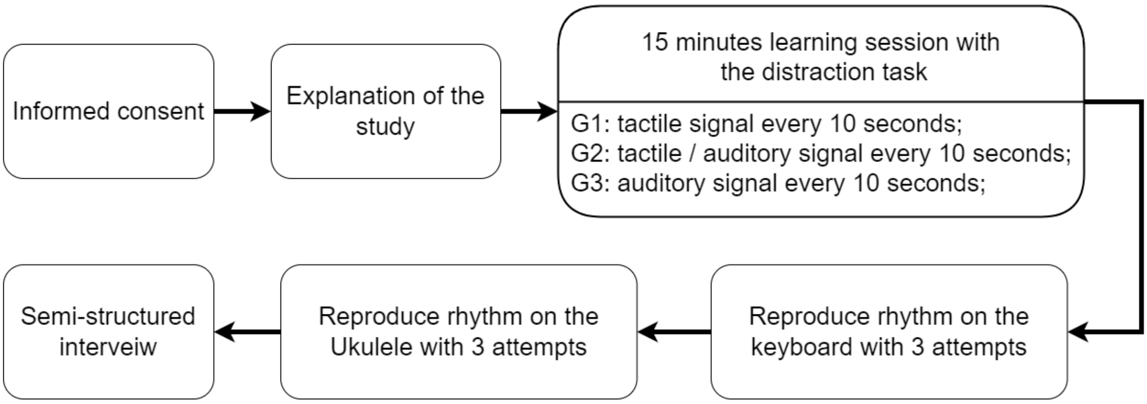


Figure 6.3: Overview of the procedure of the study.

simultaneous processing of two perceptual tasks [48], the signals were offset by a few seconds. This ensured that auditory signals were presented during pauses between tactile signals, and vice versa.

The duration of each learning session was approximately 15 minutes per participant, during which the rhythm was replayed via the glove and/or audio precisely 68 times.

Reproduction Phase: The participants were initially instructed to replicate the learned rhythm on the keyboard, with three attempts allowed. They were given the freedom to use any keys and fingers, but encouraged to use two fingers to accurately reproduce the 0ms-pauses between notes. No audio feedback was provided when pressing a key on the keyboard. To track the timing and duration of key-presses on the keyboard, a program written in C# was utilized.

Next, the participants were asked to replicate the rhythm on the ukulele, also with three attempts. They had the liberty to use any strings of the ukulele, but were instructed not to let the last note of the rhythm fade out, instead stopping it when they felt it appropriate to reproduce the rhythm. The data from the ukulele performance was recorded using the program *Audacity* for further evaluation and analysis.

Finally, a semi-structured interview was conducted with the participants to gather their comments and feedback regarding the study. An overview of the study procedure is depicted in Figure 6.3.

6.1.4 Results

The Dynamic Time Warping (DTW) algorithm, a well-known tool utilized in various fields, is effective in measuring time-series similarity by allowing for "elastic" transformation of time series [143] and finding the optimal global alignment between them. In our study, we employed the DTW algorithm [136] to calculate the distance between the note sequence reproduced by the participants and the correct note sequence for evaluation purposes.

For data analysis, we conducted a two-factor ANOVA using the DTW error from each try performed by the participants as the data and the different groups and instruments as the considered factors. The significance level α was set to 0.05 for the entire evaluation process.

6.1.4.1 Duration

Comparison in between groups: Figure 6.4 (a) illustrates the relationship between DTW correctness and duration. Concerning the reproduction of the rhythms played on the keyboard, Group 1 (**G1**) exhibited the best performance, followed by Group 2 (*G2*) and Group 3 (*G3*) with the lowest performance. The differences between the groups are not substantial. The results suggest that participants in G1 were able to establish a strong connection between the haptic feedback from the keyboard and the haptic signals received during the learning phase, resulting in the most favorable outcomes. On the other hand, participants in *G3* had difficulties in establishing a similar connection since they were provided with auditory signals during the learning phase but not during the reproduction phase.

Regarding the reproduction of the rhythms played on the Ukulele, more significant differences were observed compared to the keyboard. *G2* achieved the best result, followed by *G3* and *G1*. The results indicated that participants in *G2* and *G3* were able to match the audible feedback of the Ukulele with the audio signals they received during the learning phase. As a result, these two groups performed better than participants in *G1*, who only had haptic signals during the learning phase. Interestingly, participants in *G2*, who received both haptic and auditory signals, demonstrated significantly improved performance when reproducing the rhythm compared to those in *G3*, who had only one signal during the learning phase. This finding highlights the potential benefit of providing multiple sensory signals in passive haptic learning scenarios.

Comparison within a group:

Figure 6.5 illustrates the individual performance of each participant within the three groups. For participants in *Group Hap (G1)* (p = 0.00687), six out of eight participants performed better when reproducing the rhythm on the keyboard. This finding suggests that a haptic signal can be easily translated into a simple movement, such as pressing a key, in the context of passive haptic learning. However, the differences in errors between the keyboard and ukulele tasks indicate that matching a single felt vibration with two different types of finger movements (strumming and stopping a string) appeared to be more challenging for the participants.

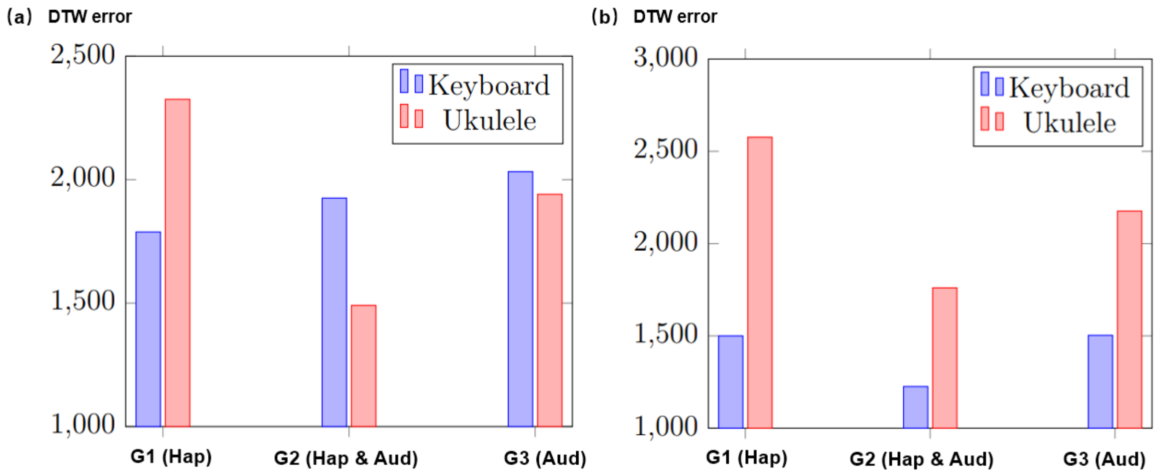


Figure 6.4: The average DTW error regarding the correctness of: (a). duration; (b). timing in three groups.

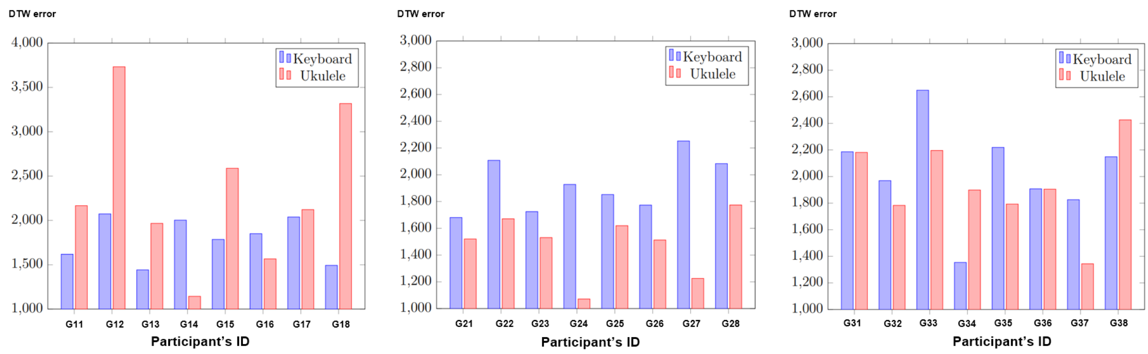


Figure 6.5: The average DTW error regarding the duration of the rhythm with participants ID in three groups.

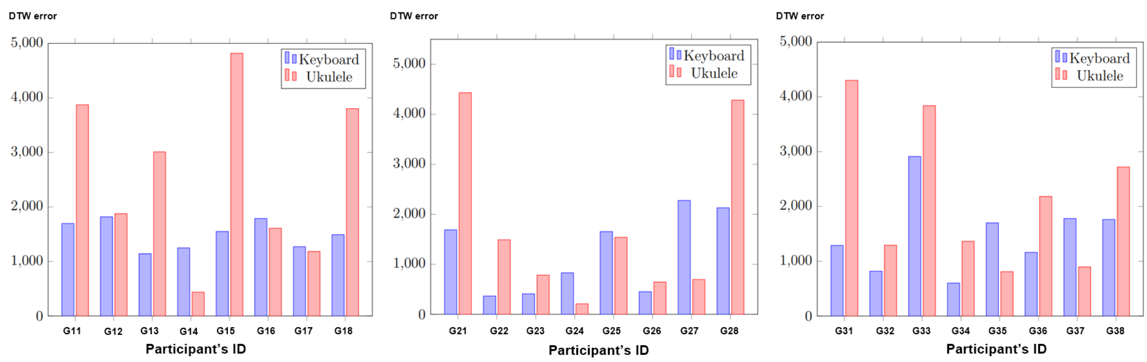


Figure 6.6: The average DTW error regarding the timing of the rhythm with participants ID in three groups.

For participants in *Group Hap & Aud (G2)* ($p < 0.001$), all participants performed better when reproducing the rhythm on the ukulele. This finding suggests that the additional audio signals received during the learning phase were crucial in enhancing the effectiveness of passive haptic learning. An unexpected observation was that the additional auditory signals had a greater impact on the participants' performance regarding the ukulele than the keyboard. One possible explanation is that the haptic signals provided additional information that improved overall memory and performance. However, the lack of audible feedback from playing the rhythm on the keyboard limited the effectiveness of the additional information.

