Thesis for the Degree of Doctor of Philosophy

Modular and Adaptable Tactile Actuating Units for Concurrent Multimodal Feedback

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August 2024

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by

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Submitted to the Department of Computer Science and Engineering and the Faculty of the Graduate School of Kyung Hee University in partial fulfilment of the requirements for the degree of Doctor of Philosophy

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Dedicated To

My mother, my beloved wife, and my siblings, who have filled my journey with love, support, and encouragement that kept me motivated. Also, a special dedication to my nephew, Muhammad Jawad, our little star, whose joyous spirit and strength inspire us every day.

Abstract

Haptic feedback significantly enhances user immersion within Virtual Reality (VR) environments by realistically simulating tactile interactions. As technological advancements integrate more sophisticated systems into daily life, the necessity for complex haptic feedback in VR becomes evident. Current technologies often combine various tactile devices to form a solution to simulate complex haptic sensations. However, this integration frequently leads to compromises in device form factor and feedback quality, ultimately diminishing the realism of user interactions. While some studies have attempted to overcome these challenges by developing multimodal haptic feedback actuators, these solutions often offer a limited range of tactile sensations, failing to fully capture the detailed dynamics of natural touch.

This thesis addresses these limitations by introducing the development of modular tactile actuating units and a novel multimodal actuating device, designed to deliver a comprehensive range of tactile sensations simultaneously. This research introduces a thorough approach to haptic feedback, aiming to transform virtual interactions into deeply immersive and lifelike experiences. To achieve this, the thesis outlines the creation of two key developments: 1) Modular Tactile Actuating Units, which are versatile and easily reconfigurable to suit various body sites and VR scenarios; 2) The Multimodal Actuating Device, capable of providing complex concurrent tactile feedback through a single end-effector.

The modular tactile acting units are designed to be adaptable, allowing for rapid customization and reconfiguration, enabling their application in diverse VR scenarios. This flexibility is achieved through innovative mounting solutions that not only secure the actuators to various body sites but also ensure comfort and stability during use. The multimodal actuating Device stands out by its ability to simulate multiple tactile sensations—such as pressure, shear, and vi-

brations—simultaneously through a single contact point, thereby closely mimicking real-world interactions.

Moreover, extensive user studies have been conducted to validate the effectiveness of these systems. These studies confirm that the developed tactile modules significantly enhance the perception of virtual environments, making them feel more realistic and immersive. Participants reported enhanced sensations of presence and engagement, highlighting the potential of these technologies to enhance VR experiences.

These contributions significantly advance the field of haptic technology, offering scalable and flexible solutions that can be integrated into a wide range of VR applications. By simplifying the design and deployment of tactile modules and enhancing the richness of the haptic feedback, this thesis paves the way for broader adoption and application of immersive haptic technologies in training, education, entertainment, and beyond, ultimately bringing virtual interactions closer to the complexities of real human experiences.

Acknowledgement

I would like to thank my supervisor Dr. Seokhee Jeon for guiding me throughout my tenure as a PhD student. His invaluable advice, suggestions, and guidance has helped me in improving my knowledge and skill set. He has put in a lot of effort in shaping me into a better researcher. I am truly grateful for all his support.

Ahsan Raza

August, 2024

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Chapter 1

Introduction

1.1 Motivation

Haptic feedback is a pivotal component in enhancing interactive experiences, particularly within Virtual Reality (VR) environments, where it significantly deepens immersion by realistically simulating tactile interactions [1]. As we witness an era of rapid technological advancement, the integration of sophisticated systems into everyday life is reshaping our modes of communication and interaction. The transition from simple telephonic communications to engaging with loved ones through complex, immersive VR scenarios exemplifies the profound impact of these technologies. They render experiences not only more engaging but also astonishingly lifelike, thereby expanding the horizons of digital interaction.

VR enables users to visually explore and interact with a multitude of environments. When this visual capacity is augmented with haptic feedback, the virtual experiences are enhanced, allowing for tactile interactions within virtual settings that contribute significantly to the realism and sensory depth of the encounter [2]. This technological synergy enhances the authenticity of virtual environments, making them more believable and physically palpable to the user.

In the domain of haptic technology, interactions are typically categorized into two primary types: tactile feedback and kinesthetic feedback [3]. Kinesthetic feedback is aimed at the user's muscles, joints, and tendons, utilizing devices that deliver force feedback to simulate the sensation of touching and manipulating real objects [4]. Tactile feedback, in contrast, leverages the skin's sensitivity to detect a spectrum of sensations such as vibrations, textures, and pressure [5]. These sensations are crucial in creating a comprehensive and engaging interactive experience that mimics real-world interactions.

Although both types of feedback are essential to the haptic landscape, this thesis primarily concentrates on the exploration and sophisticated understanding of tactile feedback across various modalities. The study aims to delve into its effectiveness in enhancing immersion within VR applications that span training, educational tools, and entertainment platforms. The ultimate goal is to boost user engagement and optimize learning outcomes by enriching the sensory experience and making virtual interactions as close to reality as possible.

This focus on tactile feedback is driven by the potential it holds to revolutionize user experiences in VR by providing nuanced and diverse haptic signals that can mimic real-world sensations accurately. The ability to deliver such detailed tactile information promises not only to enhance the realism of virtual environments but also to extend the utility and applicability of VR technologies across a broader range of fields, from education and training to entertainment and beyond.

1.2 Problem statement

Current haptic solutions are generally designed for specific body sites and lack the capability to provide multi-mode actuation within a single setup. This limitation necessitates the design of different types of actuating modules for separate body areas, complicating the task for designers aiming to create tactile sensations for diverse application scenarios. Therefore, finding a balance between compactness, multi-mode feedback provision, and usability poses a significant challenge in the realm of wearable haptic technology. To address these challenges, there is a substantial need for advancements in modular haptic technology to enhance the usability and adaptability of actuating modules across various application scenarios. This thesis focuses on developing multi-mode tactile actuating modules and guidelines for the mounting mechanisms of different tactile actuating modules, investigating their impact on users' perception, aiming to significantly enhance user experience and broaden the applications of haptic devices.

1.3 Research Goals

The primary objective of this thesis is to push the boundaries of haptic technology by developing innovative tactile feedback systems that significantly enhance user interaction across digital platforms. Recognizing the limitations of current technologies, this research is driven by the need to create more responsive, realistic, and versatile haptic feedback systems that can be seamlessly integrated into various digital interfaces. The specific goals of this research are framed to address both technical challenges and user experience enhancements in haptic technology

The development of modular tactile actuating units is the key contribution of this thesis. The aim is to engineer versatile and customizable tactile feedback systems that are easily adaptable to various body sites and interaction scenarios. This involves creating modules that can be quickly reconfigured to meet changing requirements, making them suitable for a wide range of applications from virtual reality to tactile communication devices. The ability to customize these units allows for personalization of the tactile experience, catering to the unique preferences or needs of users, thereby broadening the applications of tactile feedback technology.

Building on the modular units, the second goal is to design a multimodal actuating device that integrates multiple forms of tactile feedback into a single, compact unit. This device will be capable of delivering a synchronized output of various tactile stimuli such as pressure, shear, and vibration. The challenge lies in maintaining the device's compactness and ergonomics without sacrificing the quality of feedback. This development is expected to pave the way for more sophisticated haptic interactions, enabling more complex simulations of real-world tactile sensations.

With the hardware in place, the third goal focuses on leveraging the developed technologies to enhance the realism and immersion of digital interactions. Through comprehensive user studies, the effectiveness of the new haptic feedback systems will be validated. These studies are designed to assess how well the tactile sensations integrate with digital environments and whether they improve the overall user experience. Insights gained from user feedback will be instrumental in refining the technology to ensure it meets the high standards required for commercial and educational applications.

The final goal examines the broader implications and scalability of the developed haptic feedback systems. This includes exploring potential applications in various area such as safety training, gaming, and entertainment. The adaptability and scalability of the technology will be critical factors in its successful integration into existing and future digital platforms. Studies will be conducted to evaluate the practicality of deploying these systems in real-world settings and to identify any necessary modifications to enhance their utility and user acceptance.

By achieving these goals, this thesis will contribute to the transformation of haptic technology, setting new standards for tactile interaction in digital environments. The anticipated advancements are expected to have a profound impact on a variety of fields, making digital experiences more engaging, realistic, and accessible.

1.4 Contributions

To highlight the significance and advancement of our work, we outline the principal contributions as follows:

Modular Tactile actuating Units

- Variety of tactile actuating units:
  - Introduced a series of modular tactile actuating units including vibration, thermal and multimodal feedback modules.
  - The modules are lightweight and provide quality feedback making a perfect scenario for wearable haptic applications where complex haptic sensations are needed.
- Ergonomic and Adaptable Design:
  - Created user-friendly mounting mechanisms using velcro and body tape, allowing for easy attachment of modules to various body sites.
  - Ensured that the mounting solutions are robust and do not compromise the quality of tactile feedback, promoting comfort and usability.
- Performance Evaluation:
  - Conducted comprehensive performance evaluations through user studies, validating the effectiveness and user satisfaction of the developed modules.
  - Demonstrated that the modular units can deliver high-quality, diverse tactile feedback in various real-world scenarios, enhancing user interaction in virtual environments.

Concurrent tactile Feedback Actuator

- Innovative and Compact Design:
  - Introduced a wearable pneumatic actuator with a 3D-printed model featuring five air chambers, enabling diverse tactile signals through a single end-effector.
  - Developed a compact and lightweight design that ensures ease of wear and minimal interference with user activities.
- Variety of Tactile actuation
  - The device can provide concurrent multimodal tactile sensations, enabling complex haptic feedback.
  - Integrated advanced control mechanisms to manage simultaneous tactile outputs, enhancing the realism of the haptic experience.
- High Performance and Efficiency:
  - Achieved significant performance with high static pressure and vibration acceleration, demonstrating the device's capabilities.
  - Conducted rigorous testing to ensure the actuator's reliability and efficiency in various operating conditions.
- Adaptable Design
  - Designed for adaptability, the device can be easily attached to various body parts such as the arm, wrist, and leg, promoting ease of use in different contexts.
  - Ensured that the design supports easy integration with other haptic systems, enhancing its applicability in a wide range of scenarios.

By addressing the limitations of single-form actuation and existing multi-modal devices, this research seeks to contribute to advancing haptic technology, opening up possibilities for more immersive and realistic interactions.

1.5 Thesis Organization

The rest of the thesis is organized as follows. Chapter 2 offers an extensive review of the literature on haptic technology, focusing on the evolution and integration of actuation mechanisms in haptic devices. It systematically categorizes existing actuation technologies and examines their applications and limitations. This background serves as a crucial baseline for understanding the current state of haptic feedback systems and underscores the need for modular approaches capable of supporting a broader spectrum of tactile sensations.

Chapter 3 details the development of modularized tactile actuating units, introducing a series of newly designed modules that include vibration, thermal, and pressure actuation. Each module's design considerations, such as material selection, ergonomics, and integration feasibility, are thoroughly discussed. The chapter also delves into the innovative control strategies developed to manage these modules effectively and the unique mounting solutions designed to enhance user comfort and module adaptability across different body areas.

In Chapter 4, the focus shifts to the integration and functionality of a concurrent multimodal feedback actuator capable of delivering multiple tactile stimuli simultaneously to enhance user interaction with virtual environments. It presents the comprehensive design process, from conceptualization to the technical implementation, including detailed circuit diagrams and software algorithms used for control. Performance evaluations through structured user studies are presented, providing empirical data on the actuator's effectiveness and user reception.

The concluding chapter 5 synthesizes the research findings, reflecting on the impact and the innovative aspects of the developed tactile actuating units. It evaluates the success of the research objectives and discusses the implications of these advancements for the future of haptic technology. The chapter also proposes future research avenues opened by this work, suggesting potential improvements and new applications for the modular haptic systems in more diverse and complex environments.

Chapter 2

Background Study

In this chapter, we delve into the concept of modular haptics and review the literature to identify and categorize key types of actuation modules. Our goal is to understand their organizational structure within a systematized schema, which will aid in furthering our knowledge of how these modules can be integrated and utilized in various haptic interfaces.

2.1 Tactile Actuations: Concepts and Classification

Tactile interactions form the foundation of how humans perceive and engage with their environment, translating physical contact into recognizable haptic sensations such as vibration, temperature changes, pressure, or shear forces. These interactions are crucial for a comprehensive sensory experience, especially in virtual environments where the goal is to replicate real-world sensations as faithfully as possible. The field of haptic technology has seen significant advancements with the development of various innovative solutions designed to generate these tactile signals, effectively narrowing the sensory gap between virtual environments and real-life experiences. These technologies emulate authentic tactile interactions, allowing users to feel textures, temperatures, and other physical properties as if they were physically touching objects in the digital world.

The concept of modularity in haptic interfaces involves the use of customizable haptic modules that can be tailored to provide specific types of tactile feedback for different applications. This modularity greatly enhances the adaptability of haptic systems, simplifying the integration of diverse modules to create a rich combination of tactile sensations suited for various user needs. Modular haptic systems are designed to be versatile, enabling developers and researchers to assemble and reconfigure components as needed, which fosters innovation and experimentation within the field. As haptic modules are capable of generating different tactile actuation, we classified these modules according to their actuation type, which includes single actuation, multimode actuation, and concurrent actuation modules, each offering distinct tactile outputs and experiences.

Single Actuation Modules: These modules specialize in delivering one specific type of tactile feedback—be it vibration, pressure, or temperature. They are engineered to provide precise and reliable responses that are simple yet highly effective. For instance, temperature modules excel in creating sensations of heat or cold at the point of contact, simulating the experience of touching hot or icy surfaces within a virtual environment. Such precision is indispensable for applications that demand high fidelity in sensory simulations, enhancing the realism of virtual experiences.

Multimode Actuation Modules: These modules are versatile, capable of producing different types of tactile feedback from a single unit. However, they activate only one mode at a time while temporarily deactivating the others. This functionality is particularly valuable in scenarios where the application requires flexibility but not concurrent multimodal feedback. For example, a multimode module may provide tactile feedback that alternates between mimicking an impact sensation and a vibration feedback based on the user's interactions within a virtual scene. This capability of switching between different feedback types enhances the module's usability, making it an effective solution for varied applications that require diverse, sequential feedback.

Concurrent Actuation Modules: These modules are distinguished by their ability to deliver multiple types of tactile feedback simultaneously. This feature is crucial in complex interaction scenarios where creating a composite sensory experience enhances both realism and user engagement. For instance, an actuator mounted on the wrist in a VR simulation could simulate the varying textures and weights of a tool through pressure feedback while also providing vibration to mimic the operation of the tool. Such concurrent feedback creates a deeply immersive and realistic user experience, making it seem as if the user is genuinely interacting with physical objects.

2.2 Literature Review

2.2.1 Single Actuation Modules

These are the most commonly known haptic modules that mainly include interface vibration, pressure, thermal and shear force sensations. In this segment, we will review each actuation module based on the literature.

Vibration Feedback Compactness and lightness are essential for a wearable haptic setup, as the intention is to affix it to a body segment. Vibrotactile feedback actuators typically possess a diminutive size and weight, making them ideal for integration into a portable/wearable environment. These actuators are typically based on electromagnetic principles. Within this category, two extensively utilized types are eccentric rotary mass (ERM) and linear resonant actuators (LRAs) [6–9].

ERM actuators offer effective vibrotactile feedback. However, their actuation principle, which relies on DC motors, results in a lack of separate control over frequency and amplitude [10, 11]. In these actuators, the strength of vibration amplitude is directly tied to the input voltage. On the contrary, LRAs provide the advantage of independent control over amplitude and frequency. Nonetheless, these actuators come with a trade-off, which includes a limited frequency bandwidth and residual vibrations after actuation [12].

Another category, distinct from electromagnetic mechanisms, relies on the piezoelectric phenomenon to generate vibrotactile actuators. Vibrations are induced through the piezo effect when a high input voltage is applied to ceramic or polymer materials [13, 14]. The upside of this approach is the ability to target a broader frequency bandwidth. Nonetheless, the downside is the necessity for a substantial input voltage to achieve the desired actuation, coupled with a notably low vibration amplitude [15].

While vibrotactile actuators have been widely used due to their simplicity and compactness, they are often limited to providing only a small number of effects since the form of vibration is relatively rarely observed in real physics.

Pressure Feedback When discussing wearable haptic interfaces, numerous solutions are available that propose methods for delivering pressure feedback based on specific body sites, such as the hand/finger, wrist, arm and head. For instance, Biernacki et al. proposed a pressure feedback device that enables artists to understand the currently active musical effect and its strength [16]. Some wearable devices are built by using a pair of servo motors and belts to generate pressure feedback on the user's forearms [17, 18]. Facepush and PneumoVolley are the solutions designed to be worn on the face to provide pressure feedback while interacting with objects in a VR environment [19, 20]. A common feature of these actuators is a firm reliance on specific body sites which limits their applicability.

Thermal Feedback The conventional method of replicating temperature sensations in virtual environments involves the use of thermal conduction to simulate hot and cold experiences. A popular technique among researchers is employing Peltier devices, which adjust temperatures by either heating up or cooling down, depending on the electrical current's direction [21]. These devices are often integrated into head-mounted displays (HMDs) to provide dynamic thermal feedback. For example, Chen et al. enhanced the realism of virtual environments by integrating Peltier modules with an Oculus Rift HMD, facilitating interactions with virtual weather conditions and kitchen objects [22–24]. In a similar vein, Peiris et al. developed ThermoVR, an HMD that offers thermal feedback to aid in navigation and localization within VR applications [25, 26]. Additional advancements include Gallo et al.'s thermal displays, which allow for temperature adjustments [27], and Garbardi et al.'s development of a haptic thimble that renders transient heat in virtual settings [28]. Other innovative wearable technologies, such as Zhu et al.'s smart ring and Peiris et al.'s ThermalBracelet, provide spatial-temporal thermal feedback [29, 30]. Moreover, researchers have begun exploring water as a medium for thermal feedback, exemplified by Hayakawa et al.'s high-speed temperature display [31] and Günther et al.'s Therminator, which utilizes varying temperatures of flowing liquid to create on-body thermal sensations [32].

Shear force Evan et al. present Tasbi, a bracelet designed for easy wear at the wrist, effectively enabling the presentation of normal squeeze force around the wrist [33, 34]. Kanjanapas et al. presented a pneumatically controlled 2-Dof haptic device capable of generating a shear force up to 1N [35]. The study shows the performance of shear force display and directional cues on the user's forearm. Hamdan et al. introduced springlets an innovative shear force actuator that uses shape memory alloy springs [36].

2.2.2 Multimode Actuation modules

There have been a considerable number of efforts to provide multiple forms of actuation through a single device. These multi-mode devices encompass various actuation types such as vibration, force, pressure, and shear force, each of which contributes to a comprehensive haptic experience. Talhan et al. introduced a soft haptic tactile ring [15] and tactile thimble [37]. Both solutions leverage pneumatic systems to deliver distinct forms of feedback to human fingers. Delazio et al. [38] and Young et al. [39] achieved a combination of pressure and vibration feedback using arrays of pneumatically actuated air structures. Another study presented by Zhakypov et al. proposed a 4-DOF haptic device for fingertip [40]. The device uses pneumatic actuation to generate pressure, linear and rotational shear, and vibration feedback on the user's fingertip. Additionally, another device named HaptGlove allows users to interact with virtual objects while perceiving multiple forms of feedback [41]. These multi-mode feedback devices mark a significant step towards enriching haptic experiences by offering a wider spectrum of tactile cues. However, many multimodal actuators are designed for specific body parts, limiting their use in different scenarios. The pneumatic actuator proposed in this study overcomes this by being adaptable to different body sites offering greater usability and application potential. This adaptability is crucial for the wider implementation of haptic technology in diverse fields.

2.2.3 Concurrent Actuation modules

Providing concurrent actuation using multiple actuation modules is easy, however, integration of these modules is not straightforward. Therefore, researchers have tried to create a single actuator capable of delivering concurrent tactile actuation. Kyle et al., through a combination of a pneumatic actuator and a DC motor, proposed a 3-DOF wearable haptic device for the human forearm [42]. This device is capable of providing normal force, shear, and vibration sensations to the forearm. Another pneumatically controlled fingertip actuator is introduced by Hashem et al., which uses a dual air chamber to deliver simultaneous actuation. The actuator can provide both vibration and pressure feedback at the same time. Oleg et al., introduce a solution to provide simultaneous actuation with multiple tactile actuators at different body sites [43]. Mingyu et al. designed a haptic interface capable of providing pressure, vibration, and thermal feedback during robotic interaction scenarios [44].

2.3 Summary

This section consolidates the insights gained from the exploration of various tactile actuation modules and identifies key requirements for creating an effective environment that supports multiple tactile interactions through modular actuation. After a thorough review of numerous wearable haptic systems and considering the need for modular haptic interfaces, several critical requirements have emerged that are essential for the practical application of these systems [15, 45, 46].

Easy to Wear: The haptic interface must be designed with user comfort and practicality in mind, ensuring that it can be worn easily without assistance. This involves the use of materials and designs that conform well to the body and do not restrict movement, making the system suitable for prolonged use in various activities, whether they are everyday tasks or specialized interactions within virtual environments.

Light Weight: It is crucial that the haptic devices are lightweight to prevent user fatigue and discomfort during use. The weight of the device should be minimized to enhance user mobility and ensure that it can be worn comfortably for extended periods. This is particularly important in applications such as virtual reality gaming, training simulations, or any context where the user's experience and engagement are critical.

Quality Feedback: The tactile feedback provided by the modules must be of high quality to effectively mimic real-world sensations and enhance the realism of virtual environments. This entails precise control over the intensity, duration, and type of feedback, ensuring that it is consistent and reliable, thereby enriching the user's sensory experience and immersion.

Modularity: The system should exhibit a high degree of modularity, allowing for easy customization and adaptation to meet diverse user needs and applications. This flexibility enables the quick reconfiguration of tactile modules to suit different scenarios, facilitating rapid prototyping and iterative testing of haptic effects within various settings.

Reconfigurability: Similar to the versatility of LEGO pieces, the haptic system should be highly reconfigurable, allowing users to rearrange components and systems to explore different configurations. This adaptability is vital for research and development in haptics, where varying sensations and interactions might be tested frequently.

Multiple Kinds of Actuators: To accommodate the breadth of tactile sensations required in multifaceted haptic applications, the system must support the integration of multiple kinds of actuators. This includes actuators capable of delivering vibrations, pressure, temperature changes, and more, each potentially suited to different tactile experiences.

Multiple Techniques of Actuation: Finally, the system should support multiple actuation techniques, including electromagnetic, pneumatic, piezoelectric, and thermal methods, among others. This diversity allows designers and researchers to select the most appropriate actuation method based on specific performance characteristics and application needs, thereby enhancing the system's overall versatility and capability.

The synthesis of our research reveals several critical requirements for developing an effective modular haptic interface that supports diverse tactile interactions. Our solution incorporates a versatile range of tactile actuating units that not only deliver various types of feedback but also maintain a compact and lightweight form factor, enhancing usability and comfort. Despite the variety of existing devices, there remains a notable gap in the availability of actuators capable of delivering concurrent tactile feedback through a single end-effector without compromising the size, quality of feedback, or the ability to integrate seamlessly into user-centric applications.