For participants in *Group Aud (G3)* ($p = 0.39921$), four out of eight participants performed significantly better when reproducing the rhythm on the ukulele, compared to the keyboard. Two participants performed better on the keyboard, and the remaining two had similar results for both tasks. This observation suggests that the specific finger movements required to play the instrument had little to no impact when only auditory signals were provided during the learning phase.

6.1.4.2 Timing

In addition to analyzing the duration of notes and pauses, we also examined the timing at which participants reproduced the rhythms to monitor the pulse or rhythmical aspect of their performance.

Comparison in between groups:

Figure 6.4 (b) illustrates the relationship between DTW correctness and time. It was evident that, unlike the duration errors, each group performed significantly better when playing the rhythm on the keyboard. This observation suggests that playing the ukulele or string instruments, in general, was unfamiliar to most participants, requiring a considerable amount of their concentration for strumming and stopping the strings, thereby diverting their focus from the timing of notes. On the other hand, getting the timing right on the keyboard was perceived as a relatively easier task, as the finger movement demands less attention, allowing participants to concentrate more on recreating the original rhythm accurately. However, the differences between the groups in terms of timing accuracy were found to be statistically insignificant (P-value = 0.16451; F-value = 1.96; F-critical = 3.94).

Comparison within a group:

Figure 6.6 presents the average DTW error concerning the timing of the rhythm for each participant in the three groups. For subjects in *G1* ($p = 0.00243$), four participants performed significantly worse when playing the rhythm on the ukulele compared to the keyboard. Three participants showed similar results on both instruments, while one test subject had better results on the ukulele. Overall, the performance was better on the keyboard, suggesting that haptic signals are more effective when combined with an instrument that provides haptic feedback, consistent with the findings from the duration evaluation. The timing errors on the keyboard were relatively consistent for all participants, while the errors from the ukulele varied greatly.

For subjects in *G2* ($p = 0.1749$), four participants performed better when playing the rhythm on the keyboard rather than the ukulele. Two participants had similar results on both instruments, while the remaining two test subjects performed better on the ukulele. The instrument type did not show significant influence. However, when it comes to the error, errors decreased for most of the participants on both the keyboard and ukulele. Interestingly, participants in *G2* achieved near-perfect timing results on the keyboard compared to those in *G1* with a "mediocre" performance, suggesting that some participants were able to use the additional audio information during the learning phase to their advantage.

For subjects in *G3* ($p = 0.03599$), six participants performed better when playing the rhythm on the keyboard rather than the ukulele, indicating that the keyboard was overall considered the instrument that produced better timing results. better performances regarding the timing.

6.1.4.3 Feedback

Participants from *G1* and *G3* were asked to rate the comfortability of the glove on a scale from 1 (very uncomfortable) to 5 (very comfortable). The average score was 4.0625, with the main complaint being that the glove was too heavy. In contrast, seven out of eight participants from *G2* reported that the combination of haptic and audio signals was more effective for passive learning of the rhythm. However, one participant from *G1* reported that they were reminded of a previously known rhythm by the haptic signals and kept recalling that one in their mind. This highlights the potential risk of using haptic signals alone, as they might become mixed up with already memorized rhythms in the participant's mind and lead to incorrect results.

6.1.5 Conclusion

In this chapter, we conducted an investigation to explore the impact of haptic and auditory signals on the ability to recreate passively learned rhythms using two different instruments: a keyboard and a ukulele. The results showed that participants demonstrated only minor differences when reproducing the rhythm on the keyboard, whereas significant disparities were observed when attempting to recreate the rhythm on the ukulele. Notably, participants who received both haptic and auditory signals during the learning phase exhibited the highest performance in recreating the passively learned rhythm. This finding suggested that the combination of muscle memory and an auditory melody to recall in one's mind contributed to the best performance.

On the other hand, using haptic signals alone appeared to be the least effective approach for teaching rhythms, particularly for instruments that require more complex actions to play than simply pressing a key. This discrepancy may be attributed to the mismatch between the type of signal received during learning (haptic) and the feedback received during rhythm recreation (auditory). The unfamiliarity of the ukulele as well as the more intricate motions required to play it were identified as the main factors contributing to the challenges observed in rhythm reproduction on this instrument.

Moving forward, we plan to explore a wider range of musical instruments and diverse learning signals in our future research, which holds the potential to yield unexpected and promising outcomes. Additionally, we are interested in investigating how different types of feedback received during the recreation of a rhythm can influence the overall performance and learning outcomes. By exploring these aspects, we aim to gain deeper insights into the mechanisms underlying passive haptic learning and its implications for various musical instruments and learning contexts. Such investigations will contribute to the development of more effective and versatile passive haptic learning systems, ultimately enhancing music education and training experiences for learners of all skill levels.

6.2 Investigate the Piano Learning Rate with Haptic Actuators in Mixed Reality

Section 6.1 engaged in a thorough investigation into the impact of haptic and auditory signals on the aptitude to accurately reproduce a rhythm learned passively. This section investigates an extensive discussion and exploration of the integration of haptic interfaces with prevalent mixed reality (MR) technology, aimed at facilitating the flexible and comprehensible teaching of human motor skills.

Mixed Reality (MR) technology serves to enhance the physical environment by seamlessly integrating digital information within it. Prominent MR devices such as the Microsoft HoloLens [112] and Magicleap [1] have demonstrated their utility across a diverse array of scenarios [9, 96, 99, 158]. Haptic feedback, an integral component of human-computer interaction, has pervaded various aspects of daily life, including its ubiquity through smartphones. Researchers have historically delved into distinct haptic hardware solutions to replicate tactile sensations within MR environments [7, 88, 157, 158]. Concurrently, investigations have explored the integration of MR technology into various learning domains, such as its application for medical training with students [150, 173], visual guitar instruction [159], and piano learning [4, 16, 177]. Prior research in the domain of piano instruction using MR has predominantly revolved around the projection of overlays onto physical pianos, aiding learners by visually indicating the subsequent keys to be played.

An alternative research approach to piano pedagogy involves the utilization of haptic gloves for passive haptic learning, as demonstrated by previous works [20, 72]. Within the realm of haptic-based education, extant research highlights the superiority of haptic learning over auditory-based approaches [73], underscores the efficacy of combining audio cues with vibrations for enhanced learning outcomes compared to standalone audio or vibrational stimuli [137], and indicates that passive haptic learning yields comparable recall rates to traditional methods even after a three-day interval [29]. Moreover, advancements in soft actuator technologies [37, 105] and the emergence of on-skin electronics [118] have played a pivotal role in facilitating the haptic component of these pedagogical applications.

The preceding studies identify two interconnected research domains: (1) MR/visual-only and (2) haptic-only approaches for piano learning. Moreover, existing research substantiates the ascendancy of multi-sensory piano learning that encompasses both haptic and auditory cues, outperforming singular audio or haptic methods. Consequently, the amalgamation of MR technology and haptic interfaces present an innovative piano learning application that, to the best of our knowledge, has not been previously examined.

Within this chapter, the realization of the piano learning application is achieved through the integration of visual cues (MR) and haptic cues (on-skin actuators), thereby facilitating the instruction of a piano sequence. Our exploration is guided by two central research inquiries. Firstly, **RQ1**: How does the efficacy of our methods in instructing piano sequence performance vary with the application of distinct cues? Secondly, **RQ2**: Does the learning outcome differ between haptic-based learning and visual learning within the MR context?

To address these questions, we conducted an user study (N = 16), utilizing the MR application as the platform for our investigation. The content of this chapter was published in Proceedings of the ACM International Augmented Humans Conference 2022 [40].

6.2.1 Related Work

Other researchers have explored the integration of Mixed Reality into diverse educational domains, such as medical education with applications like cadaver visualization [150, 173], as well as visually guided guitar learning [159]. In the realm of haptic learning, prior investigations have indicated that haptic-based instruction surpasses auditory-only approaches [73], that the amalgamation of audio and vibration yields superior learning outcomes compared to individual auditory or vibrational cues [137], and that the effectiveness of passive haptic learning endures with consistent recall over a three-day span [29]. These seminal studies serve as the foundation upon which this current work is built. Furthermore, the advancement of soft actuators [37, 105] and on-skin electronics [118] plays a pivotal role in facilitating the haptic component of our learning application. Particularly, earlier research detailed in Fang et al. [37] has provided insights into the development of electromagnetic actuators, leveraging the Lorenz principle as a guiding principle.

6.2.2 Methodology

6.2.2.1 Signals and Platforms for Learning

The implementation of the piano learning application takes the form of a Unity application, utilizing the open-source Mixed Reality Toolkit [114] for the projection of a holographic piano within a designated spatial location in the room. Employing a mixed reality apparatus such as the HoloLens, individuals are afforded the capability to engage with this holographic piano using the hand tracking feature, specifically employing the five fingers of the right hand for interaction. The act of pressing a key triggers the emission of the corresponding sound, propagated through the speakers integrated into the HoloLens device. The holographic piano encompasses a total of twelve keys spanning a single octave, encompassing the inclusion of the central note, middle C (ranging from C4 to C5 according to the scientific pitch notation). This holographic piano serves as the foundational platform upon which two distinct modes of learning are proposed in this chapter: (1) *visual learning*; and (2) *haptic learning*.

Visual Learning Signal: The visual learning approach employs distinct holographic objects characterized by varying colors and shapes, which descend from a height of 20 centimeters above the piano keys, indicating the next key to be played. More specifically, a turquoise rectangle is employed to demarcate the target area. Upon the entry of a descending shape into this target zone, an identical shape materializes directly above the corresponding finger intended to press the designated piano key. When the individual synchronously activates the piano key while the shape remains within the target area, the piano emits the appropriate sound associated with the key, thus confirming the correctness of the action. Conversely, if the timing of the key press does not align with the shape's presence within the target zone, an error sound ensues. The visual cues provided by these shapes serve to guide the user in playing the requisite keys, thereby facilitating the acquisition of a musical piece. Figure 6.7 visually portrays the operational visual piano learning application as executed within the Unity3D game engine. In the displayed scenario, the pianist has accurately engaged the G key utilizing their index finger, causing the orange shape positioned within the turquoise target area above the G key to disintegrate. Additionally, the plummeting dark blue cube signals the pianist to prepare for the subsequent key press on the G key.

Haptic Learning Signal: In contrast to the visual learning method, the haptic learning approach imparts guidance on the appropriate finger to depress by eliciting vibrations on the corresponding finger. These vibrations are characterized by a frequency of 16 Hz, resulting in a tactile sensation localized at the position of the on-skin haptic actuator, strategically positioned beneath the proximal interphalangeal joint of each finger. The specific placement of each actuator is visually indicated in Figure 6.8 through marked red x's. The tactile vibration experienced by a finger serves as the instructional cue for the learner, prompting the depression of the holographic piano key situated beneath the finger subject to vibration. Lacking any concurrent visual indicator, this methodology

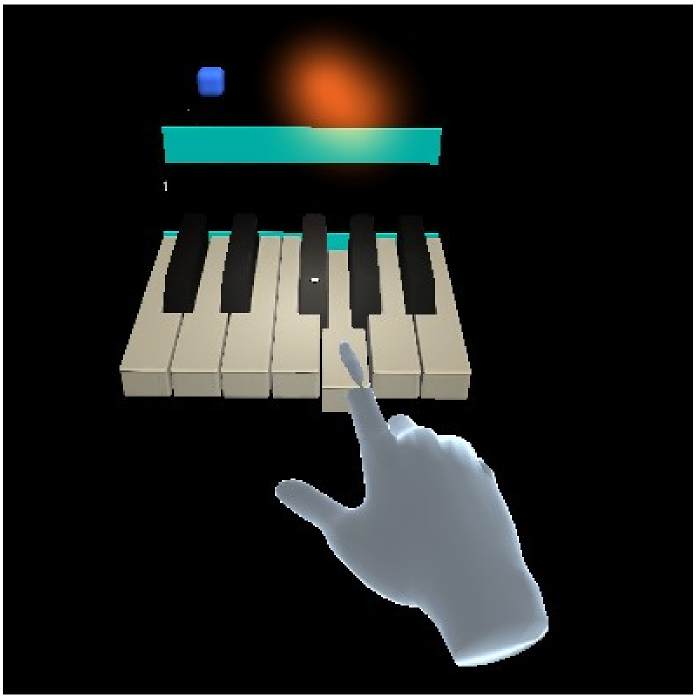


Figure 6.7: Visual learning in Unity3D.

confines the range of playable keys using a single hand to five piano keys. Within the context of the evaluation, the chosen repertoire necessitates the engagement of only these five keys. Importantly, all participating individuals were thoroughly acquainted with the key-to-finger correspondence for the designated five keys. The on-skin haptic actuators encompass the following components: (1) off-the-shelf flexible electric coils [2]; (2) neodymium disc magnets possessing dimensions of 3 mm in thickness and 10 mm in diameter; and (3) 3D-printed housings. The control unit of these actuators is an ESP32 microcontroller, with wireless activation orchestrated by the HoloLens. Upon actuation, the coil generates an electromagnetic field, causing the magnet to initiate vibrations.

As depicted in Figure 6.9, the haptic learning application is depicted in operation on the HoloLens, with the piano serving as the backdrop and hand-tracking rendered in the foreground. It is noteworthy that the piano, in this instance, lacks the visual indicators that are intrinsic to the visual piano learning application. The haptic learning method diverges from its visual counterpart in that the player dons a haptic glove, which engenders tactile vibrations in the designated finger, signaling the next key to be pressed.

[2]https://flexar.io/

Figure 6.8: Haptic glove.

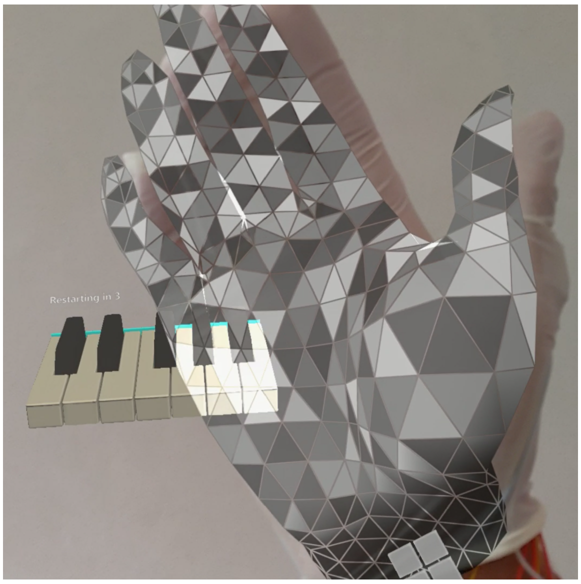


Figure 6.9: Haptic learning with HoloLens.

6.2.2.2 Study Design

We have conducted a between-subjects design user study to systematically investigate the efficacy of haptic and visual learning approaches in acquiring the skill to play Beethoven's composition, *Ode to Joy*. The procedural framework of the study is illustrated in Figure 6.10.

To initiate the study, each participant is allocated a 5-minute period to acquaint themselves with the functionalities of the HoloLens, getting familiar with the identity of the specific musical piece to be learned. Subsequently, the participants are required to perform renditions of *Ode to Joy* prior to and following the learning session, during which they are granted three attempts.

During the learning phase, participants are exposed to one of two learning methods: visual signals or haptic signals. Over 30 minutes, participants engage in the learning process facilitated by their designated learning method. The two primary metrics employed for gauging learning proficiency encompass the sequencing precision of piano key presses and the temporal accuracy of piano key press execution.

The study encompassed a participant pool consisting of 56% male and 44% female individuals, yielding a total sample size of n=16. The age distribution spanned from 18 to 56 years, with a mean age of 34 years and a median age of 27 years. Among the participants, 88% identified as right-handed, while the remaining 12% identified as left-handed.

A substantial majority of participants (75%) reported no prior experience with mixed reality (MR) devices such as the HoloLens. Regarding familiarity with the musical composition *Beethoven: Ode to Joy*, 62% of the participants indicated previous exposure to it.

Regarding musical background, the participants demonstrated varying levels of piano experience. Specifically, eight participants possessed eight years of piano experience, four participants had four years, two participants had two years, and the remaining 13 participants reported no prior piano experience.

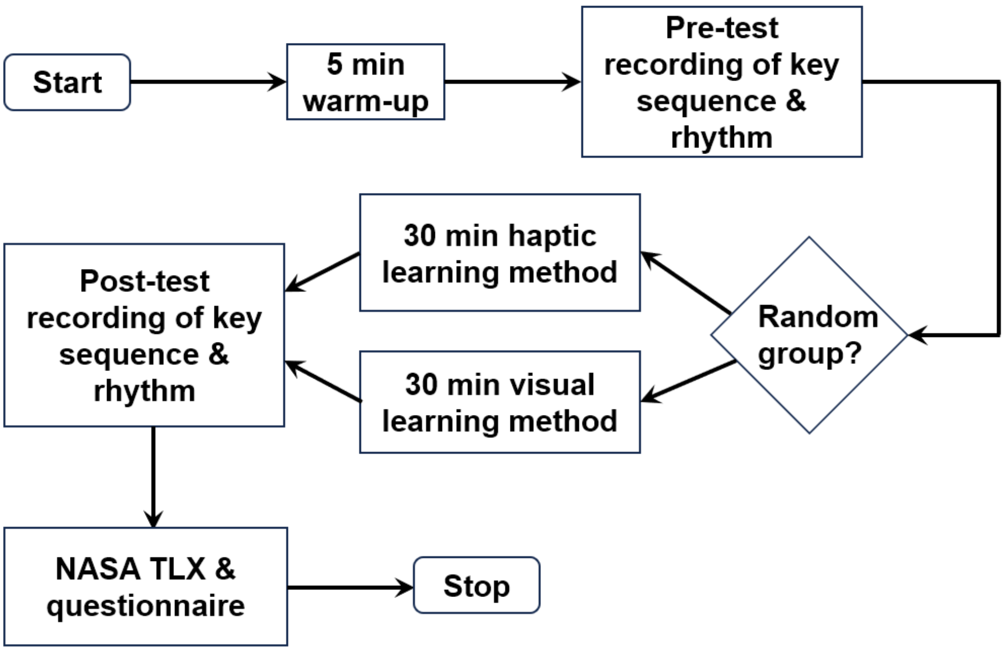


Figure 6.10: The flow chart of the study design.

6.2.3 Results

The improvements in individual participants' retention of the key sequence and rhythm are visually depicted in the bar charts presented in Figure 6.11 and Figure 6.12. Additionally, the outcomes of the subjective questions pertaining to the learning environment are illustrated through the stacked bar chart featured in Figure 6.13.

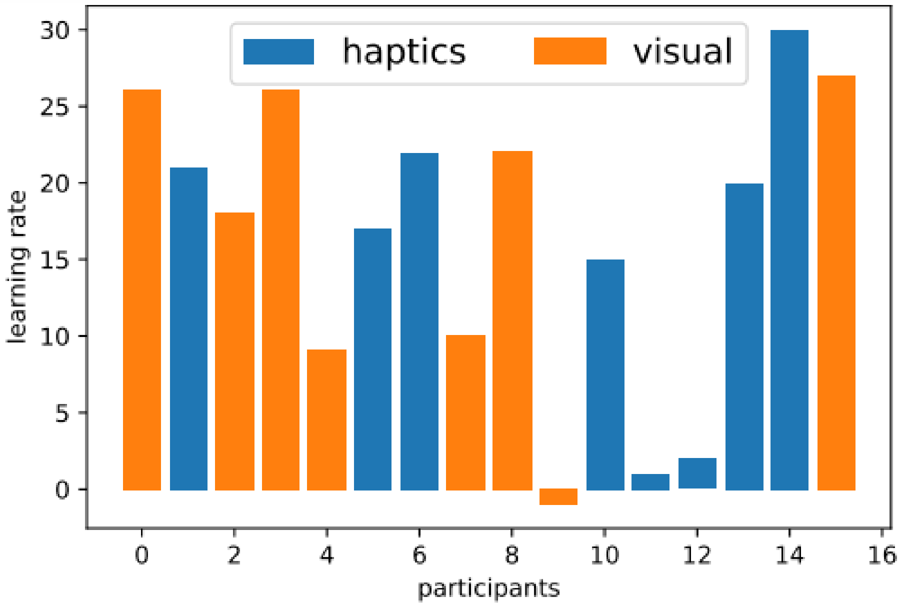


Figure 6.11: Results for each participant of the remembered key sequences.