To address this gap, we introduce a novel concurrent tactile feedback actuator. This advanced unit is capable of providing simultaneous vibration, pressure, impact, and lateral force feedback. By combining these functionalities into a single device, we aim to significantly enhance the realism and immersion of user interactions in virtual environments, setting a new standard for modularity and integration in haptic technology. This approach not only meets but anticipates the evolving needs of haptic interface design, offering a scalable solution that can adapt to a wide range of applications and user requirements.

Chapter 3

Modularized Tactile Actuating Units

The development of haptic technology has made significant strides, particularly in the domain of providing more immersive and realistic user experiences. This chapter explores the innovative approach of creating modular tactile actuating units that are capable of delivering a range of haptic feedback types. The primary aim is to design versatile and lightweight modules that can be easily integrated into various wearable systems, thereby enhancing their functionality and user adaptability.

Modularity in haptic devices allows for greater flexibility and customization, which is essential for meeting the diverse needs of users in different applications. By focusing on modular design, this research addresses the limitations of traditional haptic devices that often offer limited types of feedback and are not easily reconfigurable. The chapter explores the design, implementation, and evaluation of these modular units, emphasizing their potential to transform user interactions in both virtual and physical environments.

3.1 Overview

This chapter focuses on the development and evaluation of modular tactile actuating units designed to provide a range of haptic feedback, enhancing user experiences in various applications. The chapter is structured to detail the different types of actuating units, their design, and the methods used to evaluate their performance.

The chapter begins by introducing the concept of modular tactile actuating units and the motivation behind their development. It highlights the importance of providing diverse tactile sensations to improve the realism and immersion of virtual interactions. The types of actuating units developed, including vibration, thermal, and pressure modules, are described in detail.

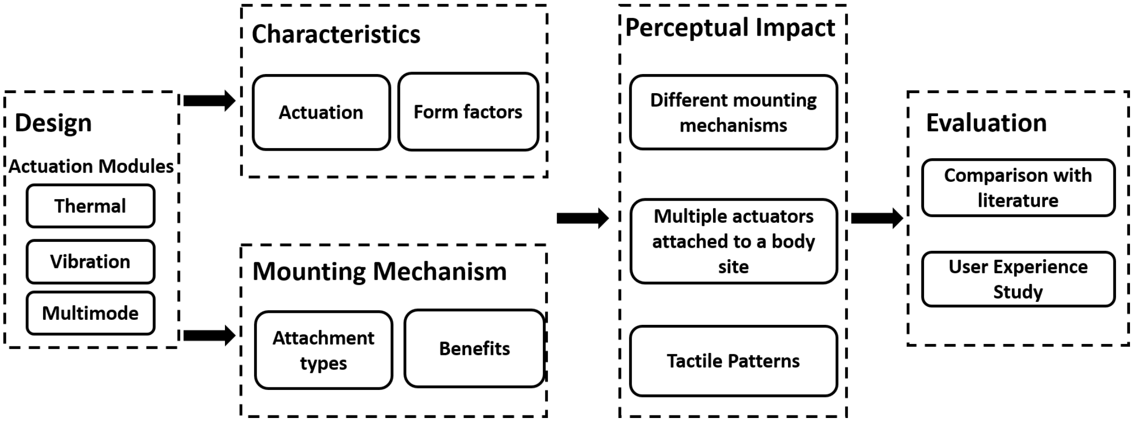

Figure 3.1: Overview of the concepts and developments discussed in this chapter

The design and integration of these modules are discussed, with an emphasis on the materials used, ergonomic considerations, and the innovative mounting mechanisms developed. The control strategies for managing the actuating units effectively are also elaborated, ensuring precise and reliable haptic feedback.

Following the design and development sections, the chapter presents the methods used to evaluate the performance of the tactile actuating units. This includes a series of user studies and experiments designed to assess the effectiveness of the modules in delivering high-quality haptic feedback. The results of these studies are analyzed to provide insights into the strengths and limitations of the developed units.

Figure 3.1 provides a visual overview of the modular tactile actuating units. This figure illustrates the key components and the overall design framework, aiding in the understanding of the subsequent detailed descriptions.

Finally, the chapter concludes with a discussion of the findings, highlighting the contributions of this research to the field of haptic technology and suggesting directions for future work. The overall goal of this chapter is to demonstrate the potential of modular tactile actuating units to enhance user interactions in various applications by providing versatile and high-quality haptic feedback.

3.2 Actuation Modules

In our research, we focused on leveraging common tactile interactions and the corresponding signal generation to create a comprehensive suite of actuation modules, each designed to enhance haptic feedback experiences. To this end, we focused on three distinct types of actuation modules. The first module is specifically designed to provide vibration feedback, essential for simulating textures and conveying alerts. The second module is engineered to offer thermal feedback, which is crucial for replicating temperature variations that can enhance the user's sensory experience in virtual environments or in simulation training. The third and most sophisticated module is capable of providing multi-modal feedback, including vibration, pressure, and impact. This versatile functionality allows for a broader range of tactile sensations, making it particularly useful in complex interaction scenarios.

The process of selecting and developing these modules was guided by several critical factors pertinent to the effective deployment of wearable haptic devices. Key considerations included ensuring the wearability of the devices, optimizing their weight and size for unobtrusiveness, and maximizing the quality and responsiveness of the feedback they provide. Each decision regarding the module design was carefully weighed to balance these factors, with the aim of enhancing user comfort while delivering precise and meaningful tactile feedback.

This section is dedicated to detailing the specifications, functionalities, and underlying technologies of each actuation module utilized in our study. It provides a thorough overview of how these modules integrate into wearable systems and how they were tailored to meet the demands of varied haptic interaction scenarios.

3.2.1 Vibration Feedback Module

We incorporated the TacHammer Drake (Model: TH-D-952395-LF) voice coil actuator from Titan Haptics [47] as the component of our vibration feedback module. This particular actuator is notable for its compact and lightweight design, weighing just about 4 grams and measuring $23 \times 9.5 \times 9.5mm$ in dimensions. Despite its small stature, it is capable of producing a significant maximum acceleration of 1.7 Grms at a frequency of 95 Hz, demonstrating a remarkable efficiency in its performance-to-size ratio. The actuator's design and its minimal weight enhance

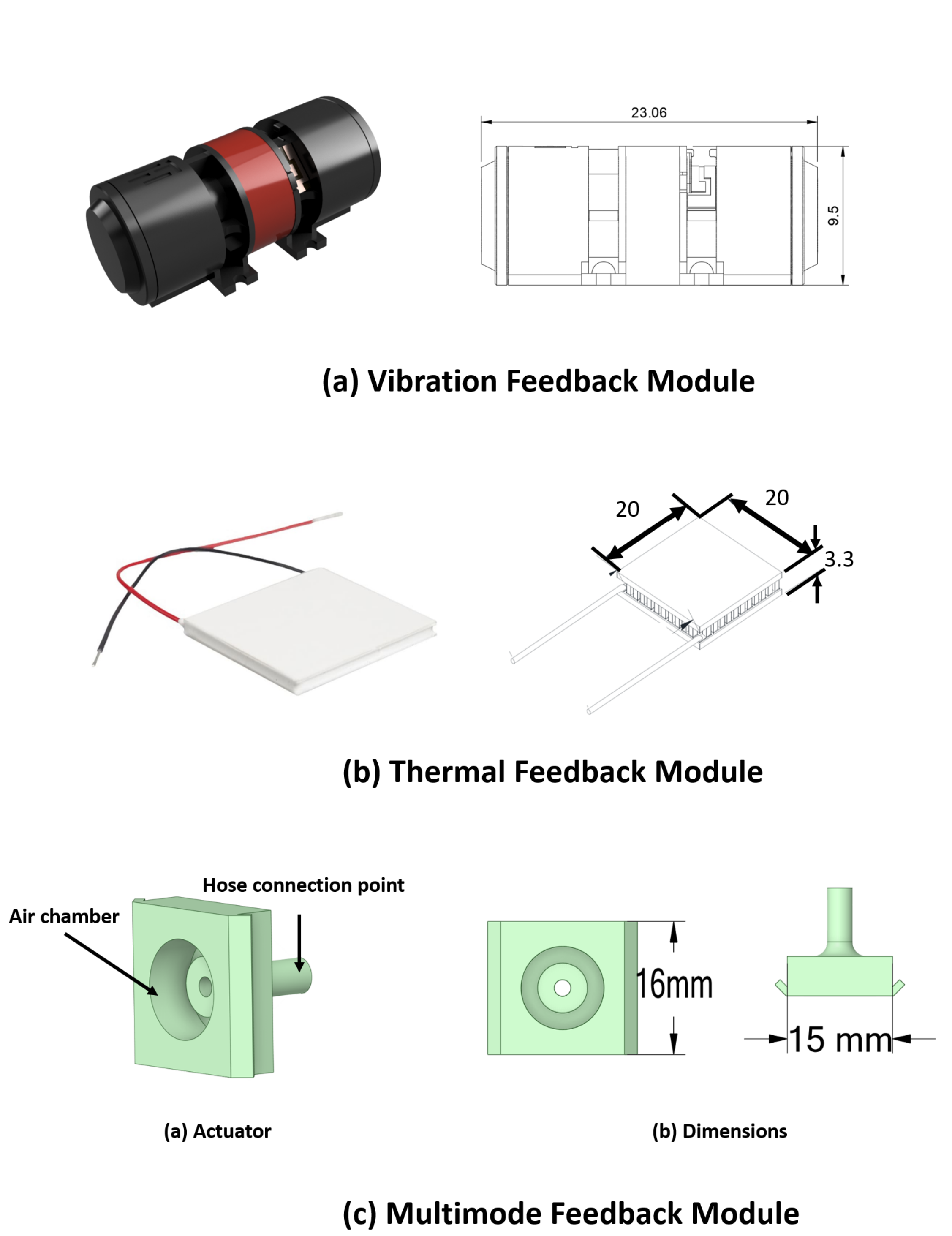

Figure 3.2: Designs and dimensions of all proposed modules: (a) TacHammer Drake actuator for vibration feedback, capable of rendering complex vibration patterns. (b) Thermo Electric Cooler (TEC) Peltier actuator for thermal feedback, providing both heating and cooling sensations. (c) Multimode tactile actuator designed to deliver vibration, pressure, and impact feedback.

its suitability for applications where wearability is crucial, making it an optimal choice for wearable technology that requires subtle yet powerful haptic feedback. Figure 3.2(a) provides a visual depiction of the actuator, highlighting its compact form factor and the design that makes it ideal for integration into user-centric haptic devices.

3.2.2 Thermal Feedback module

Peltier devices have gained significant popularity due to their efficiency and versatility, as detailed in 2.2.1. For our study, we utilized the thermo-electric cooler (TEC) model TEC-20-33-31 from Wakefield Thermal [48], chosen for its optimal integration into wearable devices. This particular module is remarkably lightweight, with dimensions of $20 \times 20 \times 3.3mm$, making it exceptionally suitable for incorporation into compact wearable technology where space is at a premium.

The selected Peltier module is adept at providing both heating and cooling sensations, thanks to its dual-sided design. This feature allows it to simulate a range of thermal sensations, enhancing the realism of haptic feedback by mimicking temperature variations that users can feel directly against their skin. The responsiveness of this module to changes in temperature is directly proportional to the input current; when operated at its maximum allowable current, the module can alter temperatures almost instantaneously, thus providing rapid feedback to the user.

Figure 3.2(b) illustrates this thermal module, showcasing its sleek form factor and compact design which make it ideal for wearable applications. The figure also highlights the dimensions of the module, emphasizing how its design is optimized for seamless integration into a variety of haptic feedback scenarios where size and weight are critical considerations.

3.2.3 Multimode Feedback Module

Following the development of modules for vibration and thermal feedback, it became essential to explore options for pressure and impact feedback. While there are commercially available devices such as solenoid push-pull valves that can provide pressure feedback, these tend to be larger and heavier, making them less suitable for our needs in compact, modular actuation systems. To address this, we opted for a pneumatic actuation unit. This unit is not only capable of delivering static pressure and impact feedback but also integrates vibration feedback, making it a versatile solution for our multimode feedback module.

Pneumatic systems have been widely adopted in haptic research, overcoming many limitations found in traditional commercial haptic devices. The advantages of using pneumatic systems include rapid response times, cost-effectiveness, a high power-to-weight ratio, straightforward control mechanisms, and inherent safety features. These benefits make pneumatics an attractive option for developing advanced haptic systems [49–54].

Our proposed multimode actuation modules incorporate a soft silicon air cell. This cell is fundamental to the module's operation as it allows for the modulation of air pressure within the chamber beneath the cell, thereby enabling it to deliver a range of tactile sensations to the user. This flexibility is crucial for providing a comprehensive haptic experience that can simulate various real-world interactions.

The development and construction of the multimode actuation module are executed through a series of precise and detailed steps, meticulously outlined within this section to ensure a comprehensive understanding of the technical processes involved. The construction process begins with designing a 3D model and printing of the actuator. Following this, the next step involves fabricating the soft silicon air cell, a critical component that interacts directly with the user. The final step integrates both the 3D-modeled actuator and the silicon air cell, culminating in the robust and reliable multimode actuation module.

3D modeling and Printing: Figure 3.2(c) displays the 3D design of the actuator, carefully developed to enhance its effectiveness in haptic applications. The actuator measures $15 \times 16 \times 6mm$, optimizing its size for the desired functionality. At the centre of the design is an air chamber configured to encase the silicon air cell, which is crucial for adjusting air pressure to deliver varied haptic feedback. Additionally, the design includes a hose that extends from the air chamber, facilitating the entry of air from an external source, which is vital for the actuator's functionality.

The actuator model was produced using an advanced 3D printing process with an Original Prusa Mk4 printer [55], renowned for its precision and reliability in producing detailed components. Acrylonitrile Butadiene Styrene (ABS) was selected as the printing material due to its durability, and thermal stability [56]. These properties are essential for parts that undergo frequent pressure changes and mechanical stresses in haptic devices.

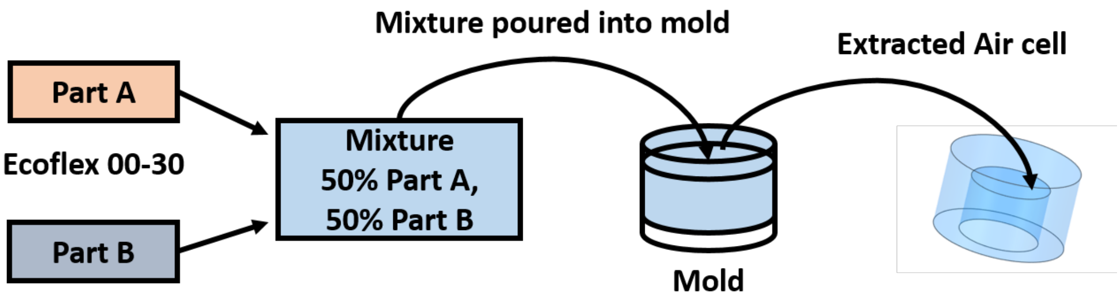

Figure 3.3: Fabrication procedure of the silicon air cell

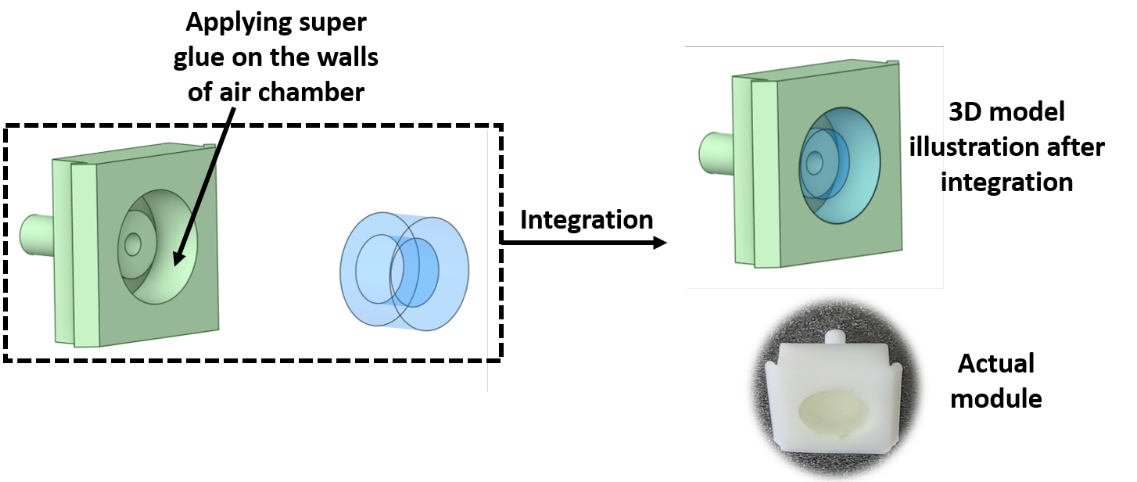

Figure 3.4: Integration process of the silicon air cell and 3D-printed actuator design

Silicon Air cell: The production of the silicon air cell was executed in two main stages. Initially, the material for the silicon air cell was prepared using Ecoflex 00-30 from Smooth-on, Inc., which has a Young's Modulus of 0.1694 Mpa at 10 Psi. This material was chosen for its excellent elasticity and strength, enabling it to withstand significant pressures without compromising the integrity of the silicon structure. Ecoflex 00-30 consists of two parts: Part A and Part B, which need to be combined in equal proportions. Thorough mixing of these components is crucial before proceeding to the next phase of fabrication.

The subsequent step involved creating a mold that matched the air chamber's design within the 3D model of the actuator. The mixed silicon solution was then carefully poured into this mold. It was left to set for approximately 4 to 5 hours, during which the silicon transitioned from a liquid state to a stretchable solid. Following this curing period, the silicon air cell was carefully removed from the mold, now ready for use. The entire fabrication process, from material preparation to the final removal from the mold, is detailed in Figure 3.3, providing a visual guide to the stages involved in creating the silicon air cell.

Integration of air cell and 3D design: within the air chamber that forms part of the actuator's structure. To ensure a secure attachment, super glue was applied to the interface between the air cell's walls and the inner surfaces of the air chamber. Once the components were joined, they were set aside to rest for approximately 20 minutes. This resting period allows the glue sufficient time to dry completely, ensuring that a strong and durable bond is formed between the two parts. Figure 3.4 provides a detailed illustration of this integration process, along with a depiction of the actual actuator following the integration, highlighting how the components fit together seamlessly within the overall design.

3.3 Control Setup

All the modules can be controlled with a microcontroller such as an Arduino. This section explains the control hardware required to operate each module.

3.3.1 Vibration Module:

The essential hardware components required to produce vibration feedback consist of an Arduino, a voltage amplifier, and a power source. The Arduino serves as the primary device for generating the specific waveform needed for the feedback system. Once the waveform is created, it is relayed to a voltage amplifier. The primary function of this amplifier is to enhance the strength of the signal to ensure it is powerful enough to drive the actuator effectively. After the process of amplification, the boosted signal is forwarded to the actuator, which then produces the physical vibration feedback. This entire sequence from waveform generation to vibration output is systematically illustrated in Figure 3.5, providing a visual representation of the overall control setup for managing vibration feedback.

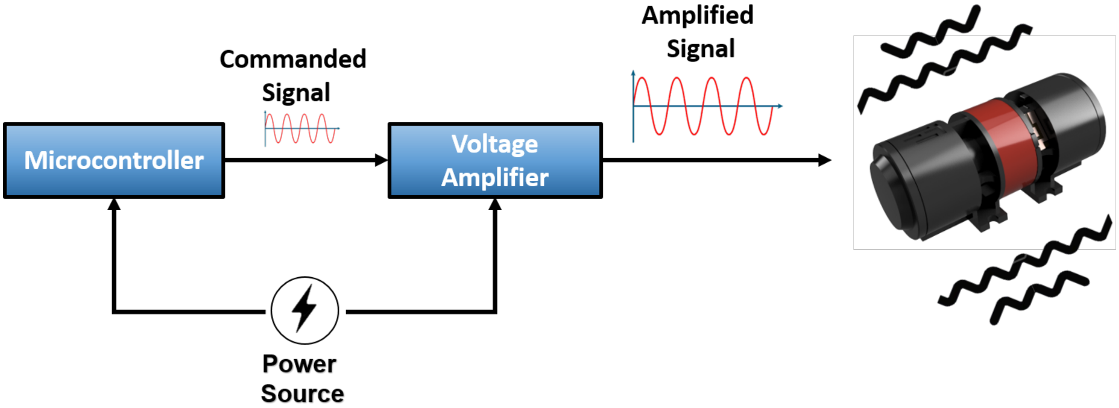

Figure 3.5: Control setup for vibration feedback

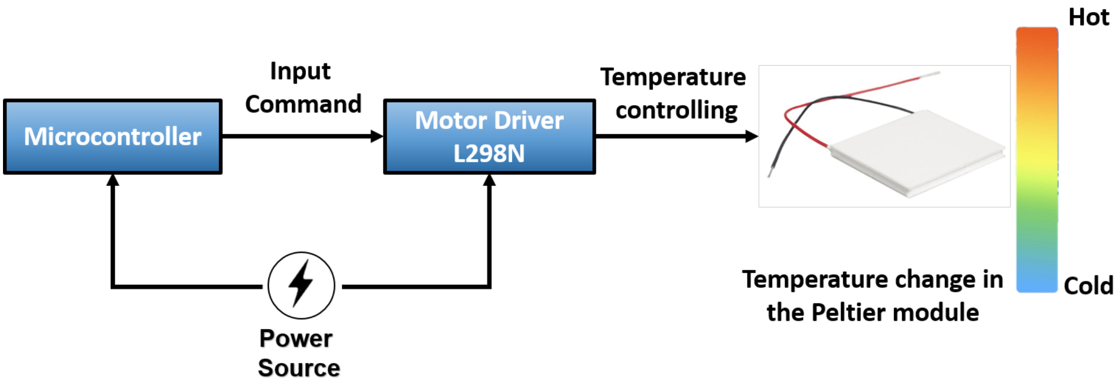

Figure 3.6: Control setup for thermal feedback

3.3.2 Thermal Module:

Similar to the previously described module, the temperature of the Peltier module can be adjusted using an Arduino. In this setup, a command is issued from the Arduino to a motor driver that is connected to it. This motor driver then manages the polarity of the current flowing through the circuit, effectively controlling whether the Peltier module produces cold or hot sensations based on the specific command received. This method allows for precise thermal control, enabling the module to switch between heating and cooling modes as required. The complete hardware configuration for this thermal control system is depicted in Figure 3.6, which visually outlines how each component is interconnected to facilitate the rendering of temperature-based sensations.