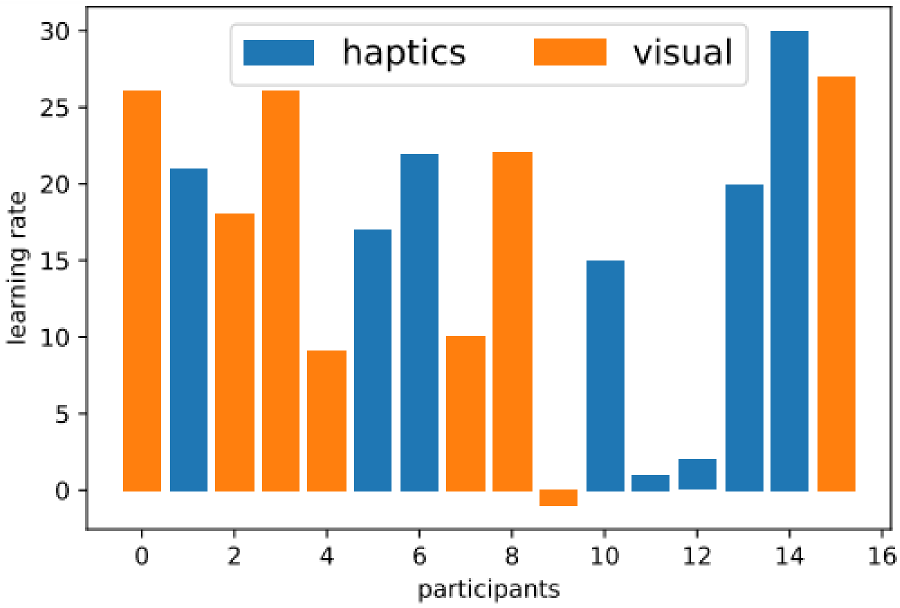


Figure 6.12: Results for each participant of the remembered rhythms.

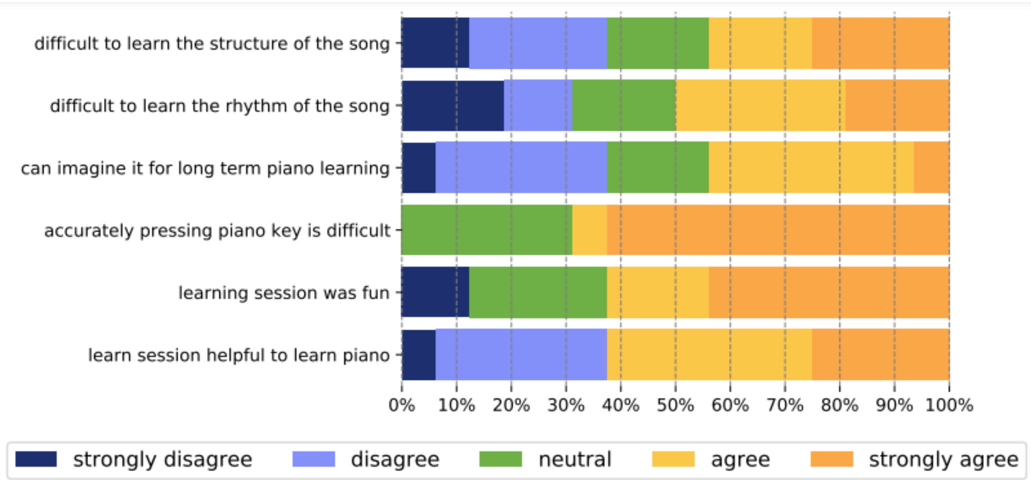


Figure 6.13: Results of the subjective questions concerned with the learning session.

Following 30 minutes of visual learning, the one-sided paired t-test revealed a noteworthy reduction in error within the key sequence ($t = -4.76, p = 0.001$, Cohen's $d = 1.68$), as well as a significant decrease in rhythm errors ($t = -3.88, p = 0.003$, Cohen's $d = 1.37$). Similarly, in the *haptic* group, t-tests demonstrated a substantial decline in key sequence errors ($t = -4.54, p = 0.0013$, Cohen's $d = 1.61$), as well as rhythm errors ($t = -3.95, p = 0.0028$, Cohen's $d = 0.87$).

A two-sided unpaired t-test was conducted, revealing no statistically significant difference in the improvement of erroneous keypresses between the *haptic* and *visual* learning sessions ($t = -0.223, p = 0.83$). Similarly, there was no significant distinction observed in rhythm errors between the *haptic* and *visual* groups ($t = -0.197, p = 0.85$).

The mean NASA TLX scores for the *visual* and *haptic* groups were $mean_{TLX,visual} = 59.08$ and $mean_{TLX,haptic} = 56.83$, respectively. Subsequent to a two-sided unpaired t-test, no statistically significant difference was found in the mean NASA TLX scores between the *haptic* and *visual* groups ($t = -0.234, p = 0.818$).

6.2.4 Conclusion and Future Work

In this study, we have successfully developed and implemented an innovative Mixed Reality (MR) piano learning application that combines both visual and haptic cues for teaching piano skills. Our application introduces a unique approach to piano instruction by integrating the capabilities of MR technology with haptic feedback, aiming to enhance the learning experience for users.

Our empirical investigation into the effectiveness of the two learning methods, visual and haptic, yielded intriguing results. We found little difference in the learning outcomes between these two methods, resulting in no significant statistical difference. This finding opens up avenues for future research and prompts us to delve deeper into understanding the interplay between visual and haptic cues in the context of piano learning.

However, the current version of the piano application has certain limitations that warrant further consideration. The restriction of playable keys to just five, corresponding to each finger, represents a constraint on the potential range of musical expression. To overcome this limitation, one potential avenue for improvement involves the incorporation of visual indicators within the MR environment. These visual cues could provide users with clear guidance on finger placement across the piano, thereby expanding the playable key range and fostering a more comprehensive piano learning experience.

An alternative strategy for enhancing the application's usability lies in the optimization of haptic feedback mechanisms. While the current implementation utilizes vibrations as cues for key presses, we propose that a more advanced approach could involve integrating actuators to provide haptic feedback directly upon pressing the correct piano key. This modification could potentially offer a more intuitive and precise learning process, eliminating the need for separate cues to indicate which key to press.

Another potential aspects to modify in the pursuit of refining the mixed reality piano learning application, advancements in hand tracking technology hold immense promise. Improvements in hand tracking accuracy and reliability could significantly enhance the application's performance, making the interaction between users and the holographic piano more seamless and responsive.

Looking ahead, our study highlights potential directions for future research. One crucial area of exploration involves the enhancement of user comfort and the refinement of on-skin actuators. Striving for optimal vibration strength and comfort could lead to a more immersive and enjoyable learning experience, driving improvements in user engagement and overall satisfaction.

In conclusion, our work represents a novel step forward in combining mixed reality technology and haptic interfaces for piano education, combining visual and haptic cues to create an immersive and versatile learning environment. While certain limitations and opportunities for improvement exist, our findings contribute valuable insights into the integration of mixed reality and haptic feedback for educational applications. This study lays the groundwork for future investigations aimed at further refining the MR piano learning experience and uncovering the intricate relationship between sensory cues and skill acquisition.

Part V

CONCLUSION

7 Conclusion

This thesis has demonstrated the development and evaluation of haptic actuators and haptic interfaces (based on the discriminative and affective touch). In this chapter, we encapsulate the pivotal discoveries and contributions that have emerged from this thesis. Moreover, we will discuss potential avenues for future investigations in this domain.

7.1 Summary

The human experience is composed of various sensations, with touch acting as the harmonious thread that connects us to the world. This dissertation has investigated how human skin and haptic technology could be combined to redefine human interaction with the environment.

We commenced with an introduction to the underlying motivation driving this research. Concurrently, We provided an in-depth exposition of the pertinent literature, thus establishing the foundational bedrock upon which this study is built. We acknowledge the significant role that our skin plays as a gateway through which we experience the tangible world. In this context, haptic user interfaces emerged as the instrument for orchestrating tactile sensations in the digital realm. We identified two key limitations of the current technologies: (1). their rigidity; and (2) their ability to evoke just one on-skin sensation. This thesis challenged this status quo, proposing a hypothesis by designing haptic interfaces with a keen focus on the dual realms of discriminative and affective touch to reshape wearable interactions. In this thesis, we tackle these limitations and make a contribution to the research field through the creation of innovative haptic interfaces with the component of wearable actuators, which we then assess through structured psychological experiments.

In Chapter 3, we delved into the realm of innovative materials and fabrication techniques, setting the stage for the creation of the *FLECTILE*. This three-dimensional-printable soft on-skin actuator shattered traditional design constraints. The marriage of a soft electromagnetic inductor with stretchable, biocompatible materials enriched a wide range of wearable computing scenarios with the potential to direct interaction. The rapid and simple production method of *FLECTILE* also serves as an advantage, enhancing the potential for personalized customization and promising to make wearables accessible to a wide spectrum of users. A user study (N = 6) revealed that the vibrations produced by the

FLECTILE were distinctly perceptible across various conditions—observing, hovering, and resting.

Building on this foundation, we presented *DragTapVib*, a haptic actuator capable of generating three distinct sensations relevant to both discriminative (vibration) and affective touch (dragging and tapping) in Chapter 4. This novel actuator extends the electromagnetic approach based on the Lorentz force principle. We have comprehensively presented the design, fabrication, and actuation mechanisms of this device, and we offer open-source resources to the broader wearable actuator community. Through systematic inquiries, we initially delineated the attributes of the stimuli and ascertained users' favored actuation locations and actuation parameters via an exploratory experiment (N = 6). Subsequently, we conducted a user study (N = 12) to thoroughly examine the perceptions and discrimination abilities associated with the three distinct stimuli. Leveraging quantitative user studies, we have showcased the efficacy of *DragTapVib* in two practical applications: enabling on-skin notifications with the integration of multiple information streams and enhancing the gaming experience. The versatile nature of *DragTapVib* enables precise and expressive interactions across various body locations, yielding a more intuitive and immersive haptic encounter. Furthermore, a notable observation emerged from the participants' responses, with the majority expressing that skin tapping and dragging sensations were consistently perceived as more pleasing and comfortable. This perception appears to stem from the silent and unobtrusive nature of these tactile cues.

Informed by the insights gained from the comprehensive investigation presented in Chapter 4, we investigated the potential utilization of affective touch as a learning signal within the domain of passive haptic learning (PHL), a methodology facilitating motor skill acquisition without active attention in Chapter 5. Previous studies have predominantly utilized vibration as the sensory signal applied to participants' skin in PHL. However, the human somatosensory system encompasses both discriminative and affective inputs, encompassing a variety of tactile sensations beyond vibration. To this end, we developed three distinct wearable systems corresponding to these sensations. A comprehensive user study was conducted (N = 17) to passively learn three different note sequences using these systems, followed by testing the participants' recall of the learned sequences. Our findings reveal that sensations such as tapping and stroking exhibit comparable effectiveness to the traditional vibration-based approach in facilitating passive haptic learning of piano songs, thus offering viable alternatives. Notably, we found that participants utilizing affective inputs (tapping or stroking) made on average up to 1.06 fewer errors compared to the vibration-based system. As pioneering work investigating various tactile sensations in PHL, our study contributes a design framework that holds promise for further exploration and advancement in this domain. The implications echoed with the promise of affective touch's ability to reshape human understanding and learning.

Drawing upon the insights garnered from earlier chapters, we embark on a deeper exploration that uncovers the symbiotic relationship existing between tactile interfaces and other interactive technologies. We illuminate the synergistic collaboration between these components, consequently presenting opportunities for enriching user experiences in

Chapter 6. This fusion, encompassing tactile, visual, auditory, and mixed reality dimensions, underscores the unexplored potential for reshaping our technological interactions. The merging of these approaches vividly paints a picture where experiences go beyond the limitations of individual senses, creating a fresh and immersive tapestry of engagement.

In summary, the work presented here provides compelling evidence that haptic interfaces founded on discriminative and affective touch possess a diverse array of prospects to expand the perception of reality and facilitate novel sensory experiences for the user. At the heart of this work lies the wearable aspect, which serves as the focal point for advancing technology to seamlessly intertwine with the tactile dimensions through haptic interfaces.

7.2 Future Work

As described in this dissertation, the conceptualization and refinement of tactile interfaces are currently undergoing a transformative phase. The research community has transcended the paradigm of constructing haptic interfaces centered solely on individual sensations. Recognizing the pivotal role of emotional touch in human interaction, technology designers are increasingly integrating this perspective into the core of interactive technology development. Advancements in tactile and touch-sensing technologies play a decisive role in fostering interest and progress within this evolving field [41, 42, 58, 123, 179]. A discernible trend has emerged, wherein affective touch is gaining deeper understanding and exploration. Consequently, a growing number of tactile interfaces are now focused on developing affective touch interfaces, emphasizing emotional relevance and proximity to human touch.

There exists a compelling opportunity for future investigations in two key areas. Firstly, considering the inherent softness and warmth associated with human touch, a critical avenue for exploration involves enhancing the material composition of haptic interfaces to closely emulate human touch. Integration of temperature modules within these interfaces stands as a promising direction to achieve a more authentic tactile experience. Secondly, in the realm of pattern design for haptic interfaces, contemporary approaches face notable limitations, primarily relying on the use of a velvet stick traversing a specific distance on the human skin [89, 179]. Future endeavors can significantly enrich and diversify these patterns, pushing beyond current constraints to unlock novel possibilities in haptic pattern design.

Then, Passive haptic learning stands out as a potent methodology for acquiring and reinforcing motor skills, as evidenced by Caitlyn's exploration of its application in aiding stroke victims in regaining specific motor skills and recovering from traumatic brain injuries to get back to normal lives [142]. This study specifically underscores the efficacy and user-friendliness of affective touch, encompassing tapping and stroking, in the context of learning to play the piano. Notably, the findings suggest that affective touch proves to be as proficient as conventionally employed vibration signals in piano learning. Thus, the potential of affective touch as a viable alternative to vibration signals in medical and rehabilitation contexts necessitates further comprehensive exploration and research. The implications and feasibility of incorporating affective touch in these domains warrant thorough investigation to ascertain its applicability and potential benefits in diverse healthcare scenarios.

Bibliography

[1] https://www.magicleap.com/magic-leap-1. 2020.

[2] Rochelle Ackerley, Helena Backlund Wasling, and Francis McGlone. "The touch landscape". In: *Affective Touch and the Neurophysiology of CT Afferents* (2016), pp. 85–109.

[3] Rochelle Ackerley et al. "Quantifying the sensory and emotional perception of touch: differences between glabrous and hairy skin". In: *Frontiers in behavioral neuroscience* 8 (2014), p. 34.

[4] *ADEPT: Exploring the Design, Pedagogy and Analysis of a Mixed Reality Application for Piano Training*. Zenodo, May 2019. DOI: 10.5281/zenodo.3249333. URL: https://doi.org/10.5281/zenodo.3249333.

[5] Jessalyn Alvina et al. "OmniVib: Towards cross-body spatiotemporal vibrotactile notifications for mobile phones". In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 2015, pp. 2487–2496.

[6] Farshid Amirabdollahian et al. "Prevalence of haptic feedback in robot-mediated surgery: a systematic review of literature". In: *Journal of robotic surgery* 12 (2018), pp. 11–25.

[7] Hideyuki Ando, Eisuke Kusachi, and Junji Watanabe. "Nail-mounted tactile display for boundary/texture augmentation". In: *Proceedings of the international conference on Advances in computer entertainment technology*. 2007, pp. 292–293.

[8] Rebecca Andreasson et al. "Affective touch in human–robot interaction: conveying emotion to the Nao robot". In: *International Journal of Social Robotics* 10 (2018), pp. 473–491.

[9] Takafumi Aoki et al. "Haptic ring: touching virtual creatures in mixed reality environments". In: *SIGGRAPH'09: Posters*. 2009, pp. 1–1.

[10] Sandra Bardot et al. "Eyes-free graph legibility: using skin-dragging to provide a tactile graph visualization on the arm". In: *Proceedings of the 11th Augmented Human International Conference*. 2020, pp. 1–8.

[11] Allan I Basbaum. "Basic mechanisms". In: *Pain Management Secrets E-Book* (2009), p. 19.

[12] Matteo Bianchi et al. "A wearable fabric-based display for haptic multi-cue delivery". In: *2016 IEEE haptics symposium (HAPTICS)*. IEEE. 2016, pp. 277–283.

[13] Malin Björnsdotter et al. "Somatotopic organization of gentle touch processing in the posterior insular cortex". In: *Journal of Neuroscience* 29.29 (2009), pp. 9314–9320.

[14] Sal Bosman et al. “Gentleguide: An exploration of haptic output for indoors pedestrian guidance”. In: *International Conference on Mobile Human-Computer Interaction.* Springer. 2003, pp. 358–362.

[15] Stephen A Brewster and Lorna M Brown. “Tactons: structured tactile messages for non-visual information display”. In: (2004).

[16] Minya Cai et al. “Design and Implementation of AR-Supported System for Piano Learning”. In: *2019 IEEE 8th Global Conference on Consumer Electronics (GCCE).* 2019, pp. 49–50. DOI: 10.1109/GCCE46687.2019.9015530.

[17] Yujie Chen et al. “Shape-memory polymeric artificial muscles: Mechanisms, applications and challenges”. In: *Molecules* 25.18 (2020), p. 4246.

[18] Vasilios G Chouvardas, Amalia N Miliou, and Miltiadis K Hatalis. “Tactile display applications: A state of the art survey”. In: *Proceedings of the 2nd Balkan Conference in Informatics.* 2005, pp. 290–303.

[19] Shao-Yu Chu et al. “Motionring: Creating illusory tactile motion around the head using 360 vibrotactile headbands”. In: *The 34th Annual ACM Symposium on User Interface Software and Technology.* 2021, pp. 724–731.

[20] Ferhat Pala, Pınar Mıhcı Türker, and Özlem Kılınçer. “The effectiveness of the haptic glove for piano education”. In: *Kocaeli Üniversitesi Eğitim Dergisi* 4 (2021), pp. 556–574. DOI: 10.33400/kuje.951015.

[21] Jonathan Cole et al. “Unmyelinated tactile afferents underpin detection of low-force monofilaments”. In: *Muscle & Nerve: Official Journal of the American Association of Electrodiagnostic Medicine* 34.1 (2006), pp. 105–107.

[22] Heather Culbertson, Samuel B Schorr, and Allison M Okamura. “Haptics: The present and future of artificial touch sensation”. In: *Annual Review of Control, Robotics, and Autonomous Systems* 1 (2018), pp. 385–409.

[23] Ravinder S Dahiya et al. “POSFET devices based tactile sensing arrays”. In: *Proceedings of 2010 IEEE International Symposium on Circuits and Systems.* IEEE. 2010, pp. 893–896.

[24] Phyllis Davis. *The Power of Touch: The Basis for Survival, Health, Intimacy, and Emotional Well-Being!* Hay House, Inc, 1999.

[25] Davide Deflorio, Massimiliano Di Luca, and Alan M Wing. “Skin and mechanoreceptor contribution to tactile input for perception: a review of simulation models”. In: *Frontiers in Human Neuroscience* 16 (2022).

[26] Patrizia Di Campli San Vito et al. “Haptic navigation cues on the steering wheel”. In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems.* 2019, pp. 1–11.

[27] Thanh Nho Do et al. “Miniature soft electromagnetic actuators for robotic applications”. In: *Advanced Functional Materials* 28.18 (2018), p. 1800244.

[28] Rumen Donchev, Erik Pescara, and Michael Beigl. “Investigating Retention in Passive Haptic Learning of Piano Songs”. In: *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 5.2 (2021), pp. 1–14.

[29] Rumen Donchev, Erik Pescara, and Michael Beigl. "Investigating Retention in Passive Haptic Learning of Piano Songs". In: *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 5.2 (June 2021). DOI: 10.1145/3463513. URL: https://doi.org/10.1145/3463513.

[30] Jesse Dosher and Blake Hannaford. "Human interaction with small haptic effects". In: *Presence* 14.3 (2005), pp. 329–344.