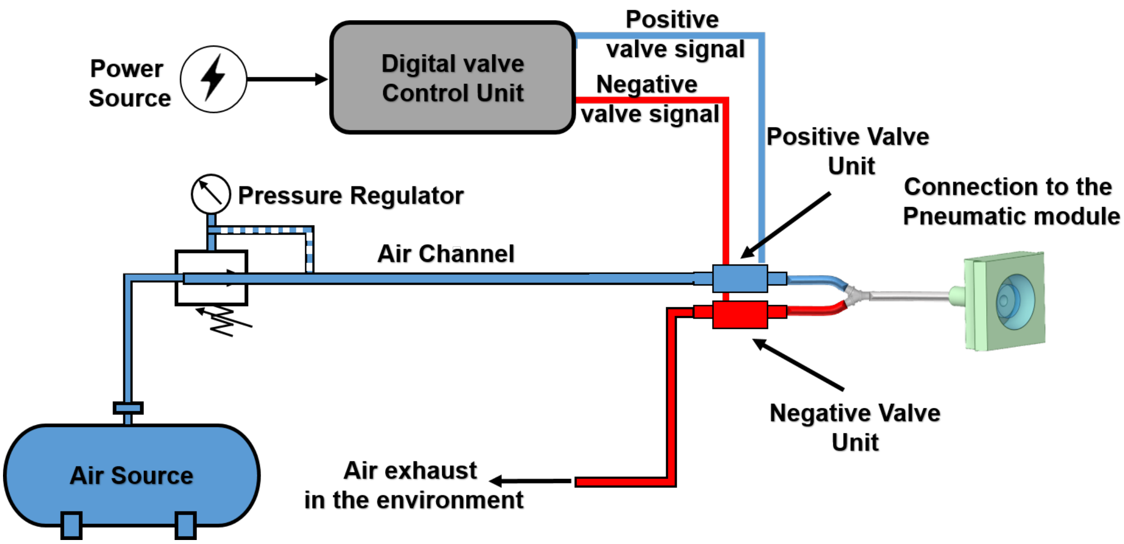

Figure 3.7: Control system for operating the pneumatic actuation.

3.3.3 Pneumatic Module:

The pneumatic module is capable of generating haptic sensations by controlling the air pressure within its air chamber. This sophisticated system relies on a pair of DC micro solenoid valves manufactured by Fspump (Model: 0520D, Voltage: 6V) to manage airflow for a single actuation module. One of the solenoid valves serves as a positive valve, which allows air to enter the chamber, enhancing the pressure. Conversely, the other valve functions as a negative valve, designed to extract air from the chamber, thereby decreasing the internal pressure. This balanced modulation of air is crucial for the accurate production of haptic sensations.

Both valves are connected in parallel using a 2-to-1 Y-shaped hose connector. The setup includes one end of the connector that is directly attached to the pneumatic module. Additionally, this connector interfaces with the positive valve via another Y-shaped connection, ensuring a seamless flow of air into the module. On the other side, the negative valve, connected to the module, actively pulls air from the chamber and expels it into the environment. This action effectively reduces the pressure inside the chamber, a critical step in resetting the system for another cycle of haptic feedback.

The solenoid valves are digitally controlled, allowing for precise manipulation of the valves through a custom board equipped with MOSFET transistors, as outlined in [57]. This board serves as a link between the Arduino Uno board's input channels and the solenoid valves, where it receives 'on' and 'off' signals to control each valve accurately. Additionally, an air source is connected to the input of the positive solenoid valve, and a pressure regulator is installed along the channel to maintain the system's overall input pressure.

This comprehensive setup of the pneumatic actuation control system is detailed in Figure 3.7. The figure illustrates how each component is interconnected, providing a visual representation of the entire process and its operation within the module.

3.4 Characterization

The performance of the voice coil actuator and thermal module can be easily found online, however, for the pneumatically controlled actuation module developed in this research, there is a need to under how the actuator behaves when the air is filled in the air chamber for vibration and pressure sensation. This section explores the performance of the actuator for these two sensations.

3.4.1 Vibration Feedback measurement

The vibration in the module can be controlled by switching the state of the positive and negative solenoid valves alternatively. The process keeps changing the pressure inside the air chamber, resulting in the for of vibration. The acceleration of the vibration feedback was measured at a set pressure for different frequencies.

Measurement Procedure The accelerometer ADXL335 GY-61 was affixed to the actuation module, as shown in Figure 3.15, to record the acceleration response induced by the actuation. Data acquisition was carried out using an NI-DAQ 6009 unit, and the collected data was stored on a PC using Matlab. The vibration frequency was varied from 1 Hz to 250 Hz, incrementing in a stepwise fashion to better analyze the response dynamics. Additionally, the input pressure was set at 7.5 Psi. Data collection at each setting lasted for 5 seconds with a sampling rate of 1 KHz. Calibration of the sensor's readings was performed prior to each measurement session.

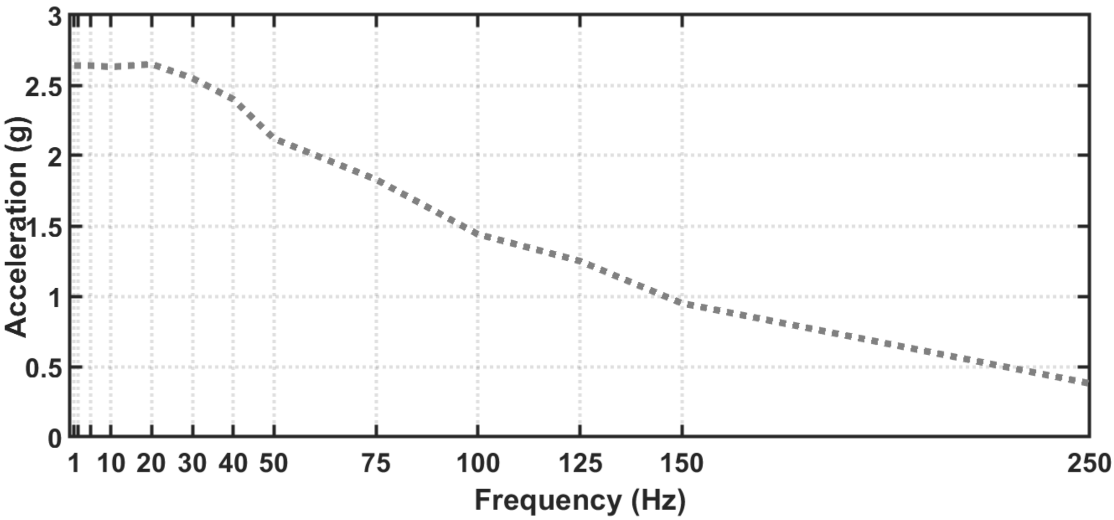

Figure 3.8: Acceleration response of the actuation module across a range of frequencies.

Result and discussion Figure 3.8 presents the results of the vibration acceleration measurements across various frequencies. It is evident that the acceleration of the vibration signal decreases as the frequency increases. For example, acceleration values are observed at 2.64 g at 20 Hz, dropping to 0.35 g at 250 Hz in the normal direction. Notably, the vibration acceleration at these frequencies exceeds the human threshold for perceiving vibrations, staying above the sensitivity limit [39–41].

To confirm the accuracy of the vibration signal in reflecting the intended frequency, sample data was recorded for a signal set at 50 Hz and 7.5 psi. Figure 3.9 (a) displays this signal in the time domain, and Figure 3.9 (b) illustrates the corresponding frequency spectrum. The system effectively generated a 50 Hz frequency signal which can be confirmed with the reported frequency analysis.

3.4.2 Pressure Feedback Measurement

The silicon air cell can withstand pressures of up to 10 psi, facilitating two distinct types of pressure effects. The first technique, referred to as static pressure, involves a process where the positive valve is left open to trap air, creating a sustained pressure within the chamber. This pressure remains until the negative valve is activated, which reduces the pressure and resets the actuator to its original state.

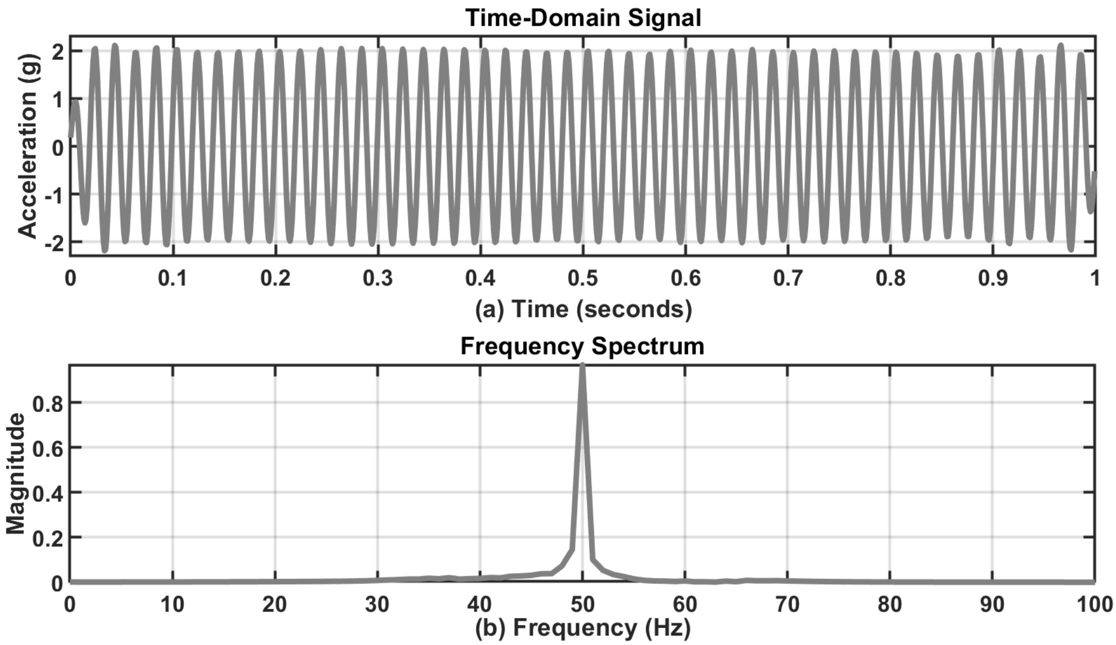

Figure 3.9: (a) Time-domain signal of the vibration feedback and (b) its corresponding frequency spectrum at 50 Hz.

Conversely, the second approach, termed impact feedback, is executed by quickly opening and then sealing the positive valve, followed immediately by opening the negative valve. This action delivers a rapid and immediate sensation of impact.

Measurement Procedure The force output of the module was quantified using a Wenzhou SF20 force sensor, positioned normally to the actuator's surface. The setup for measuring force is shown in Figure 3.10. Measurements were taken at an input pressure of 10 Psi. To adjust the air pressure within the air cell, the positive valve was sequentially opened from 0 to 250ms in increments of 10 ms. At each increment, static pressure was established within the air cell and the corresponding data was captured. This process was conducted three times to ensure reliability, and the results were averaged for each increment.

Result and discussion Figure 3.11 presents a detailed analysis showing how the force magnitude relates to the duration the valve remains open. As might be expected, a direct correlation is evident: the longer the valve stays open, the greater the force output observed. The data reveals

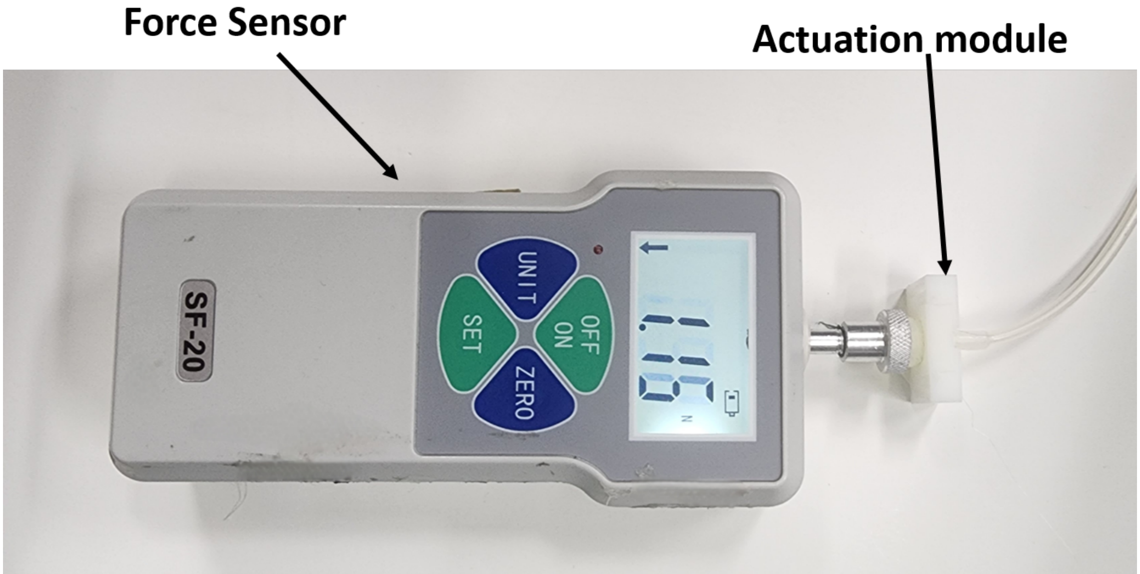

Figure 3.10: Force measurement setup

a pronounced increase in force across all directions during the initial 100 ms, with the rate of increase beginning to taper off around 150 ms. This stabilization continues, maintaining a nearly constant force level until the 250 ms mark. The highest recorded force, measured at 8.3N, occurs with the valve opened for 250 ms at an operating pressure of 10 psi, specifically in the normal direction. It's important to note, however, that there are operational risks associated with maintaining the valve open beyond this duration. Specifically, prolonged openings at this pressure level can potentially damage the silicon air cell, thus establishing 8 N as the maximum advisable force in the normal direction. Despite these constraints, an output force of 8 N is still sufficiently substantial for effectively powering a diverse array of applications that rely on haptic feedback, according to the literature cited [58]. This highlights the module's practical applicability in haptic technology, balancing performance with safety considerations.

3.5 Mounting Mechanism

The concept of modularized actuators requires an efficient mounting mechanism that allows the feedback designer to mount different modules on different body sites robustly without compromising the quality of feedback on users' perception. To achieve this, we designed three types

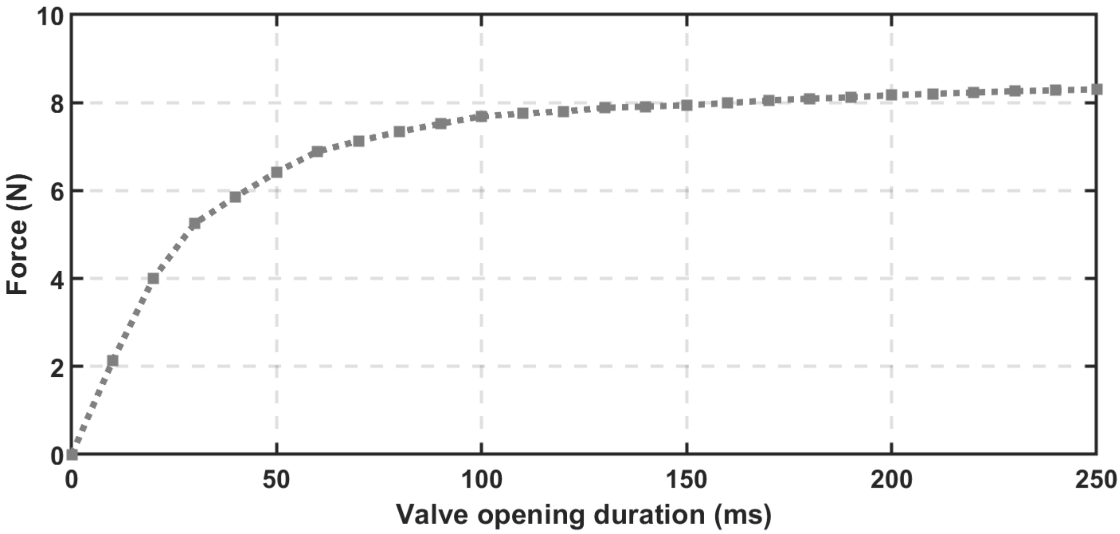

Figure 3.11: Force output of the pneumatic actuator as a function of valve opening duration. During the measurement, the input pressure was set at 10 psi

of mounting brackets that can hold actuators for each actuation type e.g. thermal, vibration, and pressure. To further attach these mounting brackets to the user's body, we propose two types of attachment methods deployed, attachment using velcro and body tape. Overall the actuators can be installed in the mounting bracket, and the mounting bracket can be attached to the user's body with the desired attachment mechanism. This whole procedure is summarized in Fig. 3.12. This sections further clarify the reason for using the two described mounting mechanisms, along with the design of the mounting brackets.

3.5.1 Mounting types

The use of velcro is a straightforward way to attach the actuating modules to the body sites. It allows a firm connection between the actuator and the body part where the actuator is targeted to be mounted. However, the only disadvantage we have with velcro is it only be used on such body parts that have cylindrical shapes. If it is required to attach the module on a flat body site, then velcro cannot hold the module. In order to resolve this issue, we introduced a second method, which involves a body tape. The use of body tape gives us enough liberty so that the actuator can be attached on any body site straightforwardly. It is safe for the skin and doesn't create any irritation when taken off. The commercially available body tape that was used can easily bear

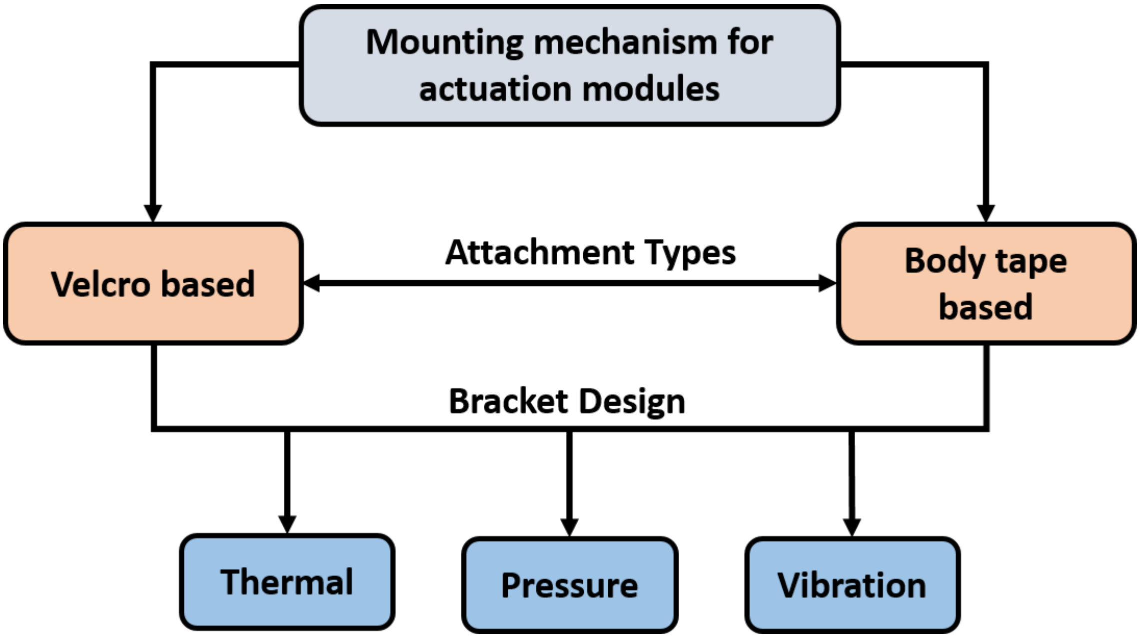

Figure 3.12: Illustration of the mounting mechanism for modular tactile actuating units, showing the two primary attachment methods: Velcro straps and body tape.

a normal force of up to 10N against the body, which is more than the amount of pressure our pressure module can generate. The only drawback of using body tape is that it can be only used once. So every time it is required to place a new tape on a new body site. Figure3.13 shows both of the mounting types when the modules were attached to the user's body.

3.5.2 Mounting Brackets

Figure 3.14 (a) presents the 3D rendering of the mounting brackets designed specifically for the thermal module employed in our study. This bracket has been engineered to allow for straightforward insertion and secure placement of the thermal modules. Integral to its design are two well-placed holes that facilitate the easy passage of wires from the thermal module, ensuring neat installation and minimal wire exposure. Additionally, the bracket features rectangular-shaped openings along its sides, which are tailored for the threading of Velcro straps, allowing for quick and adjustable mounting. These same openings are versatile enough to accommodate body tape as well, providing an alternative mounting option that ensures the module remains firmly attached under various conditions.

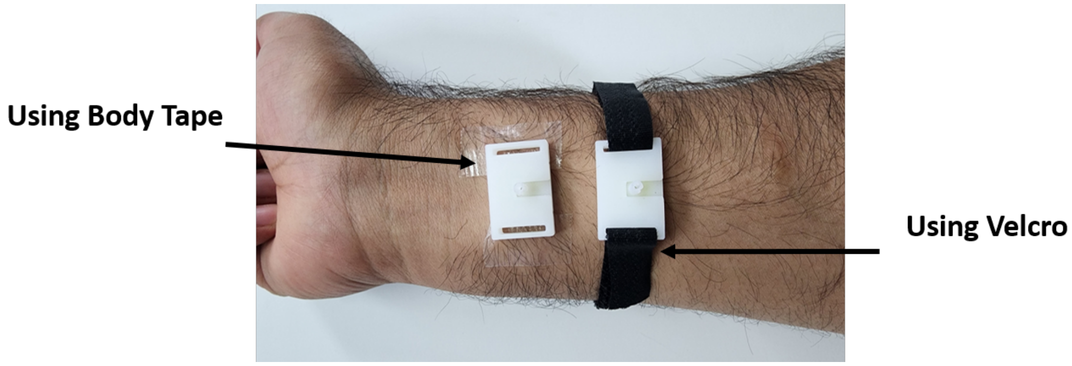

Figure 3.13: Demonstration of actuator attachment methods on a user's wrist using body tape and Velcro.

For the vibration feedback, the bracket has been designed to accommodate both the voice coil actuator and the pneumatic actuator. This versatility ensures that the bracket can support either type of actuator as they deliver vibration feedback to the user. A key feature of this design is the use of a uniform sliding mechanism that facilitates a secure and straightforward connection between the actuator and the bracket. This consistency in the mounting mechanism is crucial as it allows for the interchangeable use of either module, depending on the specific requirements of the system at any given time. This adaptability enhances the system's functionality by allowing quick modifications to the setup based on the desired feedback intensity or type. Figure 3.14 (b) illustrates this versatile and efficient mounting system designed specifically for handling vibration feedback in the system.