[31] Zehui Du et al. "Shape-memory actuation in aligned zirconia nanofibers for artificial muscle applications at elevated temperatures". In: *ACS Applied Nano Materials* 3.3 (2020), pp. 2156–2166.

[32] Basil Duvernoy et al. "Electromagnetic actuator for tactile communication". In: *Haptics: Science, Technology, and Applications: 11th International Conference, EuroHaptics 2018, Pisa, Italy, June 13-16, 2018, Proceedings, Part II 11*. Springer. 2018, pp. 14–24.

[33] Ayaka Ebisu, Satoshi Hashizume, and Yoichi Ochiai. "Building a feedback loop between electrical stimulation and percussion learning". In: *ACM SIGGRAPH 2018 Studio*. 2018, pp. 1–2.

[34] Ayaka Ebisu et al. "Stimulated percussions: method to control human for learning music by using electrical muscle stimulation". In: *Proceedings of the 8th Augmented Human International Conference*. 2017, pp. 1–5.

[35] Arie Eisenman et al. "Subconscious passive learning of CPR techniques through television medical drama". In: *Australasian Journal of Paramedicine* 3 (2005), pp. 1–5.

[36] Likun Fang et al. "DragTapVib: An On-Skin Electromagnetic Drag, Tap, and Vibration Actuator for Wearable Computing". In: *Augmented Humans 2022*. 2022, pp. 203–211.

[37] Likun Fang et al. "FLECTILE: 3D-Printable Soft Actuators for Wearable Computing". In: *Proceedings of the 2020 International Symposium on Wearable Computers*. ISWC '20. Virtual Event, Mexico: Association for Computing Machinery, 2020, pp. 32–36. ISBN: 9781450380775. DOI: 10.1145/3410531.3414307. URL: https://doi.org/10.1145/3410531.3414307.

[38] Likun Fang et al. "FLECTILE: 3D-printable soft actuators for wearable computing". In: *Proceedings of the 2020 International Symposium on Wearable Computers*. 2020, pp. 32–36.

[39] Likun Fang et al. "How Could I Learn Rhythm Better? Investigating Three Learning Signals for Passive Haptic Learning in Different Context". In: *Proceedings of the 16th International Conference on PErvasive Technologies Related to Assistive Environments*. 2023, pp. 279–283.

[40] Likun Fang et al. "Investigate the Piano Learning Rate with Haptic Actuators in Mixed Reality". In: *Augmented Humans 2022*. 2022, pp. 287–290.

[41] Likun Fang et al. "Investigating Passive Haptic Learning of Piano Songs Using Three Tactile Sensations of Vibration, Stroking and Tapping". In: *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 7.3 (2023), pp. 1–19.

[42] Nikolas Ferguson et al. "Design of a Wearable Haptic Device to Mediate Affective Touch with a Matrix of Linear Actuators". In: *International Conference on System-Integrated Intelligence*. Springer. 2022, pp. 507–517.

[43] Alberto Gallace, Hong Z Tan, and Charles Spence. "The body surface as a communication system: The state of the art after 50 years". In: *Presence: Teleoperators and Virtual Environments* 16.6 (2007), pp. 655–676.

[44] Esther P Gardner, John H Martin, et al. "Coding of sensory information". In: *Principles of neural science* 4 (2000), pp. 411–429.

[45] "A Fibers (A-Fibers)". In: *Encyclopedia of Pain*. Ed. by Gerald F. Gebhart and Robert F. Schmidt. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013, pp. 2–2. ISBN: 978-3-642-28753-4. DOI: 10.1007/978-3-642-28753-4_200002. URL: https://doi.org/10.1007/978-3-642-28753-4_200002.

[46] Francine Gemperle, Nathan Ota, and Dan Siewiorek. "Design of a wearable tactile display". In: *Proceedings Fifth International Symposium on Wearable Computers*. IEEE. 2001, pp. 5–12.

[47] Francine Gemperle et al. "Design for wearability". In: *digest of papers. Second international symposium on wearable computers (cat. No. 98EX215)*. IEEE. 1998, pp. 116–122.

[48] George A Gescheider, Lawrence C Sager, and Lydia J Ruffolo. "Simultaneous auditory and tactile information processing". In: *Perception & Psychophysics* 18.3 (1975), pp. 209–216.

[49] James J Gibson. "Observations on active touch." In: *Psychological review* 69.6 (1962), p. 477.

[50] Brian T Gleeson, Scott K Horschel, and William R Provancher. "Communication of direction through lateral skin stretch at the fingertip". In: *World Haptics 2009-Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. IEEE. 2009, pp. 172–177.

[51] Brian T Gleeson, Scott K Horschel, and William R Provancher. "Design of a fingertip-mounted tactile display with tangential skin displacement feedback". In: *IEEE Transactions on Haptics* 3.4 (2010), pp. 297–301.

[52] JC Guignard. "Human sensitivity to vibration". In: *Journal of sound and vibration* 15.1 (1971), pp. 11–16.

[53] Eric Eric Louis Gunther. "Skinscape: A tool for composition in the tactile modality". PhD thesis. Massachusetts Institute of Technology, 2001.

[54] Jianglong Guo and Jonathan Rossiter. "Stretchable bifilar coils for soft adhesion and sensing". In: *Materials & Design* 190 (2020), p. 108545.

[55] Rui Guo et al. "Liquid metal spiral coil enabled soft electromagnetic actuator". In: *Science China Technological Sciences* 61.4 (2018), pp. 516–521.

[56] *Gweled*. `https://gweled.org/`. Accessed: 2022.

[57] Nur Al-huda Hamdan et al. "Springlets: Expressive, flexible and silent on-skin tactile interfaces". In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 2019, pp. 1–14.

[58] Violet Yinuo Han et al. "Parametric Haptics: Versatile Geometry-based Tactile Feedback Devices". In: *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*. 2023, pp. 1–13.

[59] Chris Harrison, Desney Tan, and Dan Morris. "Skinput: appropriating the body as an input surface". In: *Proceedings of the SIGCHI conference on human factors in computing systems*. 2010, pp. 453–462.

[60] Sandra G Hart and Lowell E Staveland. "Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research". In: *Advances in psychology*. Vol. 52. Elsevier, 1988, pp. 139–183.

[61] Steven C Hauser et al. "Uncovering human-to-human physical interactions that underlie emotional and affective touch communication". In: *2019 IEEE World Haptics Conference (WHC)*. IEEE. 2019, pp. 407–412.

[62] Alice Haynes et al. "A wearable skin-stretching tactile interface for Human–Robot and Human–Human communication". In: *IEEE Robotics and Automation Letters* 4.2 (2019), pp. 1641–1646.

[63] Vincent Hayward et al. "Haptic interfaces and devices". In: *Sensor review* (2004).

[64] Liang He, Ruolin Wang, and Xuhai Xu. "PneuFetch: Supporting Blind and Visually Impaired People to Fetch Nearby Objects via Light Haptic Cues". In: *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. 2020, pp. 1–9.

[65] Liang He et al. "PneuHaptic: delivering haptic cues with a pneumatic armband". In: *Proceedings of the 2015 ACM International Symposium on Wearable Computers*. 2015, pp. 47–48.

[66] Matthew J Hertenstein and Sandra J Weiss. *The handbook of touch: Neuroscience, behavioral, and health perspectives*. Springer Publishing Company, 2011.

[67] J. Hey et al. "Electromagnetic Actuator Design Analysis Using a Two-Stage Optimization Method With Coarse–Fine Model Output Space Mapping". In: *IEEE Transactions on Industrial Electronics* 61.10 (2014), pp. 5453–5464.

[68] Ira J Hirsh and Carl E Sherrick Jr. "Perceived order in different sense modalities." In: *Journal of experimental psychology* 62.5 (1961), p. 423.

[69] Hunter G Hoffman. "Physically touching virtual objects using tactile augmentation enhances the realism of virtual environments". In: *Proceedings. IEEE 1998 Virtual Reality Annual International Symposium (Cat. No. 98CB36180)*. IEEE. 1998, pp. 59–63.

[70] Eve Hoggan and Stephen Brewster. “New parameters for tacton design”. In: *CHI’07 Extended Abstracts on Human Factors in Computing Systems*. 2007, pp. 2417–2422.

[71] Kevin Huang, Ellen Yi-Luen Do, and Thad Starner. “PianoTouch: A wearable haptic piano instruction system for passive learning of piano skills”. In: *2008 12th IEEE international symposium on wearable computers*. IEEE. 2008, pp. 41–44.

[72] Kevin Huang, Ellen Yi-Luen Do, and Thad Starner. “PianoTouch: A wearable haptic piano instruction system for passive learning of piano skills”. In: *2008 12th IEEE International Symposium on Wearable Computers*. 2008, pp. 41–44. DOI: 10.1109/ISWC.2008.4911582.

[73] Kevin Huang et al. “Mobile Music Touch: Mobile Tactile Stimulation for Passive Learning”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. New York, NY, USA: Association for Computing Machinery, 2010, pp. 791–800. ISBN: 9781605589299. URL: https://doi.org/10.1145/1753326.1753443.

[74] Kevin Huang et al. “Mobile music touch: mobile tactile stimulation for passive learning”. In: *Proceedings of the SIGCHI conference on human factors in computing systems*. 2010, pp. 791–800.

[75] Sungjae Hwang and Jung-hee Ryu. “The Haptic steering Wheel: Vibro-tactile based navigation for the driving environment”. In: *2010 8th IEEE international conference on Pervasive Computing and Communications Workshops (PERCOM workshops)*. IEEE. 2010, pp. 660–665.

[76] Alexandra Ion, Edward Jay Wang, and Patrick Baudisch. “Skin drag displays: Dragging a physical tactor across the user’s skin produces a stronger tactile stimulus than vibrotactile”. In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 2015, pp. 2501–2504.

[77] Ali Israr and Ivan Poupyrev. “Tactile brush: drawing on skin with a tactile grid display”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2011, pp. 2019–2028.

[78] Takahide Ito et al. “Design and Performance Analysis of a Skin-Stretcher Device for Urging Head Rotation”. In: *IEICE Transactions on Information and Systems* 103.11 (2020), pp. 2314–2322.

[79] Nina G Jablonski. *Skin: A natural history*. Univ of California Press, 2008.

[80] Seungwoo Je et al. “tactoRing: a skin-drag discrete display”. In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 2017, pp. 3106–3114.

[81] Hiroyuki Kanke, Tsutomu Terada, and Masahiko Tsukamoto. “A percussion learning system by rhythm internalization using haptic indication”. In: *Proceedings of the 12th International Conference on Advances in Computer Entertainment Technology*. 2015, pp. 1–5.

[82] Pulkit Kapur et al. “Spatially distributed tactile feedback for kinesthetic motion guidance”. In: *2010 IEEE Haptics Symposium*. IEEE. 2010, pp. 519–526.

[83] Seoktae Kim et al. "Inflatable mouse: volume-adjustable mouse with air-pressure-sensitive input and haptic feedback". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2008, pp. 211–224.

[84] H Hawkeye King, Regina Donlin, and Blake Hannaford. "Perceptual thresholds for single vs. multi-finger haptic interaction". In: *2010 IEEE Haptics Symposium*. IEEE. 2010, pp. 95–99.

[85] Louise P Kirsch et al. "Reading the mind in the touch: Neurophysiological specificity in the communication of emotions by touch". In: *Neuropsychologia* 116 (2018), pp. 136–149.

[86] M Knibestöl and Åke B Vallbo. "Single unit analysis of mechanoreceptor activity from the human glabrous skin". In: *Acta Physiologica Scandinavica* 80.2 (1970), pp. 178–195.

[87] Paul AJ Kolarsick, Maria Ann Kolarsick, and Carolyn Goodwin. "Anatomy and physiology of the skin". In: *Journal of the Dermatology Nurses' Association* 3.4 (2011), pp. 203–213.

[88] Robert Kovacs et al. "Haptic pivot: On-demand handhelds in vr". In: *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. 2020, pp. 1046–1059.

[89] Inge U Kress et al. "Direct skin-to-skin vs. indirect touch modulates neural responses to stroking vs. tapping". In: *Neuroreport* 22.13 (2011), p. 646.

[90] Herbert E Krugman and Eugene L Hartley. "Passive learning from television". In: *Public Opinion Quarterly* 34.2 (1970), pp. 184–190.

[91] Andreas Lendlein. "Fabrication of reprogrammable shape-memory polymer actuators for robotics". In: *Science Robotics* 3.18 (2018), eaat9090.

[92] Shuo Li et al. "Bio-inspired design and additive manufacturing of soft materials, machines, robots, and haptic interfaces". In: *Angewandte Chemie International Edition* 58.33 (2019), pp. 11182–11204.

[93] Yi-Chi Liao et al. "Edgevib: Effective alphanumeric character output using a wrist-worn tactile display". In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. 2016, pp. 595–601.

[94] Shu-Yang Lin et al. "Pub-point upon body: exploring eyes-free interaction and methods on an arm". In: *Proceedings of the 24th annual ACM symposium on User interface software and technology*. 2011, pp. 481–488.

[95] U Lindblom. "Properties of touch receptors in distal glabrous skin of the monkey". In: *Journal of Neurophysiology* 28.5 (1965), pp. 966–985.

[96] David Lindlbauer and Andy D Wilson. "Remixed reality: Manipulating space and time in augmented reality". In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 2018, pp. 1–13.

[97] J Lo, Roland S Johansson, et al. "Regional differences and interindividual variability in sensitivity to vibration in the glabrous skin of the human hand". In: *Brain research* 301.1 (1984), pp. 65–72.

[98] Line S Löken et al. "Coding of pleasant touch by unmyelinated afferents in humans". In: *Nature neuroscience* 12.5 (2009), pp. 547–548.

[99] Pedro Lopes et al. "Adding force feedback to mixed reality experiences and games using electrical muscle stimulation". In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 2018, pp. 1–13.

[100] S Louw, AML Kappers, and Jan J Koenderink. "Active haptic detection and discrimination of shape". In: *Perception & psychophysics* 64.7 (2002), pp. 1108–1119.

[101] Taiga Machida, Nem Khan Dim, and Xiangshi Ren. "Suitable body parts for vibration feedback in walking navigation systems". In: *Proceedings of the Third International Symposium of Chinese CHI*. 2015, pp. 32–36.

[102] Madhero88 and M.Komorniczak. *Skinlayers*. URL: `https://en.wikipedia.org/wiki/File:Skin_layers.png` (visited on 2023).

[103] Kathi C Madison. "Barrier function of the skin:"la raison d'etre" of the epidermis". In: *Journal of investigative dermatology* 121.2 (2003), pp. 231–241.

[104] Steve Mann. "Wearable computing: A first step toward personal imaging". In: *Computer* 30.2 (1997), pp. 25–32.

[105] Guoyong Mao et al. "Soft electromagnetic actuators". In: *Science Advances* 6.26 (2020). DOI: `10.1126/sciadv.abc0251`. eprint: `https://advances.sciencemag.org/content/6/26/eabc0251.full.pdf`. URL: `https://advances.sciencemag.org/content/6/26/eabc0251`.

[106] Tanya Thais Markow. *Mobile music touch: using haptic stimulation for passive rehabilitation and learning*. Georgia Institute of Technology, 2012.

[107] Alex Mazursky et al. "MagnetIO: Passive yet interactive soft haptic patches anywhere". In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 2021, pp. 1–15.

[108] Francis McGlone and David Reilly. "The cutaneous sensory system". In: *Neuroscience & Biobehavioral Reviews* 34.2 (2010), pp. 148–159.

[109] Francis McGlone, Johan Wessberg, and Håkan Olausson. "Discriminative and affective touch: sensing and feeling". In: *Neuron* 82.4 (2014), pp. 737–755.

[110] JA McGrath, RAJ Eady, and FM Pope. "Anatomy and organization of human skin". In: *Rook's textbook of dermatology* 1 (2004), pp. 3–2.

[111] Moritz Alexander Messerschmidt et al. "Anisma: A prototyping toolkit to explore haptic skin deformation applications using shape-memory alloys". In: *ACM Transactions on Computer-Human Interaction* 29.3 (2022), pp. 1–34.

[112] Mircosoft. *Mixed Reality Technology for Business*. `https://www.microsoft.com/en-us/hololens`. 2020.

[113] Sosuke Miura and Masanori Sugimoto. "T-RHYTHM: a system for supporting rhythm learning by using tactile devices". In: *IEEE International Workshop on Wireless and Mobile Technologies in Education (WMTE'05)*. IEEE. 2005, 5–pp.

[114] *Mixed Reality Toolkit*. https://learn.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk2/?view=mrtkunity-2022-05. Accessed: 2023.

[115] Mariana von Mohr et al. “The social buffering of pain by affective touch: a laser-evoked potential study in romantic couples”. In: *Social cognitive and affective neuroscience* 13.11 (2018), pp. 1121–1130.

[116] Vernon B Mountcastle. *The sensory hand: neural mechanisms of somatic sensation*. Harvard University Press, 2005.

[117] Sachith Muthukumarana et al. “Touch me gently: recreating the perception of touch using a shape-memory alloy matrix”. In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 2020, pp. 1–12.

[118] Aditya Shekhar Nittala et al. “PhysioSkin: Rapid Fabrication of Skin-Conformal Physiological Interfaces”. In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: Association for Computing Machinery, 2020, pp. 1–10. ISBN: 9781450367080. URL: https://doi.org/10.1145/3313831.3376366.

[119] Michael F Nolan. “Two-point discrimination assessment in the upper limb in young adult men and women”. In: *Physical therapy* 62.7 (1982), pp. 965–969.

[120] Håkan Olausson et al. “Functional role of unmyelinated tactile afferents in human hairy skin: sympathetic response and perceptual localization”. In: *Experimental brain research* 184 (2008), pp. 135–140.

[121] Håkan Olausson et al. “The neurophysiology of unmyelinated tactile afferents”. In: *Neuroscience & Biobehavioral Reviews* 34.2 (2010), pp. 185–191.

[122] Håkan Olausson et al. “Unmyelinated tactile afferents signal touch and project to insular cortex”. In: *Nature neuroscience* 5.9 (2002), pp. 900–904.

[123] Temitayo Olugbade et al. “Touch Technology in Affective Human–, Robot–, and Virtual–Human Interactions: A Survey”. In: *Proceedings of the IEEE* (2023).

[124] Ralph Pawling et al. “C-tactile afferent stimulating touch carries a positive affective value”. In: *PloS one* 12.3 (2017), e0173457.

[125] Fabrizio Pece et al. “MagTics: Flexible and thin form factor magnetic actuators for dynamic and wearable haptic feedback”. In: *Proceedings of the 30th annual ACM symposium on User interface software and technology*. 2017, pp. 143–154.

[126] Roshan Lalitha Peiris et al. “Thermalbracelet: Exploring thermal haptic feedback around the wrist”. In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 2019, pp. 1–11.

[127] Erik Pescara, Michael Beigl, and Matthias Budde. “RüttelFlug: a wrist-worn sensing device for tactile vertical velocity perception in 3d-space”. In: *Proceedings of the 2016 ACM International Symposium on Wearable Computers*. 2016, pp. 172–175.

[128] Erik Pescara et al. “Lifetact: utilizing smartwatches as tactile heartbeat displays in video games”. In: *Proceedings of the 16th International Conference on Mobile and Ubiquitous Multimedia*. 2017, pp. 97–101.

[129] Erik Pescara et al. "Reevaluating passive haptic learning of morse code". In: *Proceedings of the 23rd International Symposium on Wearable Computers.* 2019, pp. 186–194.

[130] Pornthep Preechayasomboon, Ali Israr, and Majed Samad. "Chasm: A Screw Based Expressive Compact Haptic Actuator". In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems.* 2020, pp. 1–13.

[131] William R Provancher and Nicholas D Sylvester. "Fingerpad skin stretch increases the perception of virtual friction". In: *IEEE Transactions on Haptics* 2.4 (2009), pp. 212–223.

[132] Anke Verena Reinschluessel et al. "Vibro-Band: Supporting Needle Placement for Physicians with Vibrations". In: *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems.* 2018, pp. 1–6.