The mounting bracket designed for the pressure feedback underwent specific modifications distinct from the one used for the vibration module. To effectively convey pressure sensations to the user, it is crucial to maintain a deliberate gap between the body site and the pneumatic module. This spacing is facilitated by incorporating an elevated extension on the side of the bracket that connects directly to the body. This extension has been calibrated to a height of 3mm, ensuring that the pressure module remains slightly separated from the skin, thus preventing any unintentional contact when the system is inactive. The amount of spacing was decided based on the gap that was placed between the pneumatic actuator and the force gauge in the measurement setup (4.11). This careful design consideration helps to avoid any unsolicited stimulation and enhances user comfort by engaging the silicon air cell only during active pressure application. The details of

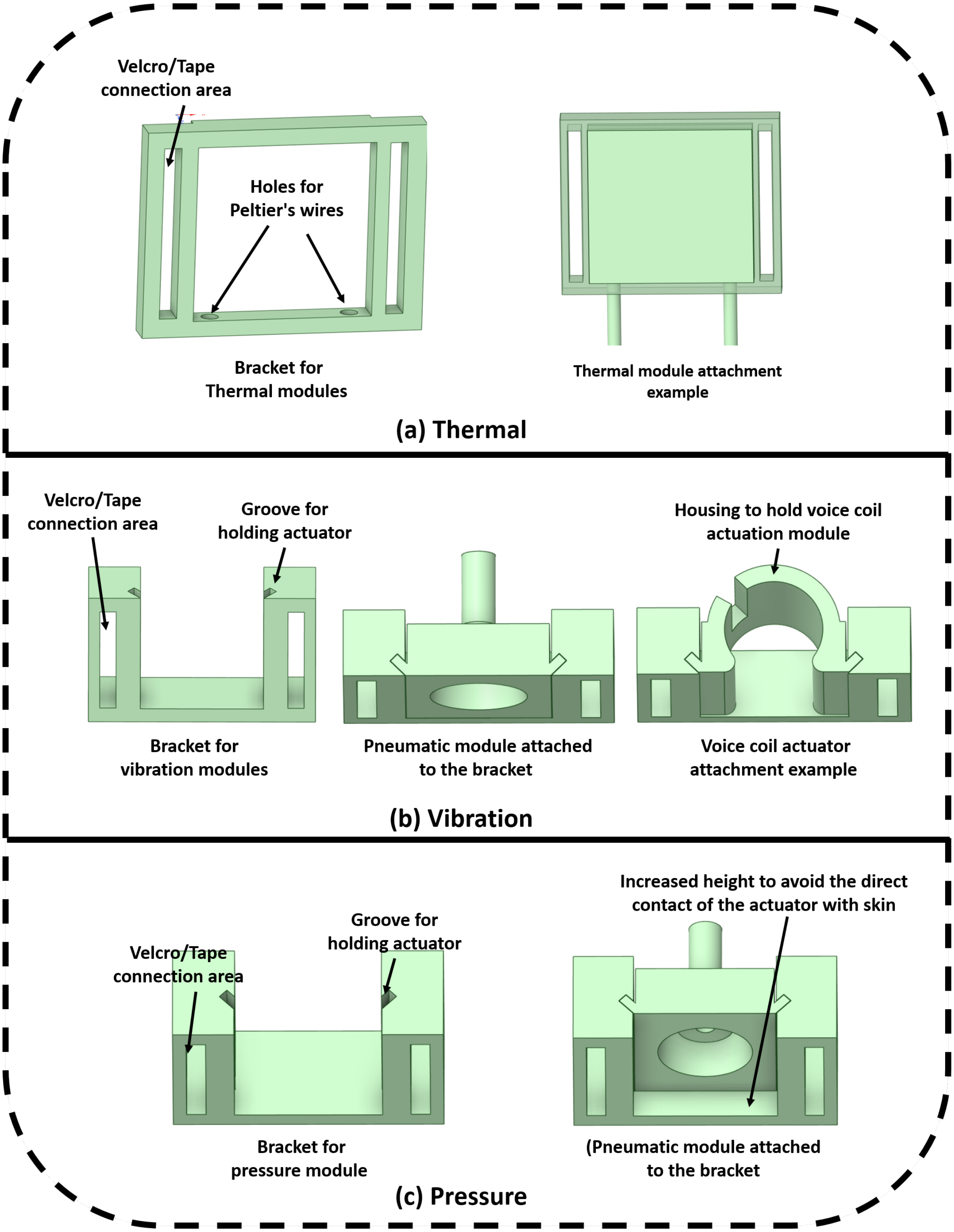

Figure 3.14: 3D design of the mounting brackets for all modules, showing (a) The Peltier module, (b) Vibration modules, and (c) The pressure module.

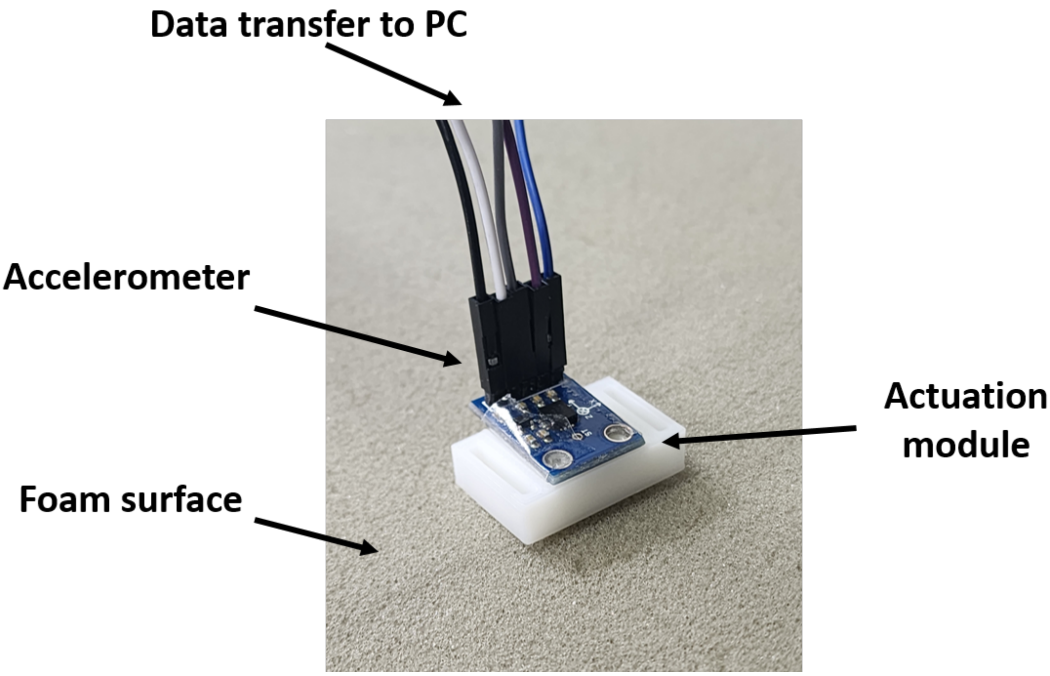

Figure 3.15: Experimental setup showing the actuation module, accelerometer, and data transfer setup.

this specially adapted bracket are depicted in Figure 3.14 (c), highlighting its unique structure and functional enhancements designed to optimize the delivery of pressure feedback to the user.

3.6 Perceptual Performance Evaluation

This section aims to delve into the perceptual comparisons across two critical scenarios discussed in the earlier parts of this study. Specifically, we examine two distinct types of solutions applied within each scenario. The first scenario involves the generation of vibration feedback, where we compare the outputs from a voice coil actuator and a pneumatic module. The second scenario focuses on the efficacy of mounting techniques, comparing velcro-based attachments to body tape-based methods. Our objective here is to assess the perceptual similarities between the solutions within each scenario, aiming to determine the conditions under which each solution can be considered perceptually equivalent. By identifying the key factors that influence user perception, this analysis seeks to establish whether both solutions could be used interchangeably in their respective scenarios without significant loss in effectiveness or user satisfaction. This understanding is pivotal for optimizing the design and application of tactile feedback systems in practical settings.

3.6.1 Case 1: Vibration feedback

This segment of the study focuses on evaluating the perceptual equivalence of vibration waveforms produced by two different actuators: the TacHammer Drake voice coil actuator, known for its ability to generate complex vibration patterns, and a newly designed pneumatic module capable of producing simpler waveforms. The primary objective is to determine whether the basic waveforms emitted by each device are perceived similarly by users.

Participants: We enlisted ten healthy volunteers, aged between 24 and 33 years (Average age 28.2), to participate in this segment of the research. All participants were in good health and provided informed consent before participating in the experiments.

A power analysis was undertaken to validate whether a sample size of 10 participants would be sufficient to achieve statistically significant results. This analysis incorporated insights from the specific research field, robust statistical methodologies, and the unique demands of the experiment to accurately determine the necessary minimum sample size. To conduct this analysis, several key variables were considered: the anticipated mean difference between two experimental conditions, a pre-assumed standard deviation, the target p-value, and the desired level of statistical power. The calculations for determining the sample size were executed using a two-sided test, ensuring equal sizes for both groups involved in the study [59]. The equation used to estimate the sample size is outlined below [60]:

$$N = \frac{4\sigma^2(z_{\text{crit}} + z_{\text{pwr}})^2}{D^2} \tag{3.1}$$

In this equation, N denotes the estimated sample size needed, σ represents the assumed standard deviation, z_{crit} is the Z-value corresponding to the desired p-value, z_{pwr} is the Z-value associated with the desired power level, and D stands for the minimum expected difference between the means of the two conditions. For this particular study, the expected difference between the means was predetermined at 30, based on insights from a pilot study. This difference of 30 points on a

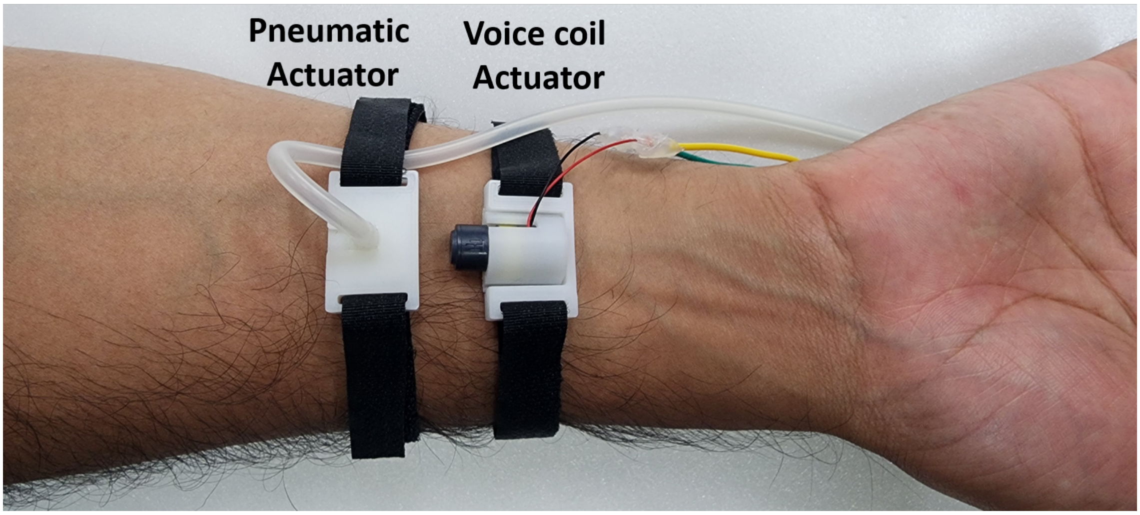

Figure 3.16: Experimental Setup for vibration feedback comparison

100-point scale was judged to reflect a meaningful perceptual contrast between the two conditions. The significance level was set at $p = 0.05$ ($z_{\text{crit}} = 1.96$), the power at $\beta = 0.95$ ($z_{\text{pwr}} = 1.64$), and the standard deviation was assumed to be 15 points. The chosen power level signifies the probability of detecting an actual effect in the data, thereby underscoring the importance of a higher power value for more reliable results. According to this formula, the analysis suggested a minimum required sample size of approximately 5.76 participants. To account for any potential outliers and to ensure robustness in the results, a decision was made to utilize a sample size of 10 participants for the experiment.

Experiment Procedure: The experimental setup involved securing both actuators to each participant's forearm using a Velcro strap to ensure a standardized placement. To minimize discomfort and maintain consistency, participants rested their arms on cushions. Before commencing the trials, the participants were familiarized with the sensations they would feel during the actual procedure by demonstrating the different vibration frequencies on their forearms beforehand. During the test, vibration stimuli were administered in pairs, with each stimulus in a pair set to a specific frequency. Participants were asked to assess the similarity of the vibrations in each pair on a scale from 0 (least similar) to 100 (most similar), with frequencies ranging from 30 Hz to 120 Hz. In total, each participant evaluated 25 different pairs of stimuli, including comparisons

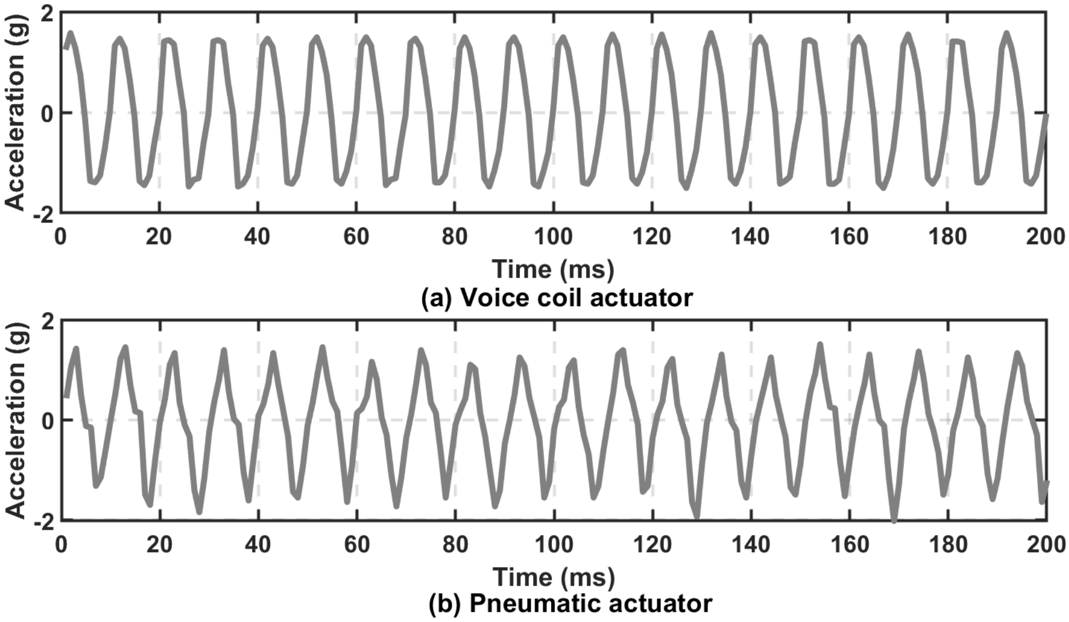

Figure 3.17: The vibration response of 100 Hz signal when rendered with (a) voice coil actuator and (b) pneumatic actuator. For the pneumatic actuator, the input pressure was set at 7.5 psi

of each frequency against itself and against the other four frequencies. The sequence of stimulus presentation was randomized, and participants had the option to request repeats of any stimuli. Noise-cancelling headphones were used to isolate the participants from any auditory distractions that might influence their perception. Each session lasted approximately 10 minutes. Figure 3.16 illustrates the experimental setup and the scenario in which the study was conducted.

Stimuli pair design Due to the distinct operational mechanics and placement of the actuators involved in this study, the direction in which vibration feedback is transmitted to the skin from each module varies. The voice coil actuator delivers vibrations tangentially relative to the skin surface, while the pneumatic actuator, positioned as illustrated in Figure 3.16, provides vibrations perpendicularly. This difference in vibration direction could potentially impact how similarly users perceive the vibrations.

To ensure that the vibrations emitted by both actuators are perceived similarly, it was necessary to adjust the amplitude of vibration acceleration carefully for each pair operating at the same frequency. This adjustment process was performed to align the perception of the vibration wave-

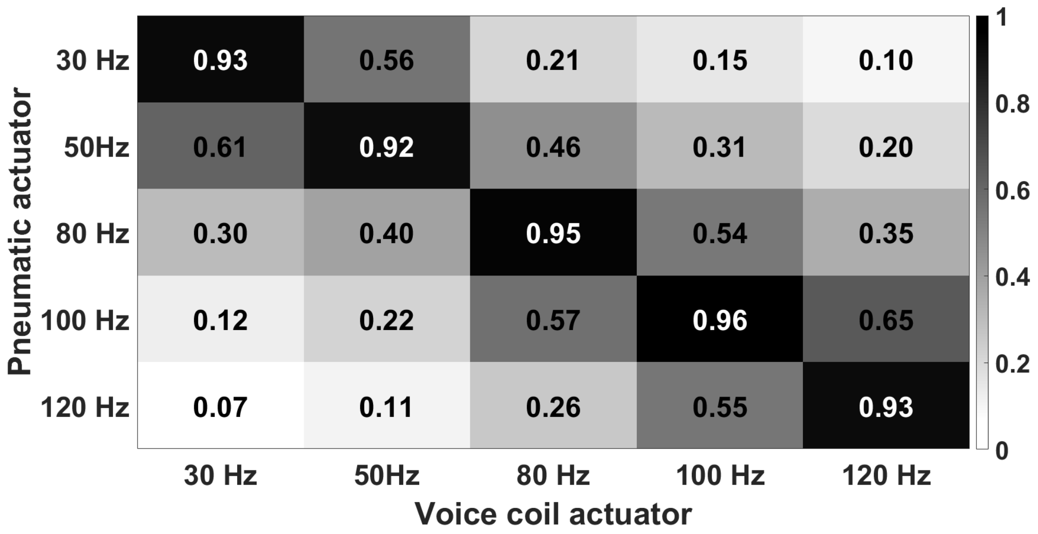

Figure 3.18: Similarity matrix showing the perceptual comparison between vibration frequencies of the pneumatic actuator and the voice coil actuator.

form produced by both the voice coil and pneumatic actuators. Figure 3.17 shows an example of a vibration waveform generated by both modules.

Results and discussion The result of the experiment is shown in Fig. 3.16, where the original data collected that was collected between 0 to 100 scale was normalized between 0 to 1. The outcomes of the experiment reveal that a significant majority of participants successfully identified the pairs consisting of the same vibration frequencies. The accuracy rate recorded was 93.8%, indicating a high level of perceptual similarity in the vibration signals produced by both the voice coil and the pneumatic actuators. This result suggests that either type of actuator could be employed interchangeably when the application calls for simple vibration waveforms.

The findings also highlight a crucial consideration: while both actuators are suitable for basic vibrations, the voice coil actuator is necessary for applications requiring the generation of complex vibration patterns. The pneumatic system's control mechanisms currently lack the capability to produce arbitrary waveforms, which limits its use in more sophisticated haptic feedback scenarios. Therefore, when simple vibration is needed and the pneumatic module is already in place on a user, it can effectively deliver the required haptic feedback, thus enhancing the system's flexibility and overall utility in various applications.

3.6.2 Case 2: Mounting Techniques

This section delves into the nuances of mounting techniques and their impact on the tactile feedback received by users, particularly focusing on the relationship between the mounting force and the perceived intensity of vibrations. Influenced by findings from a recent study by Lee et al., which demonstrated that increased contact force enhances the perceived intensity of vibrations from a voice coil actuator [61], this experiment aims to determine if a similar dependency on contact force applies to pneumatic modules. Moreover, this study seeks to ascertain the specific level of contact force that yields comparable perceptual outcomes when actuating modules are secured using either a Velcro strap or body tape, exploring the effectiveness and perceptual consistency of different attachment methods.

Participants: Ten healthy volunteers, aged between 24 and 31 years (average age 27), were recruited for this experiment. All participants were physically fit to participate and provided informed consent prior to the start of the study.

To verify the adequacy of the participant count, the power analysis previously described was applied, using the equation referenced as Equation 3.1. The analysis assumed a mean difference of 35 between the two experimental conditions, which was sufficient to demonstrate statistically significant differences. The standard deviation, denoted σ, was set at 15 for this study. All other parameters remained consistent with the initial conditions of the formula. The power analysis determined that a minimum of 9.52 participants was necessary to achieve statistical significance; thus, recruiting 10 participants was deemed sufficient for the experiment.

Experimental Procedure This experiment was designed to meticulously analyze multiple variables affecting the perception of haptic feedback. Initially, to assess the impact of contact force on tactile perception, a pneumatic module was secured to each participant's forearm using a Velcro strap set to three specific forces: 0.5 N, 1.5 N, and 2.5 N. A precision instrument, the ATI nano17 load cell, was employed to accurately measure these forces. Concurrently, an identical module was affixed adjacent to the Velcro-fastened one but was attached using body tape (see Fig.

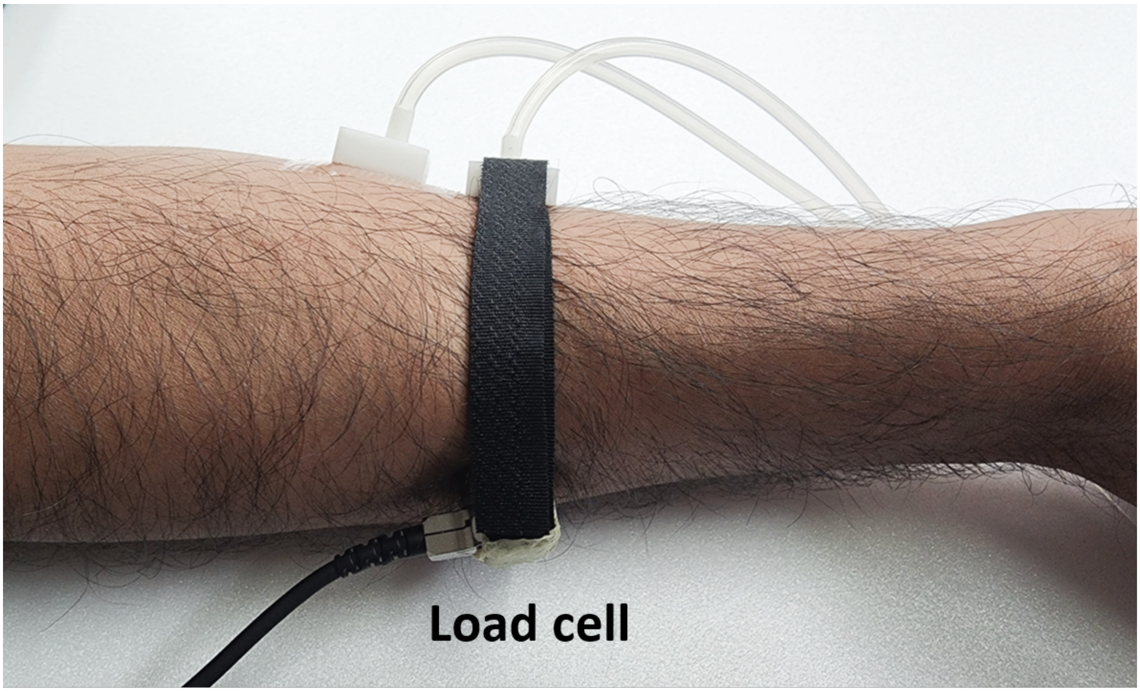

Figure 3.19: Experimental Setup: Actuators are attached with body tape and velcro. A load cell is attached with velcro to measure contact force.

3.19), providing a comparative analysis between two distinct mounting techniques. Each module delivered vibration stimuli at two frequencies—50 Hz and 100 Hz—across all levels of applied force.