[133] Martin S Remland, Tricia S Jones, and Heidi Brinkman. "Interpersonal distance, body orientation, and touch: Effects of culture, gender, and age". In: *The Journal of social psychology* 135.3 (1995), pp. 281–297.

[134] Tobias Röddiger et al. "PDMSkin: On-Skin Gestures with Printable Ultra-Stretchable Soft Electronic Second Skin". In: (2020).

[135] Uta Sailer and Siri Leknes. "Meaning makes touch affective". In: *Current Opinion in Behavioral Sciences* 44 (2022), p. 101099.

[136] Hiroaki Sakoe and Seibi Chiba. "Dynamic programming algorithm optimization for spoken word recognition". In: *IEEE transactions on acoustics, speech, and signal processing* 26.1 (1978), pp. 43–49.

[137] Caitlyn Seim, Tanya Estes, and Thad Starner. "Towards Passive Haptic Learning of piano songs". In: *2015 IEEE World Haptics Conference (WHC).* 2015, pp. 445–450. DOI: 10.1109/WHC.2015.7177752.

[138] Caitlyn Seim, Tanya Estes, and Thad Starner. "Towards passive haptic learning of piano songs". In: *2015 IEEE World Haptics Conference (WHC).* IEEE. 2015, pp. 445–450.

[139] Caitlyn Seim et al. "Passive haptic learning of Braille typing". In: *Proceedings of the 2014 ACM International Symposium on Wearable Computers.* 2014, pp. 111–118.

[140] Caitlyn Seim et al. "Tactile taps teach rhythmic text entry: passive haptic learning of morse code". In: *Proceedings of the 2016 ACM International Symposium on Wearable Computers.* 2016, pp. 164–171.

[141] Caitlyn E Seim, David Quigley, and Thad E Starner. "Passive haptic learning of typing skills facilitated by wearable computers". In: *CHI'14 Extended Abstracts on Human Factors in Computing Systems.* 2014, pp. 2203–2208.

[142] Caitlyn E Seim, Steven L Wolf, and Thad E Starner. "Wearable vibrotactile stimulation for upper extremity rehabilitation in chronic stroke: clinical feasibility trial using the VTS Glove". In: *Journal of NeuroEngineering and Rehabilitation* 18.1 (2021), pp. 1–11.

[143] Pavel Senin. “Dynamic time warping algorithm review”. In: *Information and Computer Science Department University of Hawaii at Manoa Honolulu, USA* 855.1-23 (2008), p. 40.

[144] Youngbo Aram Shim, Jaeyeon Lee, and Geehyuk Lee. “Exploring multimodal watch-back tactile display using wind and vibration”. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 2018, pp. 1–12.

[145] Alejandro Jarillo Silva et al. “Phantom omni haptic device: Kinematic and manipulability”. In: *2009 Electronics, Robotics and Automotive Mechanics Conference (CERMA)*. IEEE. 2009, pp. 193–198.

[146] MA Srinivassan. “The impact of visual information on the haptic perception of stiffness in virtual environments”. In: *Proc. ASME Dynamic Systems and Control Div.* 58 (1996), pp. 555–559.

[147] International Organization for Standardization. *Guide for the evaluation of human exposure to whole-body vibration*. The Organization, 1978.

[148] Susan Standring and E Gray’s Anatomy. *Book: The Anatomical Basis of Clinical Practice*. 2015.

[149] Timothy Daryl Stanley and David Calvo. “Rhythm learning with electronic simulation”. In: *Proceedings of the 10th ACM conference on SIG-information technology education*. 2009, pp. 24–28.

[150] M. Stojanovska et al. “Mixed Reality Anatomy Using Microsoft HoloLens and Cadaveric Dissection: A Comparative Effectiveness Study”. In: *Medical science educator* 30.1 (2020), pp. 173–178.

[151] Hans-Dieter Stölting. “Electromagnetic actuators”. In: *Actuators: Basics and Applications* (2004), pp. 85–153.

[152] Evan Strasnick, Jessica R Cauchard, and James A Landay. “Brushtouch: Exploring an alternative tactile method for wearable haptics”. In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 2017, pp. 3120–3125.

[153] Hongye Sun, Zongyou Han, and Norbert Willenbacher. “Ultrastretchable Conductive Elastomers with a Low Percolation Threshold for Printed Soft Electronics”. In: *ACS Applied Materials & Interfaces* 11.41 (2019), pp. 38092–38102.

[154] Y. Sun, Y. S. Song, and J. Paik. “Characterization of silicone rubber based soft pneumatic actuators”. In: *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2013, pp. 4446–4453.

[155] Juulia T Suvilehto et al. “Topography of social touching depends on emotional bonds between humans”. In: *Proceedings of the National Academy of Sciences* 112.45 (2015), pp. 13811–13816.

[156] Kosuke Takano and Shiori Sasaki. “An interactive music learning system in ensemble performance class”. In: *2011 International Conference on Broadband and Wireless Computing, Communication and Applications*. IEEE. 2011, pp. 65–74.

[157] Shan-Yuan Teng et al. "Pupop: Pop-up prop on palm for virtual reality". In: *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*. 2018, pp. 5–17.

[158] Shan-Yuan Teng et al. "Touch&Fold: A Foldable Haptic Actuator for Rendering Touch in Mixed Reality". In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 2021, pp. 1–14.

[159] Carlos Torres and Pablo Figueroa. "Learning How to Play a Guitar with the HoloLens: A Case Study". In: *2018 XLIV Latin American Computer Conference (CLEI)*. 2018, pp. 606–611.

[160] Wen-Jie Tseng et al. "A Skin-Stroke Display on the Eye-Ring Through Head-Mounted Displays". In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 2020, pp. 1–13.

[161] ÅB Vallbo, Hakan Olausson, and Johan Wessberg. "Unmyelinated afferents constitute a second system coding tactile stimuli of the human hairy skin". In: *Journal of neurophysiology* 81.6 (1999), pp. 2753–2763.

[162] Velko Vechev et al. "Tactiles: Dual-mode low-power electromagnetic actuators for rendering continuous contact and spatial haptic patterns in VR". In: *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE. 2019, pp. 312–320.

[163] Ronald T. Verrillo. "Vibration Sense". In: *Encyclopedia of Neuroscience*. Ed. by Marc D. Binder, Nobutaka Hirokawa, and Uwe Windhorst. Berlin, Heidelberg: Springer Berlin Heidelberg, 2009, pp. 4253–4257. ISBN: 978-3-540-29678-2. DOI: 10.1007/978-3-540-29678-2_6318. URL: https://doi.org/10.1007/978-3-540-29678-2_6318.

[164] Mariana Von Mohr, Louise P Kirsch, and Aikaterini Fotopoulou. "The soothing function of touch: affective touch reduces feelings of social exclusion". In: *Scientific reports* 7.1 (2017), p. 13516.

[165] Chi Wang et al. "Masque: Exploring lateral skin stretch feedback on the face with head-mounted displays". In: *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. 2019, pp. 439–451.

[166] Dangxiao Wang, Kouhei Ohnishi, and Weiliang Xu. "Multimodal haptic display for virtual reality: A survey". In: *IEEE Transactions on Industrial Electronics* 67.1 (2019), pp. 610–623.

[167] Sidney Weinstein. "Intensive and extensive aspects of tactile sensitivity as a function of body part, sex and laterality". In: *The skin senses* (1968).

[168] Johan Wessberg, Ulf Norrsell, et al. "A system of unmyelinated afferents for innocuous mechanoreception in the human skin". In: *Brain research* 628.1-2 (1993), pp. 301–304.

[169] Nicholas Wettels et al. "Biomimetic tactile sensor array". In: *Advanced Robotics* 22.8 (2008), pp. 829–849.

[170] Anusha Withana, Daniel Groeger, and Jürgen Steimle. "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*. 2018, pp. 365–378.

[171] Tae-Heon Yang et al. "Development of a miniature pin-array tactile module using elastic and electromagnetic force for mobile devices". In: *World Haptics 2009-Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. IEEE. 2009, pp. 13–17.

[172] Lining Yao et al. "PneUI: pneumatically actuated soft composite materials for shape changing interfaces". In: *Proceedings of the 26th annual ACM symposium on User interface software and Technology*. 2013, pp. 13–22.

[173] Valeda Yong et al. "Cadaver vs. Microsoft HoloLens: A Comparison of Educational Outcomes of a Breast Anatomy Module". In: *The FASEB Journal* 32 (2018).

[174] Xinge Yu et al. "Skin-integrated wireless haptic interfaces for virtual and augmented reality". In: *Nature* 575.7783 (2019), pp. 473–479.

[175] Hanafiah Yussof, Jumpei Takata, and Masahiro Ohka. "Measurement principles of optical three-axis tactile sensor and its application to robotic fingers system". In: *Sensors, Focus on Tactile, Force and Stress Sensors*. I-Tech Publishers, 2008, pp. 123–142.

[176] Clint Zeagler. "Where to wear it: functional, technical, and social considerations in on-body location for wearable technology 20 years of designing for wearability". In: *Proceedings of the 2017 ACM International Symposium on Wearable Computers*. 2017, pp. 150–157.

[177] Hong Zeng, Xingxi He, and Honghu Pan. "FunPianoAR: A Novel AR Application for Piano Learning Considering Paired Play Based on Multi-Marker Tracking". In: *Journal of Physics: Conference Series* 1229 (May 2019), p. 012072. DOI: 10.1088/1742-6596/1229/1/012072.

[178] Bowen Zhang and Misha Sra. "Pneumod: A modular haptic device with localized pressure and thermal feedback". In: *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology*. 2021, pp. 1–7.

[179] Yiran Zhao et al. "Affective Touch as Immediate and Passive Wearable Intervention". In: *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 6.4 (2023), pp. 1–23.

[180] Mengjia Zhu et al. "Pneusleeve: In-fabric multimodal actuation and sensing in a soft, compact, and expressive haptic sleeve". In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 2020, pp. 1–12.

[181] Mengjia Zhu et al. "Soft, wearable robotics and haptics: Technologies, trends, and emerging applications". In: *Proceedings of the IEEE* 110.2 (2022), pp. 246–272.

[182] Cliff Zukin and Robin Snyder. "Passive learning: When the media environment is the message". In: *Public Opinion Quarterly* 48.3 (1984), pp. 629–638.