Prior to the onset of data collection, participants received detailed instructions regarding the experiment's protocol and objectives, followed by the signing of informed consent forms to ensure ethical compliance and participant awareness. To minimize external auditory distractions and thus refine the focus on tactile feedback, noise-cancelling headphones were provided to all participants. Additionally, to prevent fatigue which could potentially affect perceptual accuracy, participants' arms were comfortably positioned on cushions.

The methodological approach to evaluating the perceived intensity of the vibrations utilized the absolute magnitude estimation technique, a proven method in psychophysical research for its accuracy and reliability [62–65]. Participants were instructed to freely rate the intensity of each vibration on an unbounded numeric scale, where higher numbers indicated stronger perceived intensities. Each vibration exposure lasted for two seconds, with participants given the option to

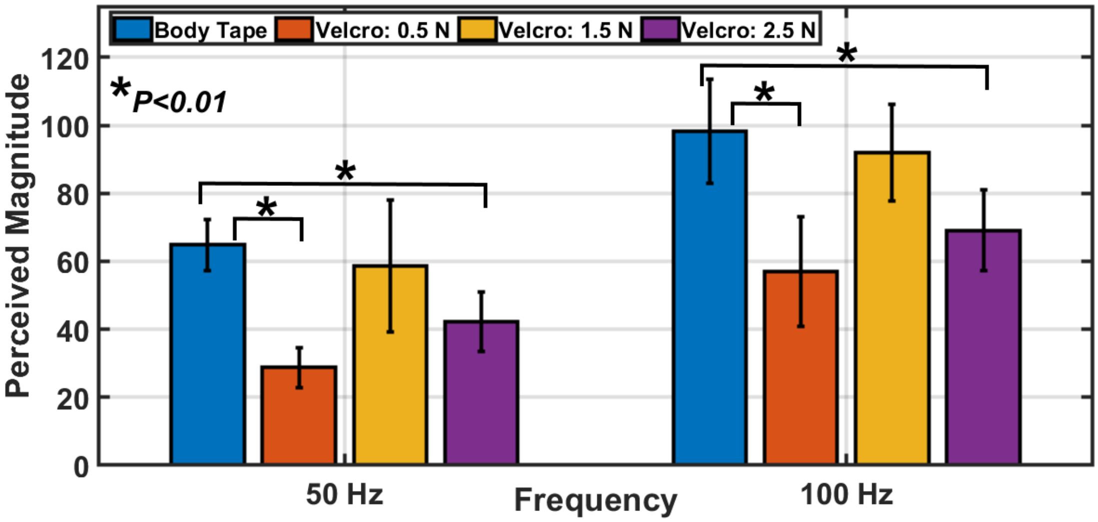

Figure 3.20: Perceived magnitude of vibration at 50 Hz and 100 Hz frequencies for different mounting methods (Body Tape and Velcro with varying contact forces). Significant differences are marked with p <0.01.

request a repeat to ensure their ratings reflected their true perception. The experimental design included a total of 24 trials per participant, systematically covering four contact force conditions and two vibration frequencies, repeated three times to enhance the robustness and reproducibility of the findings.

This comprehensive procedure was not only crucial for understanding the influence of contact force and mounting technique on vibration perception but also vital for gathering reliable and nuanced data that could inform future improvements in haptic device design and application.

Results and Discussion The experimental data collected from participants exhibited variability in their individual rating scales. To address this and normalize the data for meaningful comparison, we implemented a standardization process using the mean deviation method [66]. Initially, we calculated the average scores for each condition, which were then used to determine the subjective geometric mean (GM_s) for each participant across all conditions. Subsequently, we computed an overall geometric mean (GM_g) by aggregating the GM_s values from all participants. A normalization factor was derived as $GM_{norm} = GM_g/GM_s$, which was applied to adjust the participant scores, standardizing the results across the board. This normalization process ensured that individual variations in scale perception did not skew the collective data analysis.

The analysis revealed distinct patterns in the perception of haptic feedback relative to the applied contact forces. As shown in Figure 3.20, there was a noticeable increase in perceived intensity of the vibration with increasing contact force up to 1.5 N. Beyond this point, the perception began to diminish. This reduction at higher forces could likely be attributed to the mechanical limitations of the pneumatic actuator; excessive force may impede the actuator's movement, thereby diminishing its effectiveness and altering the intended haptic sensation.

To further dissect the influence of the mounting techniques—Velcro versus body tape—we conducted a two-way ANOVA, supplemented by a post hoc analysis using the Tukey-Kramer method to pinpoint specific differences between these attachment methods. The analysis showed that at a contact force of 1.5 N, there was no statistically significant difference in perception between the Velcro and body tape methods ($p > 0.01$), suggesting comparable effectiveness in transmitting haptic feedback under these conditions. However, at lower (0.5 N) and higher (2.5 N) contact forces, significant differences were observed ($p < 0.01$), indicating that the efficacy of the attachment method varied with the amount of force applied.

These findings imply that while both attachment methods can be effectively used to mount haptic actuators, the choice of method and the amount of contact force need careful consideration to ensure optimal haptic feedback. This is especially crucial when designing wearable haptic systems where consistent performance is essential for user satisfaction and system reliability.

3.7 Perceptual Effects of Multiple Modules

Different kinds of tactile stimuli are detected by sensory receptors. Based on the modules introduced in this study, a total of 2 sensory receptors are engaged, mechanoreceptors and thermoreceptors, to deliver information to the brain [67, 68]. In order to, understand how can we render different tactile patterns using multiple actuating modules first we need to study how users feel different tactile actuations that trigger different sensory receptors. A very popular study, the two-point discrimination test allows us to understand how a certain sensory receptor perceives information of two tactile stimuli when presented on a body site by keeping a distance between the stimuli. In this section, we focus on analyzing the two-point discrimination when two different stimuli are delivered from the pneumatic and thermal module, i.e. pressure and temperature feedback, which are perceived by 2 different sensory receptors. Based on the analysis, we further experimented with different tactile patterns on a certain body site to observe if a user can successfully perceive the pattern that is being delivered.

3.7.1 Two point discrimination (TPD) threshold

This section explores the two-point discrimination (TPD) threshold concerning the application of multiple types of actuating units—specifically, thermal and pressure modules. The experiment was structured to determine how closely two distinct stimuli need to be placed before they are perceived as separate by participants. This perceptual measurement was conducted across three different body sites: the forearm, the area between the shoulders (just below the neck), and the leg, as depicted in Figure 3.21.

Participants: We recruited a group of 10 participants (8 males, 2 females), with ages ranging from 24 to 31 years old (average age: 26.4). Each participant was healthy and met all conditions necessary for safe participation in the study. Written informed consent was obtained from all participants prior to their involvement in the experimental procedures.

Procedure: Prior to the main experiment, a pilot study was executed to determine the perceptual distance at which participants could distinguish between two simultaneously activated modules positioned at different points on their skin. This preliminary phase helped establish a baseline range for stimulus separation needed in the main TPD experiments.

The primary TPD assessment utilized an adaptive staircase method, specifically the one-up, one-down approach, which targets the 50th percentile of a psychometric function. This method included two divergent starting points: Staircase A initiated trials from a greater initial separation, and Staircase B from a closer one. For each participant's response of "yes, I feel two separate points," the distance for the subsequent trial was increased, while a "no, I do not feel them separately" response decreased the separation. This adaptive testing continued until each sequence had achieved eight reversals, thereby ensuring robust data for determining the TPD threshold. The adjustments in distance between stimuli were done in small increments, and the precise measurements were recorded using slide calipers for accuracy.

To ensure the comfort and focus of participants, breaks of approximately five seconds were provided between trials to mitigate potential sensory fatigue and bias. Additionally, participants were equipped with noise-canceling headphones and an eye mask to eliminate auditory and visual distractions, thereby focusing their perception solely on the tactile sensations. The methodology for this staircase procedure is adapted and refined from the protocol described by Raza et al. [69].

This experimental setup aimed to accurately map the spatial acuity of tactile perception across different body areas, providing valuable insights into how different tactile stimuli are processed and differentiated by the human sensory system. The results from this detailed investigation are crucial for the development of haptic devices that aim to deliver precise and discernible tactile feedback in various applications.

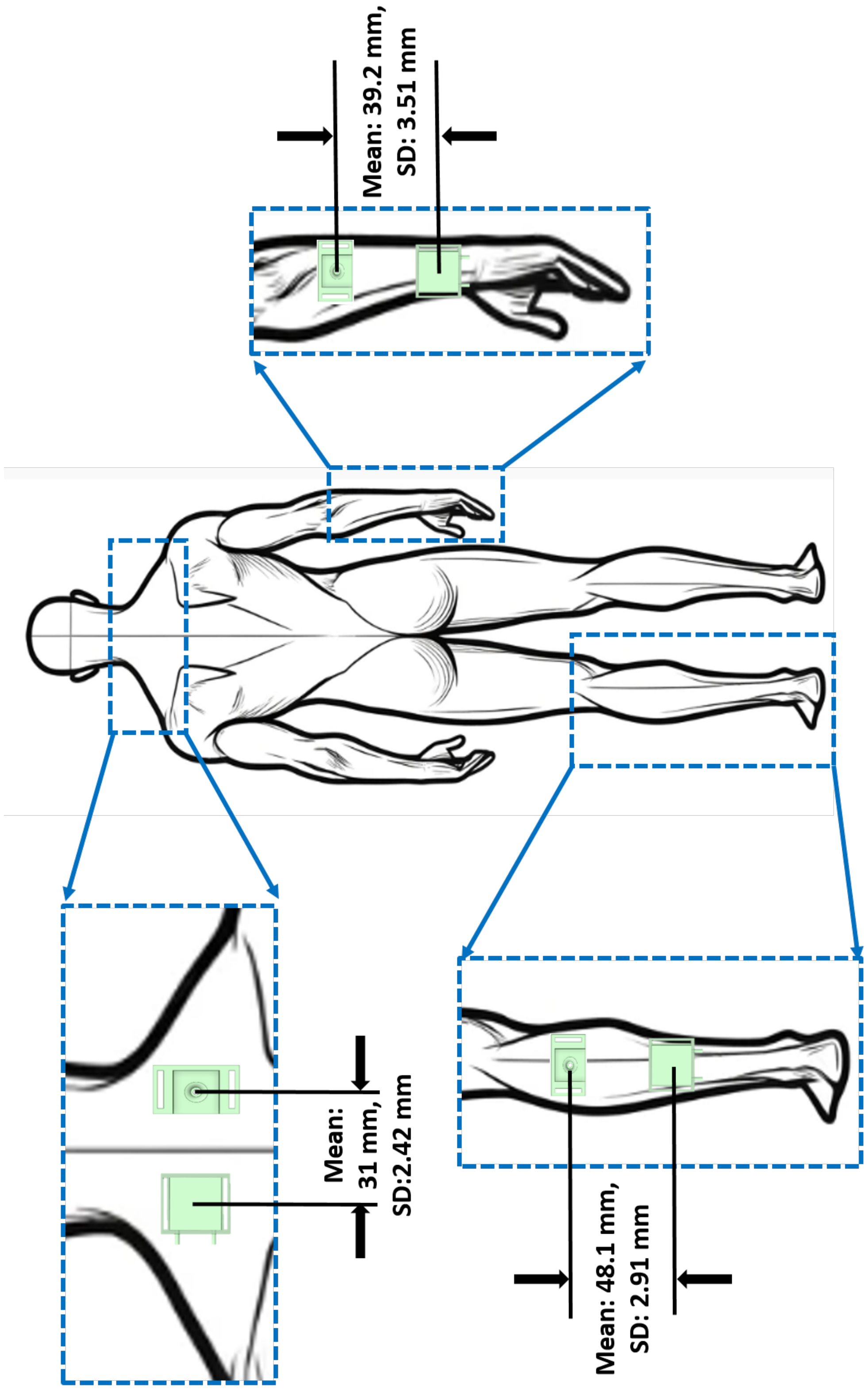

Figure 3.21: Two-point discrimination (TPD) threshold measurements at various body sites, including the area between the shoulders, forearm, and leg, with corresponding mean values and standard deviations.

Results and Discussion In selecting the body sites for our study, we aimed to encompass a variety of regions that differ significantly in tactile acuity and offer distinct insights into tactile perception. This selection strategy facilitates the integration of various tactile modules while enabling a thorough exploration of tactile interactions across different anatomical areas. The forearm and leg are commonly used in two-point discrimination (TPD) studies due to their relevance in everyday tactile interactions and their established baselines in sensory research. These sites provide a foundational comparison for assessing the effectiveness and perceptual impact of our tactile actuators.

Additionally, we included the area at the base of the neck—a region less commonly studied in standard TPD research—to investigate its unique sensory characteristics, which might be influenced by varying factors such as skin thickness and local nerve density. This particular site is often affected in individuals experiencing chronic pain conditions, making it relevant for applications in medical diagnostics and therapeutic interventions [70–73]. By studying this area, we aimed to gather insights that could inform the design of tactile systems for pain management, where precise and localized feedback could play a crucial role in treatment efficacy. Moreover, the selection of these diverse body sites allows us to test the modular adaptability of our tactile devices across different body contours and types. Understanding how tactile perception varies across these regions helps in designing devices that can be customized for personal use or specific medical applications, such as delivering soothing tactile stimuli for pain relief or replicating the touch of a loved one in a therapeutic context.

The findings from our two-point discrimination (TPD) threshold experiment are visually summarized in Figure 3.21, which presents the TPD distances across three selected body sites: the area under the neck, the forearm, and the leg. The observed mean TPD distances were 31 mm (SD: 2.42 mm) for the area under the neck, 39.2 mm (SD: 3.51 mm) for the forearm, and 48.1 mm (SD: 2.91 mm) for the leg. These results are consistent with established research in tactile discrimination, confirming that spatial acuity varies by body location [74]. It is noteworthy that our measurements specifically quantified the distances between the centres of two actuators, providing a direct assessment of how spatially distinct tactile stimuli need to be for an individual to perceive them as separate.

The implications of these findings are significant for the design and application of tactile devices using multiple actuation methods. If the objective is to convey distinct tactile stimuli at a single point, the separation between actuators must not exceed the TPD thresholds identified, ensuring each stimulus remains perceptibly independent. This precise arrangement allows for a more controlled delivery of tactile information, which can enhance user interaction with haptic technologies by maintaining clear and distinct tactile feedback.

Conversely, for applications aiming to induce more complex tactile illusions, such as phantom sensations or cutaneous rabbit effects, our results suggest that actuators should be positioned beyond the TPD thresholds. Such configurations exploit the merging of sensory inputs at higher thresholds to create unique perceptual experiences that could enrich interactions in virtual environments or sophisticated training simulations. This strategic use of tactile spacing opens up new possibilities in haptic design, allowing for the exploration of nuanced sensory interactions that go beyond simple stimulus presentation.

3.7.2 Perception of tactile patterns

In this section, we explore the capability of multiple tactile actuating units when they are applied to various locations on a body site. Our primary objective was to explore the potential for delivering recognizable tactile patterns using a configuration of these actuating units. To achieve this, we initiated a user study focused on evaluating how participants perceive and interpret these patterns, and whether these tactile cues can be associated with familiar sensations or actions.

Participants and Tactile Patterns: The experiment involved 8 participants (age range: 24-31, average: 27.4), for whom we designed and presented four distinct tactile patterns. These patterns utilized three pressure modules, each configured to activate on the forearm of the participants. The patterns were categorized into two main types based on their orientation: linear and radial. Each orientation type was further differentiated by the sequence of actuation—either overlapping or step sequence. In the overlapping sequence, the modules were activated in succession, maintaining the pressure until all were simultaneously active. The step sequence, on the other hand, activated each module consecutively, with each module deactivating before the next activated. This setup aimed to create a clear distinction in the tactile experience between continuous and segmented stimulation. The specific designs of these tactile patterns are illustrated in Figure 3.22, providing a visual reference to their strategic configuration on the forearm.

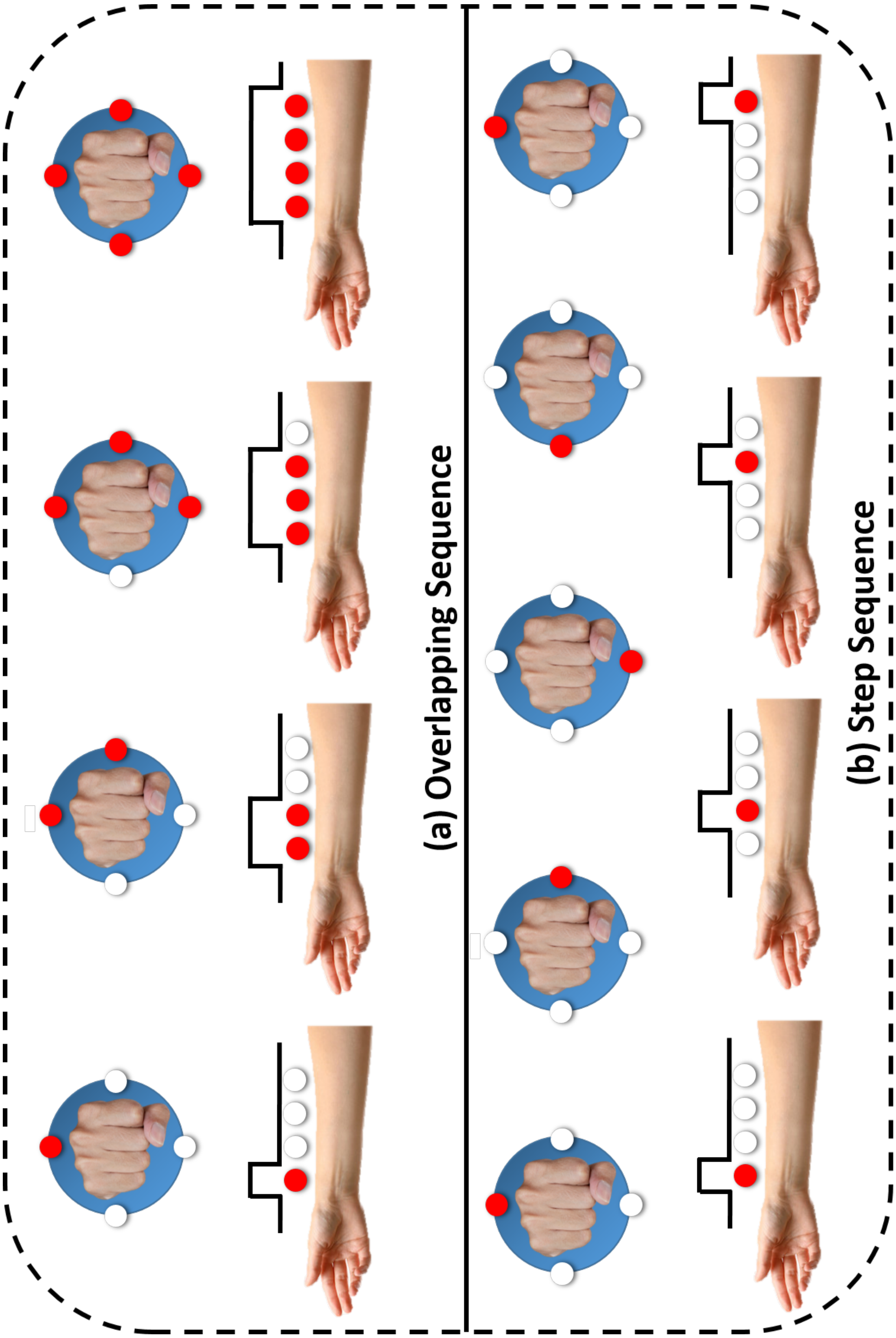

Figure 3.22: Actuation pattern illustration for linear and radial direction.

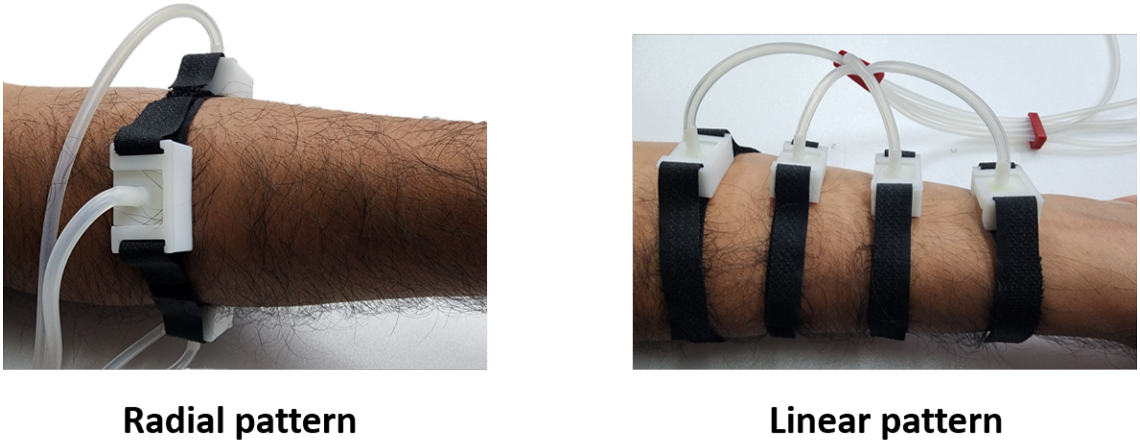

Figure 3.23: Experimental setup for tactile pattern rendering

Experiment Procedure: The experimental procedure was methodically divided into two phases to systematically address the response to linear and radial patterns. Within each phase, the patterns were presented in a randomized order to prevent any order effects from influencing the results. Each tactile pattern was demonstrated across twelve trials, repeated thrice to ensure consistency in participant response and familiarity with the sensation. To isolate the tactile experience and enhance concentration, participants were equipped with headphones to cancel out ambient noise and wore blindfolds to eliminate visual cues. They were tasked with identifying the direction of the tactile stimulation and providing qualitative feedback on their experience, noting any real-world sensations that the patterns might evoke. Figure3.23 shows a scenario for the actuator attachment to render linear and radial patterns.

Results and discussion: As depicted in Figure 3.24, the study yielded significant insights into the recognizability of tactile patterns. Linear patterns and radial step sequences were identified with high accuracy, suggesting that these configurations were effective in conveying directional and sequential tactile information. The overlapping radial patterns, however, saw slightly lower accuracy rates, indicating possible challenges in perceiving simultaneous stimulations without distinct temporal separation. Participants described the step sequence patterns as evocative of recognizable physical interactions, such as something ”walking” or ”tapping” on the arm, suggesting a strong correlation with natural physical contact. In contrast, the overlapping sequences were often

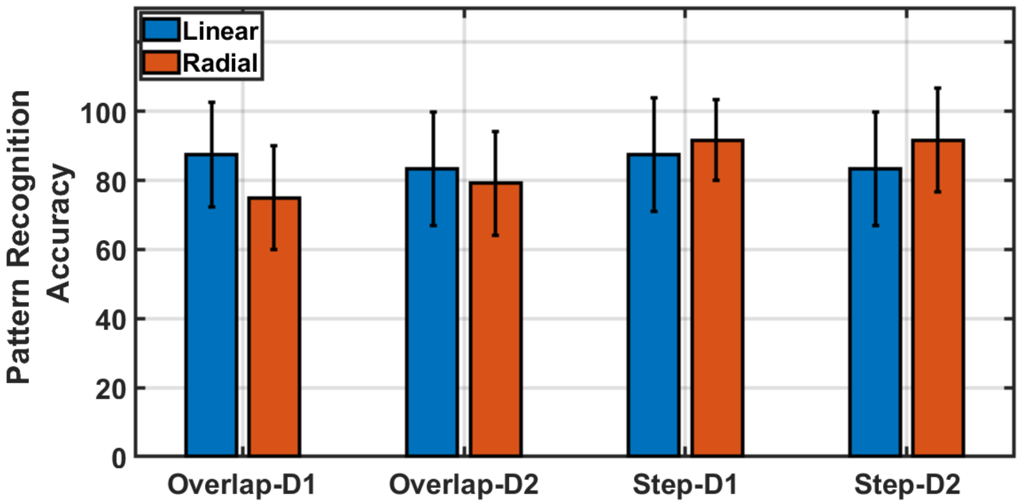

Figure 3.24: Pattern recognition percentage accuracy result. D1 and D2 are the directions in which patterns were displayed. In the case of linear, D1: towards the elbow and D2: towards hand. For Radial, D1: clockwise, D2: anticlockwise

perceived as a fluid, continuous motion, akin to gentle gliding across the skin, which might suggest a potential application in creating seamless and continuous tactile sensations for user interfaces.

These findings underscore the effectiveness of the developed tactile patterns in not only delivering directional information but also in enriching user interaction with intuitive and meaningful tactile feedback. The study highlights the potential applications of such tactile modules in enhancing navigational aids, virtual reality setups, or even in therapeutic contexts, where precise and interpretable tactile feedback can significantly augment user experience and engagement.

3.8 Evaluation

This section provides an evaluation of the developed modularized tactile units. The evaluation is conducted through a comparison with existing literature and a detailed user experience study. These evaluations aim to highlight the strengths and potential areas for improvement of the developed system, ensuring its effectiveness and relevance in real-world applications.

3.8.1 Comparison with existing studies

To contextualize the advancements presented in this work, we compared our modularized tactile units with similar systems reported in the literature. This comparison focuses on modularity, actuation methods, actuation types, the number of modules, form factor, and the key differences between the existing systems and our proposed solution.

The table above highlights key distinctions between our proposed system and other existing systems. Our system stands out due to its high versatility, lightweight, small form factor, and performance across multiple actuation types. While existing systems are modular to varying extents, they often suffer from limitations such as larger sizes, heavier weights, and restricted types of tactile feedback. Our design integrates voice coil actuators, pneumatic actuators, and Peltier modules to provide a comprehensive range of tactile sensations, including vibration, pressure, impact, and temperature feedback. This makes our system more adaptable and effective for diverse applications in virtual and augmented reality environments.

Study	Actution Methods	Actuation Types	Form Factor: Types of modules	Form Factor: Size	Difference with our work
Zhou [75] (2023)	Servo motor	Squeez, Tap, Push, shake	1	80 x 50 x45 mm 72 g each module	Limited actuations Lacks complete Reconfigurability
Israr [76] (2016)	Speakers	Vibration feedback	2	40mm x 40 mm (estimated)	Limited modules One types of actuation
Endow [77] (2021)	Pneumatic Bladders	Compression, Vibration	3	Glove: 11.6 cm2 Elbow Brace: 165.3 cm2 Grater: 171.2 cm2	Limited modules Large size
Park [78] (2018)	Vibrotactile actuators	Vibrations	3	Piezo: 3.8 x 3.2 x 35 mm Haptuator II: 9 x 9 x 32 mm Haptuator Planer: 12 x 12 x 6 mm	Limited modules One types of actuation
Messerschmidt [79] (2022)	Shape Memory Alloy	Skin Deformation	1	50 x 100 mm (When attached to the body)	Single module One types of actuation
Delazio [38] (2018)	Pneumatic Bladders	Pressure Vibration	1	120 x 120 x 0.4 mm (estimated)	Single module Large size
Zhang [80] (2021)	Peltier Pneumatic	Thermal Pressure Vibration	2	Diameter: 11 mm Height: 11 mm (Peltier module attached within the area)	Large size modules Low Output Range
Proposed	**Voice coil Actuator Pneumatic Peltier**	**Vibration Pressure Impact Temperature**	**3**	**Voice coil: 23mm x 9.5 mm(dia) Pmeumatic: 15 x 15 x 6 mm Peltier: 20 x 20 x 3.3 mm All modules less than 7 g**	

Table 3.1: Comparative analysis of modular haptic devices from different studies, highlighting their actuation methods, types, number of modules, size, and key differences with the proposed work. It can be seen that over actuator is capable of providing a variety of tactile actuation with in a small form factor.

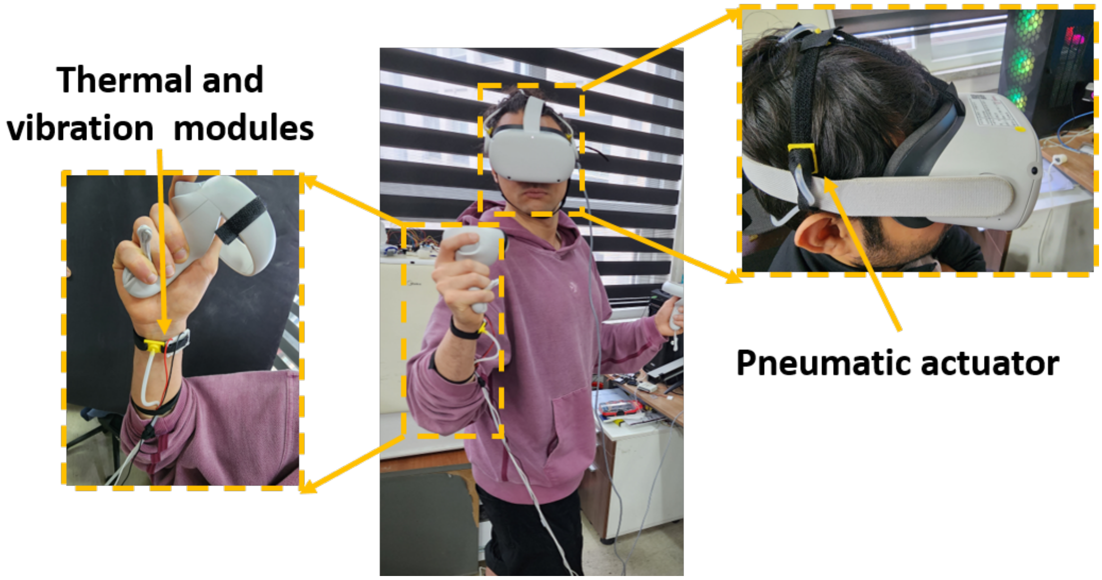

Figure 3.25: Experimental setup showing a participant using thermal and vibration modules on the wrist and a pneumatic actuator on the head during a user study in a virtual reality environment.

3.8.2 User experience study

In order to gauge the practical application and efficacy of the modularized tactile units across real-world scenarios, we conducted a user experience study. This study focused on assessing the subjective experiences provided by the device when deployed in various settings. Specifically, the study examined the device's performance in two distinct scenarios: operational tool use in a virtual reality (VR) environment and a safety training simulation involving falling objects during an earthquake. Detailed descriptions of these scenarios are provided below to illustrate how the integration of different actuation modules can significantly enhance user experience.

Participants The study involved eight participants whose ages ranged from 24 to 30, with an average age of 26.8 years. Notably, six of these participants had previously engaged in studies involving our haptic modules, providing them with a baseline familiarity with the technology used.

Procedure The study was divided into two primary tasks designed to test the effectiveness of the haptic feedback under different conditions:

Tool Operation in VR: Participants engaged with two tools—a drill and a welding machine—within a virtual environment. The initial phase of the task involved operating these tools without any haptic feedback, serving as a control setup. In the subsequent session, haptic feedback from two specific modules—thermal and vibration—was introduced. These modules were strategically attached to the user's wrist to enhance the realism of tool operation. Vibration frequencies of 50 Hz and 100 Hz were used to mimic the sensations typically experienced when using these tools. Additionally, the thermal module alerted users to the overheating of tools—a drill after 10 seconds and a welding machine after 5 seconds—prompting them to cease operation temporarily.

Earthquake Safety Simulation: The second task placed participants in a VR scenario simulating an earthquake. This setup included three impact actuation modules attached to the user's head to mimic the sensation of debris impact during seismic activity. As participants navigated the virtual environment, they could visually and physically experience the effects of the earthquake, including the impact from falling objects simulated by the haptic feedback.

Throughout these tasks, participants wore an Oculus Rift headset to interact with the VR environment, enhancing the immersive quality of the experience. The setup used for this study is depicted in Figure 3.26.

During the pilot study, the observed mean difference between the two conditions was approximately 40, with a standard deviation of $\sigma = 10$. To ascertain whether the number of participants in this study was sufficient, we conducted a power analysis as described by Equation 3.1. This analysis was based on a projected mean difference of 40 between the conditions, which was considered adequate to achieve statistical significance. The standard deviation used in this analysis was $\sigma = 15$. All other parameters were consistent with the original setup of the formula. The power analysis indicated that a minimum of 7.29 participants would be required. Consequently, a sample size of 8 participants was deemed sufficient for the experimental requirements.

Feedback Quesitonnaire Feedback was systematically gathered using a questionnaire adapted from a methodology developed by Fang and Harrison [81]. This instrument was designed to measure participants' perceptions of realism, fun, and immersion within each scenario. Participants provided ratings on a scale from 0 to 100 for each aspect, considering scenarios with only visual feedback and those with combined visual and haptic feedback.

This study aims to elucidate the added value of haptic feedback in virtual environments and training simulations, focusing on how it can enhance the realism and engagement of such experiences. The findings are expected to demonstrate the significant role of tactile feedback in enriching user interactions within diverse virtual settings, thereby validating the design and implementation of our haptic modules.

Results and Discussion The results from the user study, as illustrated in Fig. 3.26 (a) and 3.26 (b), clearly demonstrate the significant impact of integrating visual-haptic feedback into virtual reality scenarios. The participants exhibited a marked preference for the enhanced realism and immersion provided by the combination of visual and haptic feedback compared to visual feedback alone.

To quantify the effectiveness of haptic feedback in the VR experiences provided, we conducted a one-way ANOVA, which identified statistically significant differences in the scores across different feedback modalities. This was complemented by a post hoc pairwise comparison using the Tukey-Kramer method, which was applied to delve into specific differences between the groups. The statistical significance was established at ($p < 0.05$), confirming that the differences observed were indeed meaningful.

In the first task, participants operated tools such as a drill and a welding machine within a VR environment. The introduction of haptic feedback, particularly through thermal and vibration modules, significantly enhanced the user experience. This was evident in the increased ratings for immersion and realism when haptic feedback was added. Participants felt more engaged and reported that the experience was much closer to real-life tool operation. Notably, the vibration feedback mimicking actual tool operation and the thermal cues indicating tool overheating were highlighted as particularly effective. This dual feedback system helped in creating a more intuitive and interactive environment, leading participants to feel more connected to the virtual task at hand.

The realism score, in particular, saw a notable increase from an average of 40 with just visual feedback to nearly 90 when haptic feedback was incorporated. This leap underscores the importance of tactile sensations in enhancing the believability of interactive scenarios. Similarly, fun and

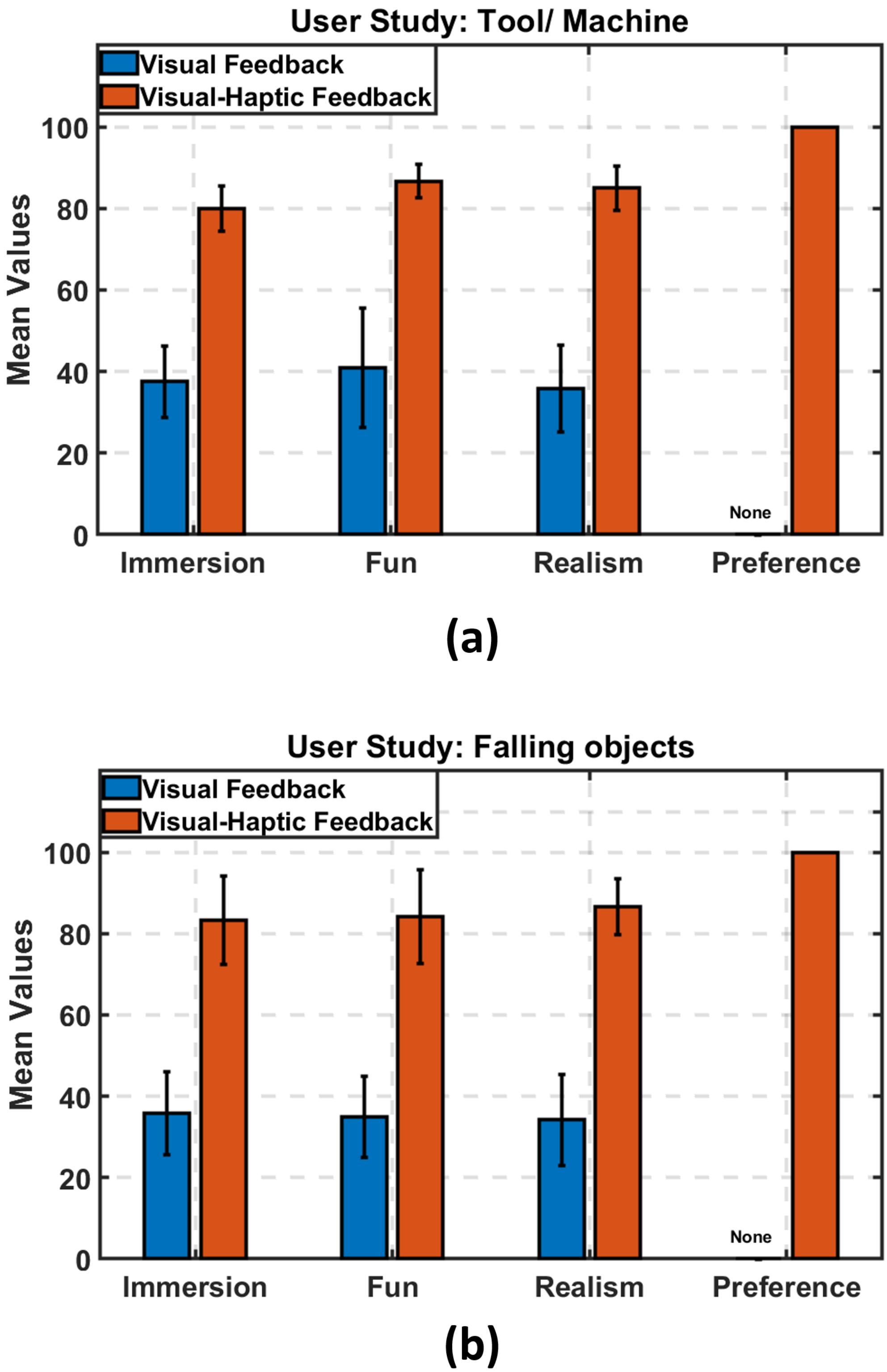

Figure 3.26: User study results comparing the mean values of immersion, fun, realism, and preference between visual-haptic feedback and visual feedback alone in the (a) tool/machine operation scenario and (b) falling objects scenario.

preference ratings were significantly higher with haptic feedback, suggesting that the additional sensory input not only made the simulation more realistic but also more enjoyable.

The second task involved experiencing an earthquake scenario with potential hazards such as falling objects. Here, the impact actuation modules attached to the user's head played a crucial role. These modules provided immediate physical feedback when objects struck the user in the VR environment, significantly enhancing the sense of danger and urgency. The added realism was crucial for safety training applications, where a realistic portrayal of hazards can be vital for effective learning and preparedness.

Participants rated immersion and realism very highly in scenarios with visual-haptic feedback, with scores again nearing the upper limit of the scale. The preference for haptic feedback was unanimous among participants, emphasizing its effectiveness in conveying the physical aspects of an earthquake, such as impacts from debris.

The conclusion of this study emphasizes the potential of the modular haptic setup to enhance user interaction within specific virtual reality scenarios. The participants demonstrated greater engagement and reported an improved experience, which they attributed to the effective integration of visual and haptic feedback. However, it is important to recognize that the current experiment does not fully evaluate the comprehensive capabilities of the modular setup across a broader spectrum of applications.

There is a need for additional research involving thorough user studies that test the modular setup in various configurations and applications. Such studies should investigate the perceptual impacts of employing different haptic modules in diverse patterns and formations. This would allow for a better understanding of the dynamics of haptic sensations and their influence on user perception in more complex scenarios. For example, examining how different patterns of tactile feedback affect user responses during intricate tasks could provide essential insights into optimizing haptic feedback for realistic and effective user interactions.

Expanding the research to include a variety of haptic configurations and more complex interaction scenarios will help to thoroughly assess the effectiveness of the modular haptic systems. This will not only validate the flexibility of the setup but also enhance its application, making it a more useful tool in VR and other digital interaction platforms where realistic tactile feedback is essential.

3.9 General Discussion

The development of modular tactile actuating units, as explored in Chapter 3, represents significant progress in the field of wearable haptic technology. These units enhance digital interactions by providing tailored tactile feedback that can be easily adjusted to fit various scenarios and user needs. This adaptability is crucial in applications ranging from immersive virtual reality (VR) environments to complex training simulators and interactive educational platforms.

One of the key advancements of these modular units is their high degree of versatility. Each unit can be individually tailored and configured to meet specific tactile requirements of different applications, making them suitable for a wide range of digital interaction scenarios. This customization is facilitated by the modular design, which allows for the easy addition, removal, or reconfiguration of tactile elements to achieve desired feedback effects.

The modular tactile actuating units have been designed to closely mimic natural tactile sensations, thereby enhancing the realism and depth of virtual interactions. This is particularly beneficial in VR applications where the realism of the environment greatly depends on the accuracy and authenticity of sensory feedback. By providing nuanced tactile cues that mimic real-world textures and forces, these units significantly improve user immersion and engagement.

Another significant advancement is the scalability of these units. They are designed to be integrated into existing systems with minimal disruption, making them an ideal choice for upgrading current haptic feedback setups. This scalability extends to various applications where customized tactile feedback is beneficial, such as in healthcare for rehabilitation, in automotive interfaces for enhanced driver awareness, and in entertainment for more engaging gaming experiences.

The impact of these modular units on user experience has been validated through rigorous user studies. Participants consistently reported improved satisfaction and a greater sense of presence when interacting with environments equipped with these tactile units. The ability to experience detailed and varied tactile feedback made virtual tasks more intuitive and engaging, bridging the gap between digital simulations and real-world experiences.

In conclusion, the advancements discussed in Chapter 3 not only underscore the technological innovation behind modular tactile actuating units but also highlight their potential where tactile feedback is utilized in digital interactions. As we continue to push the boundaries of what is possible with haptic technology, these modular units stand at the forefront, offering promising solutions for a multitude of applications where enhanced tactile feedback is paramount.

3.9.1 Limitations of our work

While the advancements in modular tactile actuating units detailed in Chapter 3 present significant opportunities for enhancing digital interactions, there are inherent limitations that must be acknowledged and addressed in future research.

One of the primary limitations is the dependency on specific types of actuators. The current designs primarily utilize a limited range of actuator technologies, which may not fully cover the spectrum of tactile sensations required for all potential applications. This limitation restricts the versatility of the modular units, as each type of actuator has inherent characteristics that may not be suitable for all tactile feedback requirements. For instance, some actuators may excel in delivering fine textures but fall short in simulating larger force feedback, which is crucial for applications involving heavy machinery simulation or medical training.

The experimental setups used to validate the effectiveness of these modular units, while comprehensive, were confined to controlled environments and did not fully explore the broader range of real-world conditions that users might encounter. Factors such as varying ambient temperatures, humidity, and long-term wear and tear could significantly affect the performance and durability of the tactile modules. Additionally, the integration of these units into existing systems was not extensively tested outside of usual settings, leaving questions about their performance in diverse operational environments.

One notable limitation of this study involves the custom-designed actuator, specifically the dynamics of the actuation module when the silicon air cell contacts different body sites under varying contact forces. The expansion behaviour of the air cell is critical to the fidelity of the tactile feedback. If the air cell does not expand fully, it could lead to inconsistent haptic sensations. Moreover, the actuator's response time might be affected if the air cell remains in a partially inflated state. These issues are pivotal in understanding the reliability and effectiveness of the actuator in delivering consistent haptic feedback.

Another aspect that requires refinement is the lack of extensive exploration into the psychological impacts of prolonged exposure to modular tactile feedback. The studies conducted focused primarily on short-term user interactions and did not consider long-term effects, such as user fatigue, adaptation to tactile sensations, or the psychological comfort of wearing and using these devices over extended periods. Understanding these aspects is crucial for ensuring the practical usability of modular tactile units in everyday applications, as well as for designing systems that are both effective and comfortable for long-term use.

Addressing these limitations is crucial for the continued development and refinement of modular tactile actuating units. Future work will need to explore a broader range of actuator types, extend testing to more realistic and varied environmental conditions, and deepen the investigation into the long-term psychological and physiological impacts of using such technology. This will help ensure that the benefits of modular tactile feedback can be fully realized across a wider array of applications and user scenarios.

Chapter 4

Concurrent Multimodal Feedback Actuator

The development and integration of haptic feedback technologies in virtual and augmented reality, wearable devices, and interactive systems have revolutionized user experiences, offering more immersive and intuitive interactions. Among the advancements in this domain, multi-modal haptic feedback actuators have emerged as a critical innovation, enabling the simulation of a variety of tactile sensations through a single device. This chapter delves into the intricacies of a novel multi-modal haptic feedback actuator designed to enrich interactive experiences by providing a wide range of tactile feedback, from vibrations and pressures to directional cues, through a singular compact and wearable device.

The exploration and subsequent creation of such a device necessitate a comprehensive understanding of haptic feedback mechanisms, particularly the distinctions and applications of tactile versus kinesthetic feedback. Tactile feedback, focusing on surface sensations such as vibrations, texture, and pressure, offers immense potential for enhancing the realism of virtual interactions. Kinesthetic feedback, on the other hand, involves the perception of movement and force, engaging the user's muscles, tendons, and joints. This chapter, however, concentrates on advancing tactile feedback technology, aiming to overcome the limitations posed by traditional single-modal actuators by introducing a versatile, multi-modal actuator capable of delivering a more complex and nuanced range of tactile sensations.

4.1 overview

The core of this chapter presents the design, development, and evaluation of a pneumatically controlled multi-modal tactile actuator (MMTA), which represents a significant leap forward in wearable haptic feedback technology. The actuator's design is centered around a unique 3D-

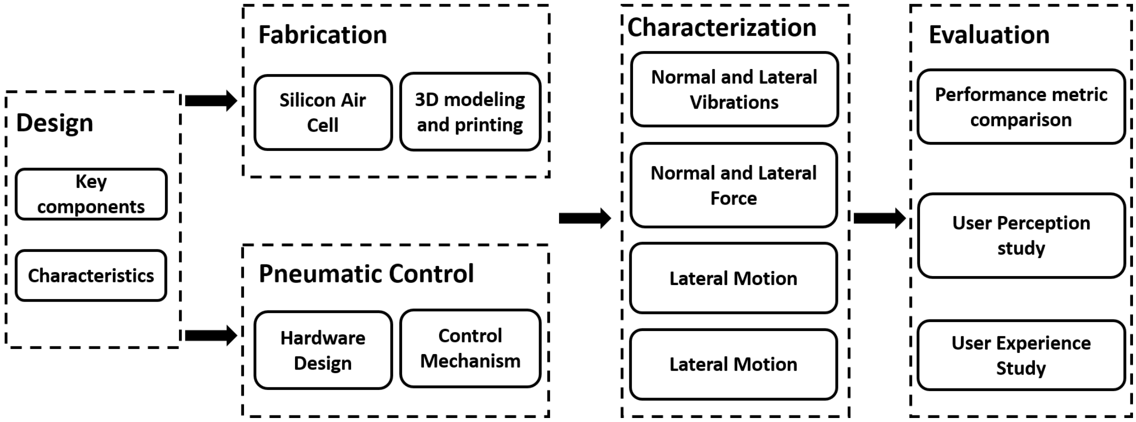

Figure 4.1: Overview of the key components and design framework of the concurrent multimodal feedback actuator.

printed structure housing multiple air chambers, each equipped with soft silicon inflatable air cells. This design enables the actuator to deliver diverse forms of tactile feedback, including but not limited to vibrations (in various directions), static pressure, impact, and lateral force cues, through a single end-effector.

The development process is meticulously detailed, from the initial hardware design and pneumatic system setup to the fabrication of the inflatable air cells and the final assembly of the actuator. Special attention is given to the challenges of integrating multiple actuators in a compact form factor, ensuring wearability and user comfort, and achieving precise and reliable control over the diverse feedback modes.

Subsequent sections provide a thorough examination of the actuator's performance through various measurement experiments and user studies. These include characterization of actuation modes, system response time, and a comparison of performance metrics against existing state-of-the-art devices. Furthermore, the chapter discusses user perception experiments designed to validate the effectiveness of the actuator in delivering distinguishable tactile sensations, as well as a user experience study that highlights the actuator's potential to enhance the interactive experiences in gaming scenarios. Figure 4.1 provides a visual summary of the key components and the overall design framework of the concurrent multimodal feedback actuator, illustrating the integration of various elements discussed in this chapter.

Finally, the chapter encapsulates the significant contributions of the proposed multi-modal

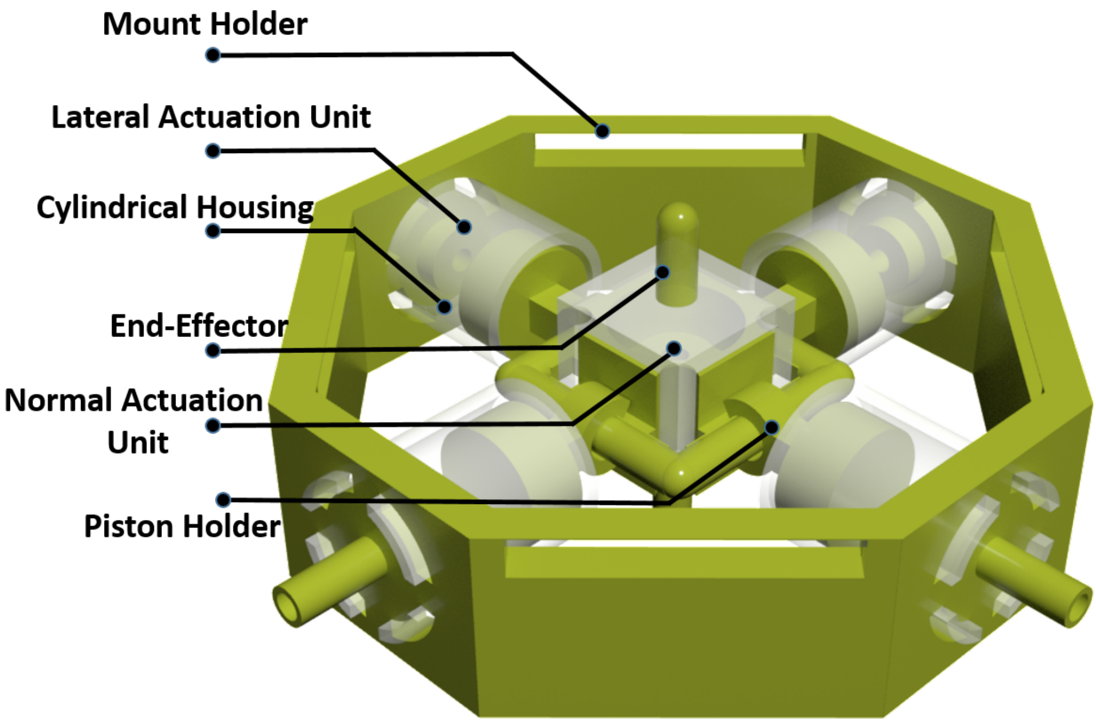

Figure 4.2: 3D Design of Pneumatically controlled Multi-Modal Tactile Actuator (MMTA)

haptic feedback actuator to the field of wearable technology and interactive systems. It underscores the importance of multi-modal tactile feedback in achieving highly immersive and realistic user experiences and outlines potential future applications and directions for research in haptic feedback technology. Through a blend of innovative design, rigorous testing, and user-centric evaluation, this chapter not only presents a novel haptic feedback solution but also sets the stage for further advancements in multi-modal tactile technologies.

4.2 Concept and Design of Actuator

The proposed multimodal haptic device's foundation lies in several criteria essential for wearable haptic technology, such as wearability, usability, and the capacity to deliver strong multimodal feedback with a single end-effector. To incorporate the aforementioned criteria, the proposed device consists of three components; a 3D-printed design, a pneumatically-controlled actuation system, and a soft silicon air cell. This section explains how the proposed solution embodies these pivotal factors.

4.2.1 Hardware Design

The proposed multimodal haptic actuator is shown in Fig. 4.2. The multimodal actuator is designed to provide diverse feedback using a single end-effector. Its octagonal form houses five actuation points (APs), each covered with a soft silicon inflatable air cell. Four of these points are positioned at the edges of the octagonal body called the lateral actuation units (LAUs), while the fifth is located in the centre called the normal actuation unit (NAU). The LAUs are geared towards lateral-directional vibrations and force feedback, while the NAU is tailored for normal-directional vibrations and pressure feedback. The key design aspect in this assembly is that the NAU is the only unit that establishes contact with the user during actuation. It gathers feedback from all other units, includes its normal feedback if required, and delivers it to the user. Such a design enables the deliverance of concurrent multimodal feedback using a single end-effector.

4.2.2 Pneumatic System

Pneumatic actuation holds a prominent position in the field of wearable haptics for delivering haptic feedback [82]. The system's inherent ability to produce substantial pressure levels and execute swift actuation changes establishes it as an effective haptic interface [83–85]. In the present study, we employ pneumatic actuation to establish a multimodal haptic feedback mechanism. This is facilitated by an air cartridge designed to supply pressurized air to the actuating device, managed by a pressure regulator. Considering the user's mobility during wearable application scenarios, a 16-gram CO_2 cartridge would be sufficiently lightweight and portable, allowing for more freedom of movement [86]. It is estimated that such a cartridge can provide a steady air supply for up to an hour in typical interaction scenarios, as noted in [15]. We use electronically controlled solenoid valves, with a response time of 2 ms, to control the rapid pressure change. Figure 4.3(a) and 4.3(b) illustrate the example actuation caused by controlling the solenoid valves.

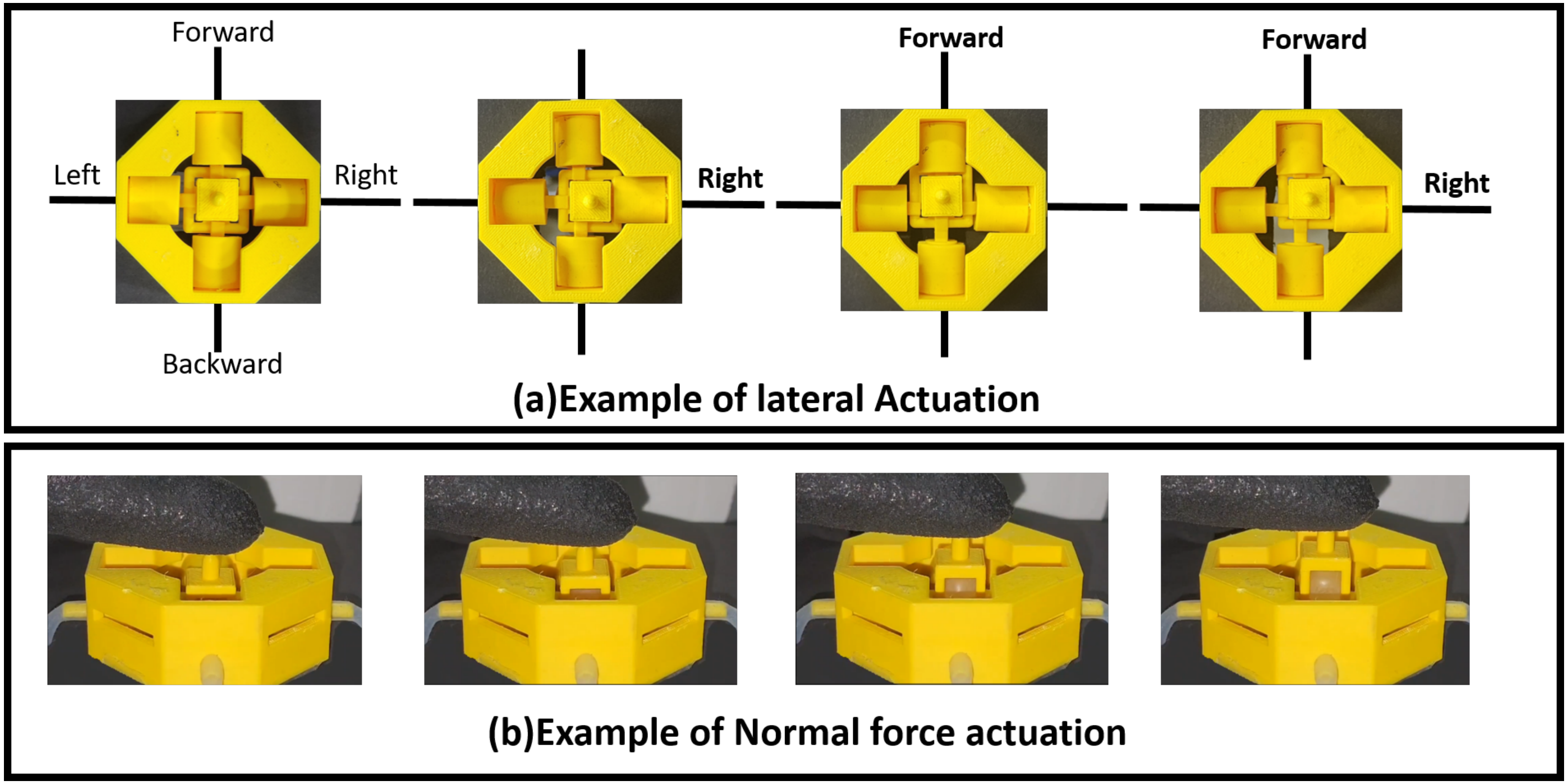

Figure 4.3: (a)Example of actuation in 2D area. The first picture on the left shows the actuator in its default state of no actuation, the second picture shows lateral motion to the right, the third picture shows actuation forward, and the rightmost picture shows right-forward actuation. (b) Example of actuation in the normal direction. The pictures from left to right show increasing normal force as the end-effector moves up.

4.2.3 Silicon air cell

Air from the source cartridge is channelled into specially designed chambers within the device. To facilitate accurate actuation, a design incorporating a soft silicon air cell is used to securely encase all the device's internal air chambers. The fabrication of these silicon air cells employs Ecoflex 00-30(Smooth-on, Inc.). This material, with its resilience and elasticity, has previously proven beneficial in the domain of pneumatic-based haptic feedback mechanisms. Figure 4.4 (c) illustrates the design of the air cell.

4.3 Fabrication Procedure

The creation of the multimodal actuator involved a two-phase fabrication process. The first phase involved 3D printing the components required for the device. The subsequent phase focused on the creation of soft silicon inflatable air cells. The procedures for each are detailed below.

4.3.1 3D Modeling and Printing

The two main components of the design are the NAU and the LAUs. Their details are provided below.

Normal Actuation Unit (NAU): This unit adopts a cubical form, further augmented with a rail-like structure that extends from its sides as shown in Fig. 4.4(a). A cylindrical groove, with dimensions of 6 mm in diameter and 5 mm in height, was incorporated to house the air. An air channel, attached to this cavity, ensures a steady flow of air from the inlet valves.

Lateral Actuation Unit (LAU): This unit is distinguished by its octagonal form. Four of its sides house the APs, each of which is connected to air channels, mirroring the configuration explained above (Fig. 4.4(b)).

While both the NAU and LAU have independent actuation capabilities, they can be connected for integrated feedback. To achieve this, supplementary components were designed and 3D printed: a cylindrical housing, a piston-shaped holder, and an end effector. The cylindrical housing is aligned with the four LAUs and directs the pneumatic actuation in a linear path. The

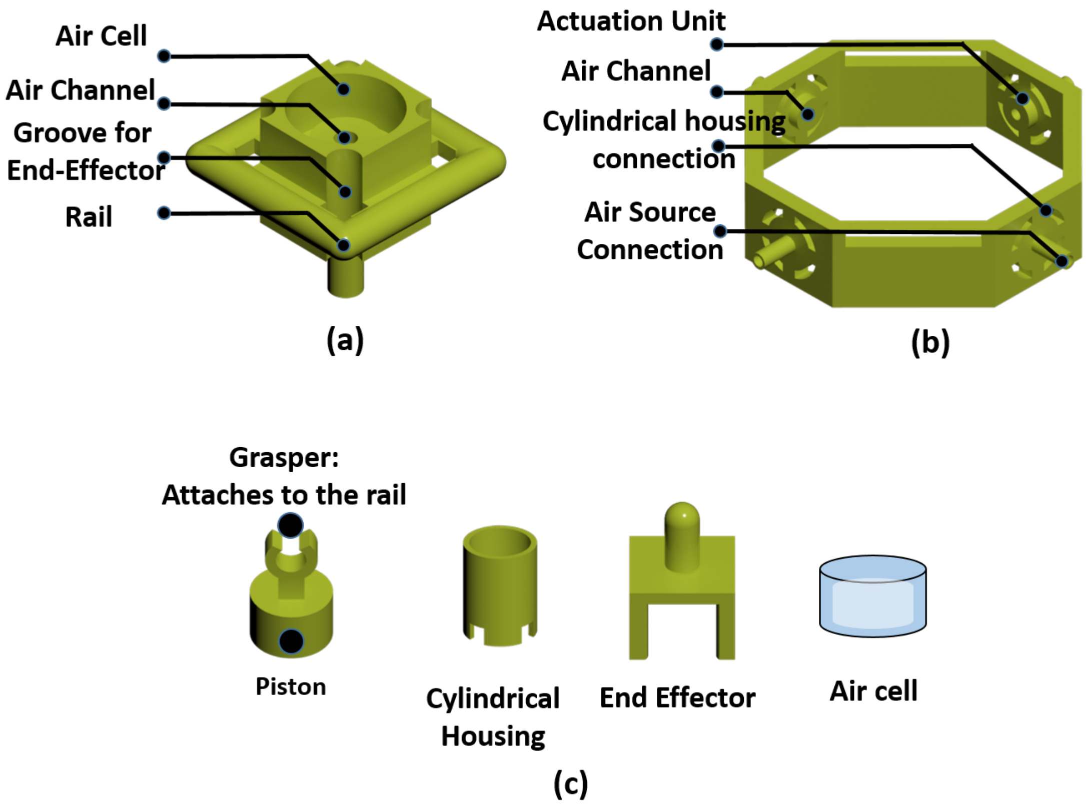

Figure 4.4: (a) Normal Actuation Unit (NAU), (b) Lateral Actuation Unit (LAU), (c) Components used to form the complete actuator

piston-shaped holder slides along the rails of the NAU and operates within the confines of the cylindrical housing. This mechanism ensures that the initiation of pneumatic actuation transmits motion feedback to the piston holder, which in turn transmits linear motion to the NAU. The end effector serves to convey feedback to the user. Its design allows for smooth movement along the corners of the NAU, making it responsive during normal actuation and stable during lateral actuation. Fig. 4.4(c) presents the remaining component designs.

The complete set of components was produced using a Zortrax M200 3D printer, utilizing ABS plastic as the fabrication material.

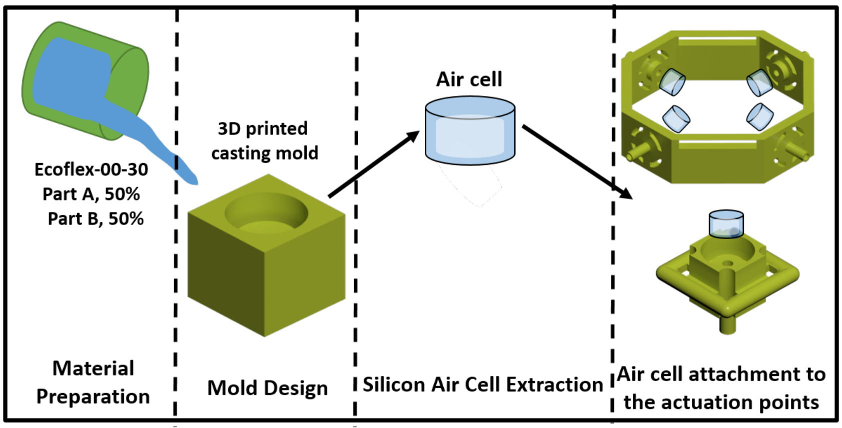

Figure 4.5: Fabrication procedure of the Air Cell

4.3.2 Fabrication of the Inflatable Air Cell

This air cell is tailored to fit the cylindrical groove in the NAU and LAUs. The fabrication is carried out in a series of steps. The following sections explain each step in detail.

Mold Design: A casting mold was crafted using the 3D printer. This mold aimed to ensure the air cell's dimensions were ideal for compatibility with both the NAU and the LAUs. The mold's 3D model and its integration with NAU and LAUs are depicted in Fig. 4.5.

Material Preparation and Air Cell Formation To fashion the stretchable silicon air cell, we employed Ecoflex 00-30 (Smooth-on, Inc., Young's modulus of 0.1694 Mpa at 10 Psi). This material comprises two components: Parts A and B. These were amalgamated in equal measures. Once the components were thoroughly mixed, the resultant material was decanted into the casting molds for NAU and LAUs. These were then left to set for approximately 4 to 5 hours, to form the stretchable silicon air cells.

Integration of Air Cells Once set, the silicon air cells were gently taken out from their molds and glued to each actuation point. This ensured the air chamber was entirely enveloped by the silicon air cell, creating the ideal environment to generate pressure upon inflation. The detailed procedure, starting from the fabrication of the air cell to its attachment with the 3D printed components, resulting in the creation of the multimodal pneumatic actuator, is showcased in Fig. 4.5.

4.4 Control Mechanism

The actuator's haptic feedback is primarily driven by modulating the air pressure within the air chamber at the actuation points. Two DC micro solenoid valves (Fspump, Model: 0520D, Voltage: 6V) are integrated into each AP. These are the positive valve, which controls air inflation, and the negative valve, responsible for air deflation.

Each valve is conjoined to a 2-to-1 Y-shaped hose connector in parallel. The opposite end of this connector attaches directly to the AP. The air source engages one end of the positive valve, with its other end being connected to the AP via the Y-shaped connector. One end of the negative valve links to the AP, drawing air from the chamber and releasing it into the environment through the other end, which reduces the chamber's pressure. The overall pneumatic actuation control system is illustrated in Fig. 4.6

To cater to the five APs, a total of 10 solenoid valves (comprising five positive and five negative valves) were used. Given the digital controllability of these valves, a custom circuit board with MOSFET transistors is designed according to instructions given in [57] This board acts as an intermediary between the input channels of the microcontroller (Arduino Uno board) and the solenoid valves. The input channels send 'on' and 'off' commands to each solenoid valve, facilitating precise control. The valve control unit is illustrated as a block in Fig. 4.6.

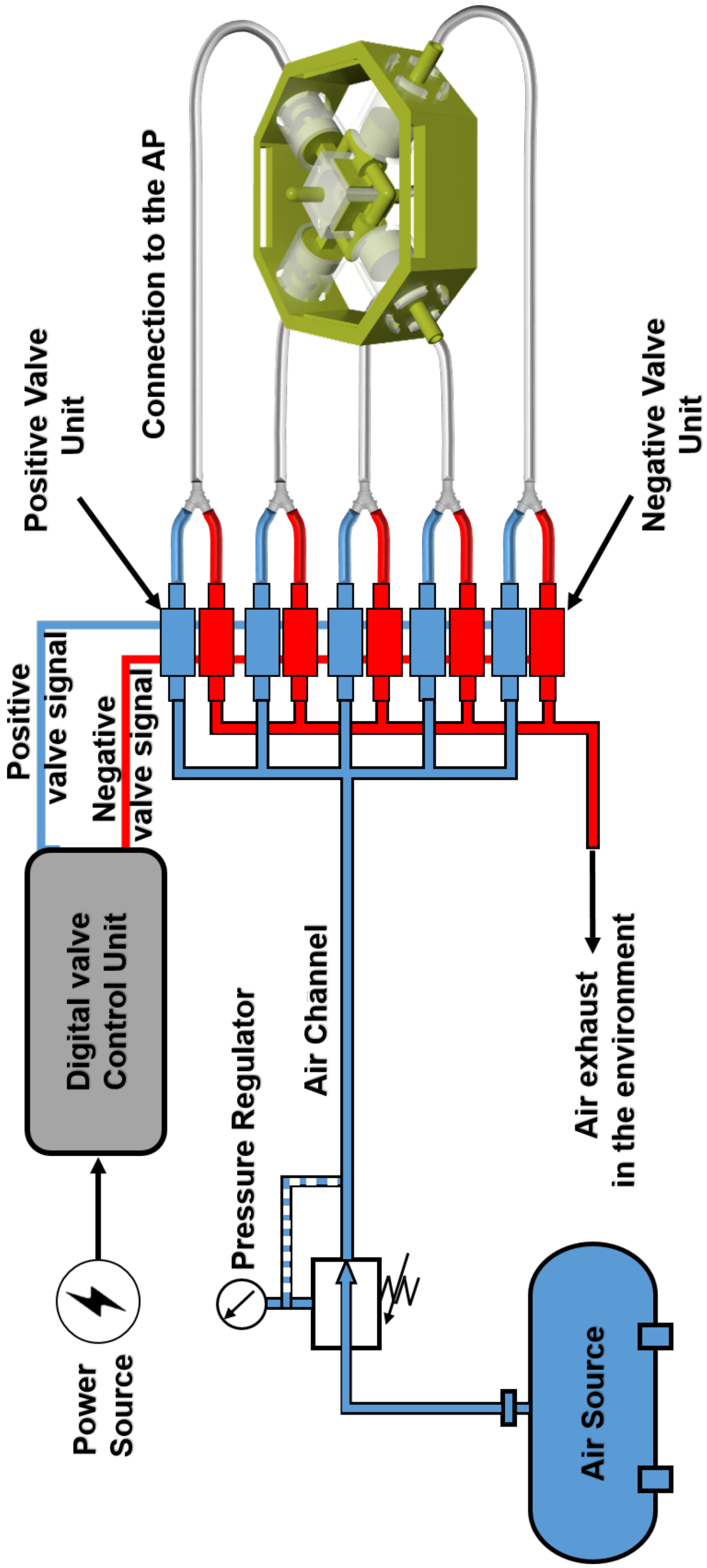

Figure 4.6: Pneumatic Actuation Control System

Various control strategies have been employed to yield specific haptic effects using the proposed multimodal haptic actuator explained as follows.

4.4.1 Vibration Control

Each actuation point's paired positive and negative valves enable either normal or lateral vibration control. The method initiates by briefly opening the positive valve and then closing it. Once the chamber is saturated with air, the negative valve is opened and closed to evacuate the chamber's air. This cycle, when perpetually executed, simulates a vibration sensation. By modulating the valve's opening span and duty cycle, the vibration's frequency and amplitude can be adjusted. Fig. 4.7(a, b) depicts this vibration control approach for rendering a signal with a 50 Hz frequency.

4.4.2 Pressure and Impact Feedback Control

The silicon air cell retains pressures up to 10 psi. Two distinct pressure effects can be generated. The first, termed static pressure, involves a sustained opening of the positive valve, followed by its closure, entrapping air and establishing a consistent pressure effect. By subsequently opening the negative valve, the chamber's pressure is reduced, reverting the actuator to its primary state. Fig. 4.7(c) illustrates an example of valve control for pressure feedback

The second method, called impact feedback, is realized by swiftly opening the positive valve, followed by its closure and the immediate opening of the negative valve, rendering an instantaneous impact sensation. Fig. 4.7 (d) illustrates the control mechanism for impact feedback.

4.4.3 Lateral Motion and Position Control

Lateral motion control capitalizes on the four APs. Unique movement patterns can be derived either by singular actuation point control or a combined approach. For instance, to initiate a leftward signal, the right actuation point's valve is activated. Compound motions, such as diagonally, necessitate synchronized control of multiple APs. This is explained in Fig. 4.7(e).

Position control requires the synchronized operation of two APs. If the end effector has to traverse a short forward distance, the valves of both the back and front APs must be activated sequentially, with a time interval between activations. The rear valve must be activated first for a set duration, propelling the end effector forward. Subsequently, the forward actuation valve activates as resistance and halts the end effector at a designated location. This control mechanism is illustrated in Fig. 4.7(f). It is to be noted that the percentage values in 4.7(f) are shown as a reference to understand valve state control duration for a pair of valves involved in position control.

4.4.4 Multimodal Feedback Control

The integrated digital control unit is designed to issue commands that target each AP independently. This intricate level of control provides the user with the capability to produce the activation of several APs concurrently, creating a rich multimodal feedback experience. Consider a scenario where a user desires to produce a specific haptic effect that combines both normal pressure and lateral vibrations. In such a case, by harnessing the control mechanisms illustrated in Fig. 4.7(b) and 4.7(c), the intended synchronized action can be adeptly achieved.

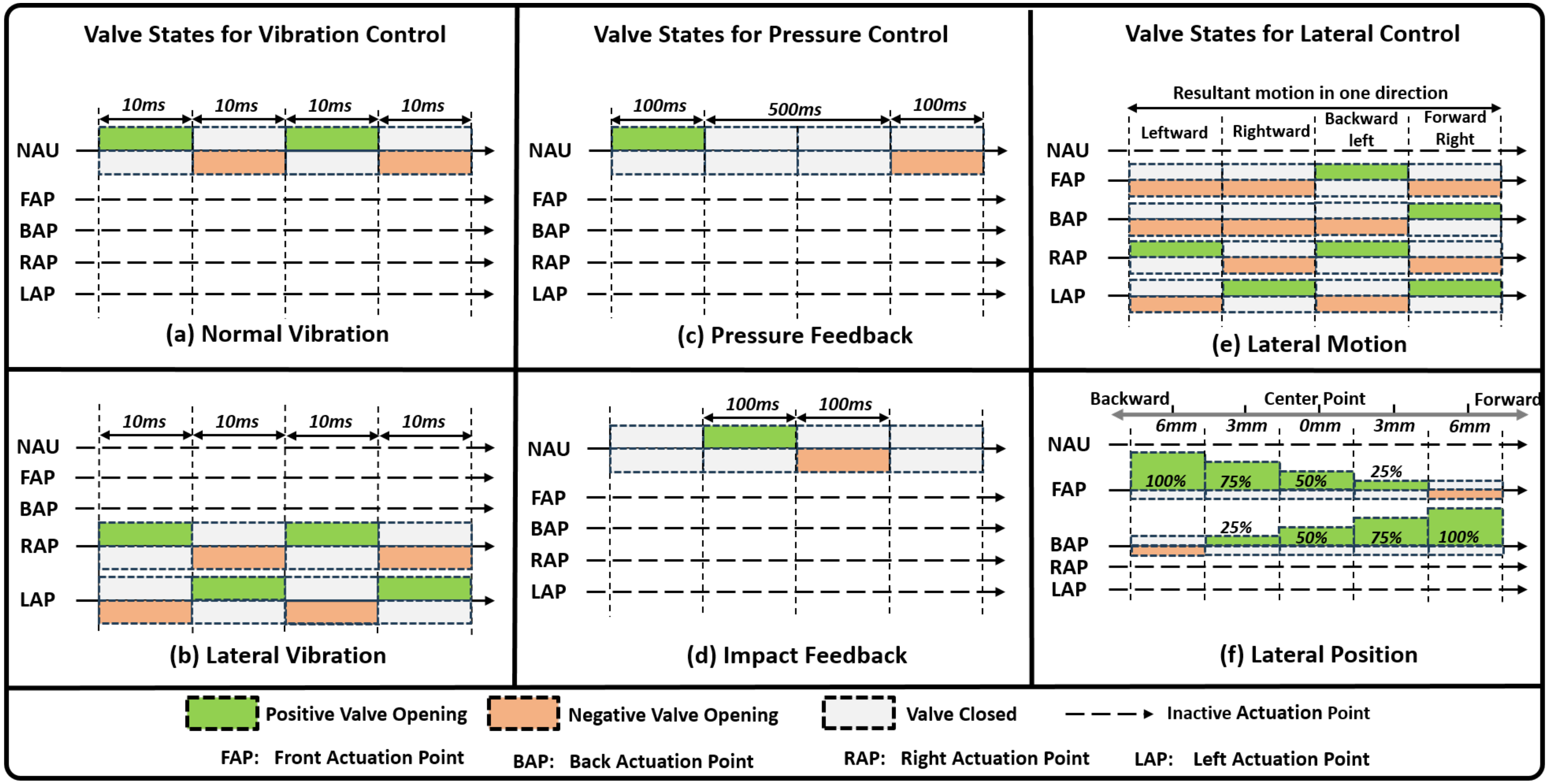

Figure 4.7: Valve control mechanism to produce different modes of actuation

4.5 Characterization of Actuation Modes

The primary actuation modes of the device are examined by conducting a series of measurement experiments. Separate measurement setups are designed for each actuation mode. The following subsections detail each actuation mode.

4.5.1 Vibration Feedback Measurement

The device can render vibration feedback in both normal and lateral directions. The valve control mechanism, shown in Fig. 4.7(a), explains an example of a valve control setup to render vibration with a specific frequency. The acceleration response of the rendered vibrations was measured under the combination of different pressure levels and vibration frequencies.

Measurement Procedure: To measure the acceleration response from the actuation, the accelerometer, ADXL335 GY-61, was attached to the NAU (illustrated in Fig. 4.8). The acceleration data was recorded using a data acquisition unit (NI-DAQ 6009), and Matlab was used to store the data on the PC. During measurement, the vibration frequency ranged from 1Hz to 250 Hz with a gradual increase in the step sizes of frequency to analyze the response. In addition, each frequency level was commanded at 3 different pressure levels, i.e. 5, 7.5 and 10 psi, adjusted with a pressure regulator. Each data measurement was done for 5 seconds at 1 KHz. The sensor's reading was calibrated before each measurement.

Result and Discussion: The result of vibration acceleration measurement for different frequencies is provided in Fig. 4.9. It can be observed that the acceleration of the vibration signal drops with the increase in the signal frequency. This pattern persists across all set pressure levels, both in normal and lateral directions. Specifically, the acceleration values range between 3.15 g (20 Hz at 10 psi) and 0.15 g (250 Hz at 5 psi) in the normal direction. On the other hand, the lateral measurements change from 2.05 g (20 Hz at 10 psi) to 0.19 g (250 Hz at 7.5 psi). Importantly, the vibration acceleration produced at varying frequencies surpasses the threshold for human perception of vibrations, with even the smallest measured acceleration, that is, 0.15 g or 1.47 m/s^2 at 250 Hz and 5 psi, remaining above the sensitivity limit [87–89]

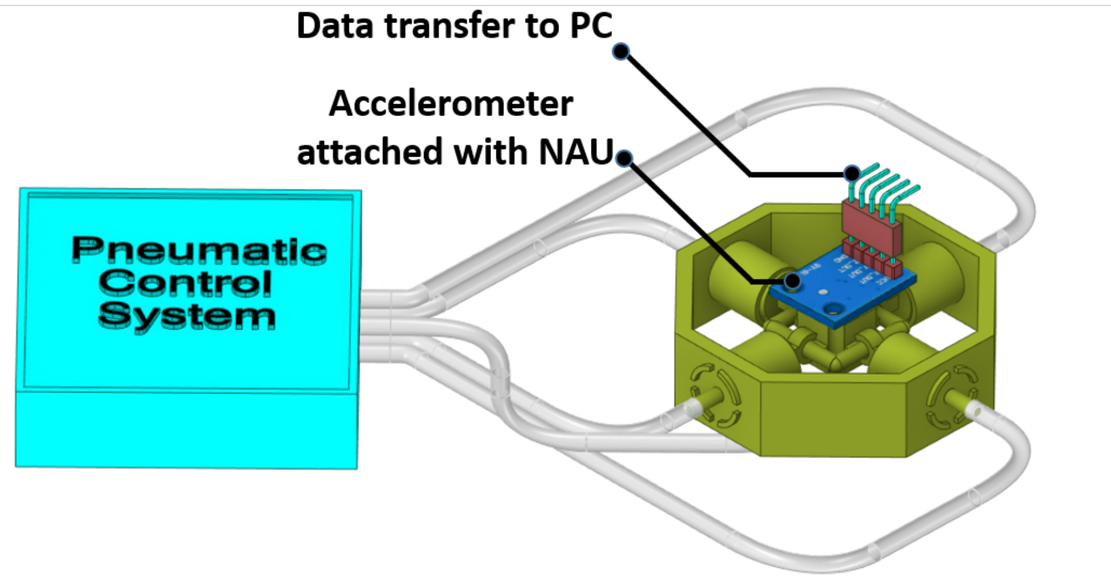

Figure 4.8: Acceleration measurement setup

In order to verify if the rendered vibration signal truly rendered the targeted frequency, a sample vibration data is recorded of a signal rendered with 100 Hz frequency at 7.5 psi. Fig. 4.10 (a) shows the recorded signal in the time domain while Fig. 4.10 (b) shows the corresponding frequency spectrum. The system rendered a 100 Hz frequency signal with a minor error of 1% as the recorded signal showed a peak at 99 Hz.

Vibrations below 20 Hz at 10 psi were not recorded in the normal direction due to concerns about damaging the silicon air cell due to prolonged exposure to high pressures. However, lesser pressures of 5 psi and 7.5 psi did not pose the same harm and were used for low-frequency vibrations. This adverse effect was not observed in the lateral direction, as the cylindrical housing combined with the piston-shaped holder adeptly absorbed and transmitted all linear motion to the NAU. Furthermore, during the experimental phase, it was discerned that lateral vibrations capped at 150 Hz (at 5 psi) as a rapid change in pressure failed to induce noticeable vibrations in the apparatus.

In summary, the pneumatic control setup is capable of producing high-amplitude acceleration vibrations. However, it is important to note that the current setup utilizes a manual pressure regu-

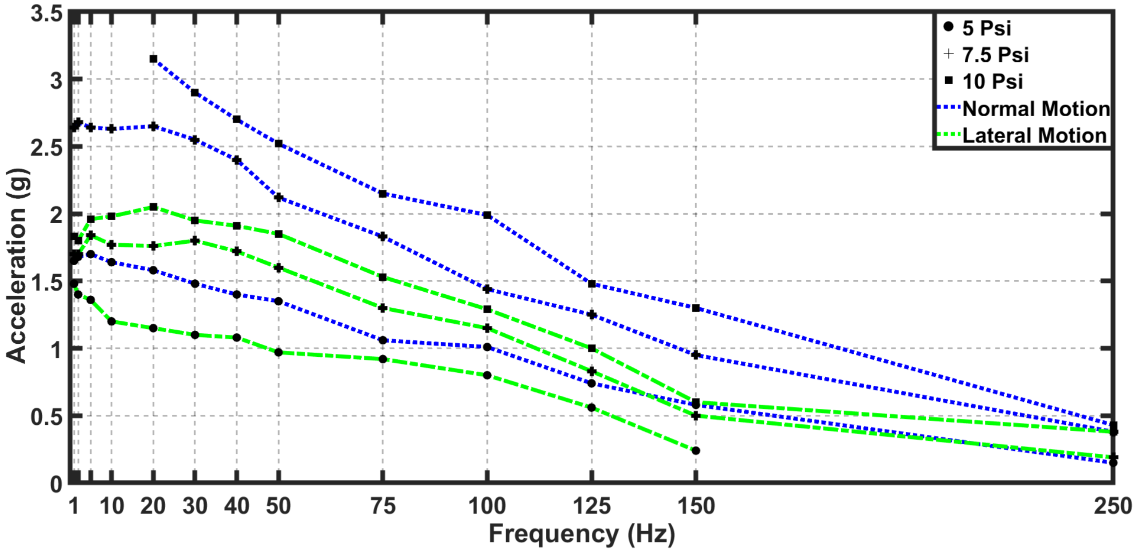

Figure 4.9: Valve control mechanism to produce different forms of actuation

lator, restricting vibration amplitude adjustments to manual changes only. Replacing this with an electronically controlled pressure regulator would allow for precise automated control over vibration amplitudes. Data collected at various pressure levels reveal a consistent relationship between input pressure and vibration amplitude, suggesting a potential avenue for developing an automated system to control vibration amplitude in pneumatic setups.

4.5.2 Pressure Feedback Measurement

NAU and LAUs are responsible for normal force(pressure) and lateral force feedback. In the case of normal force rendering, the valve control mechanism is shown in Fig. 4.7(b). For lateral force rendering, the valve opening mechanism is similar as explained in Fig 4.7(b), however, the direction of motion in lateral space is controlled by the valve opening patterns in Fig. 4.7(d).

Measurement Procedure: To measure the force output of the device, a force sensor (Wenzhou SF20) is used. The device was placed in two different setups to measure the normal force and lateral force. For normal force, the sensor is placed right above the actuation point as illustrated in Fig. 4.11 (a). The data was recorded for 3 pressure levels i.e. 5, 7.5, and 10 Psi. For each pressure level, the air pressure inside the air cell was changed by opening the positive valve from

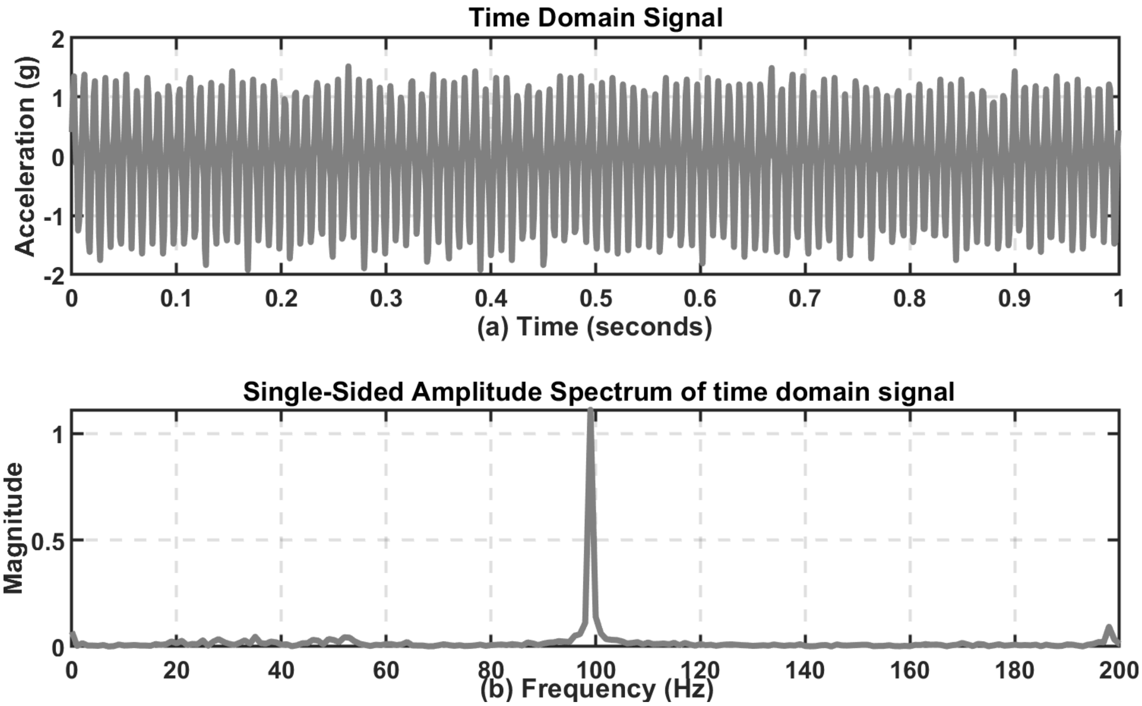

Figure 4.10: Time domain and respective frequency spectrum of the 100 Hz signal rendered at 7.5 psi

0 to 250ms with a step size of 10 ms. At each step size, a static pressure was generated in the air cell, and the data was recorded. This measurement procedure was repeated 3 times and the data points were averaged for each step size.

For lateral force measurement, a 3D-printed module was attached with NAU (illustrated in Fig. 4.11 (b)), so that the force from the lateral APs could be transferred to the force sensor. During measurement, the same pressure levels were used. The goal was to measure the maximum force in 2 directions i.e. lateral, and diagonal, based on the pressure levels. Therefore, force data at each pressure level were recorded in each direction. The pressure inside the air cell was maintained for recording the data. The same pressure levels and step size are used for normal force.

Result and Discussion: Figure 4.12 depicts the relationship between the force magnitude and the duration of valve opening. As anticipated, there's a direct correlation between the force output and the duration for which the valve remains open. For the initial 100 ms, there's a noticeable change in force output across all three directions. This rapid force increase tapers off by 150 ms

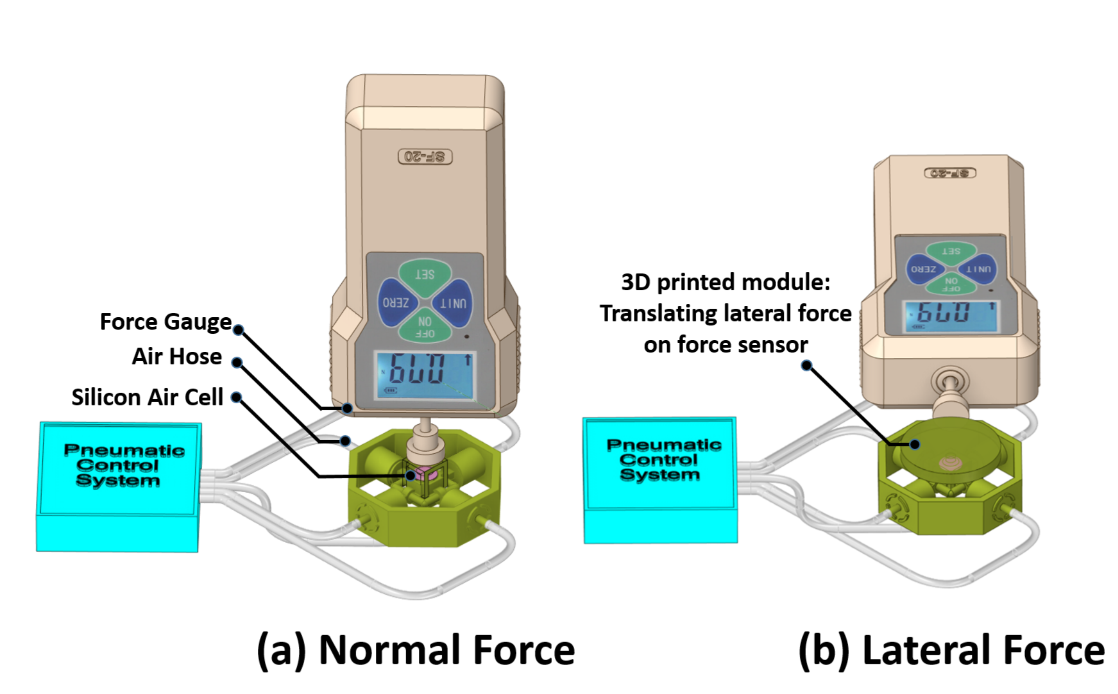

Figure 4.11: Force measurement setup

and saturates, maintaining a near-constant force until 250 ms. The peak force observed is 8.3N (with a valve opening of 250 ms at 10 psi) in the normal direction. Yet, there's a risk of damaging the silicon air cell if the solenoid valve stays open beyond 250 ms at an input pressure of 10 psi. Hence, the safest maximum force that can be achieved is approximately 8 N in the normal direction. Nevertheless, the output force of 8 N is still well within the range suitable for a variety of applications involving haptic feedback [58].

It must be noted that the response time of the solenoid valve is 2 ms in the pneumatic control system. The force control of the system is dependent upon the input pressure and the solenoid valve opening duration. Considering the solenoid valve requires at least 2 ms to open, the finest resolution of control you can achieve is bounded by this minimum actuation time. This is except for scenarios involving lateral force at 5 psi and 7.5 psi, which necessitated valve openings of 5 ms and 3 ms, respectively, to achieve a consistent force variation. Within the transient time phase, the force resolution varies from 0.02 N to 0.11 N depending on the input pressure and direction of motion. Complete details of force resolution are provided in the Table 4.1.

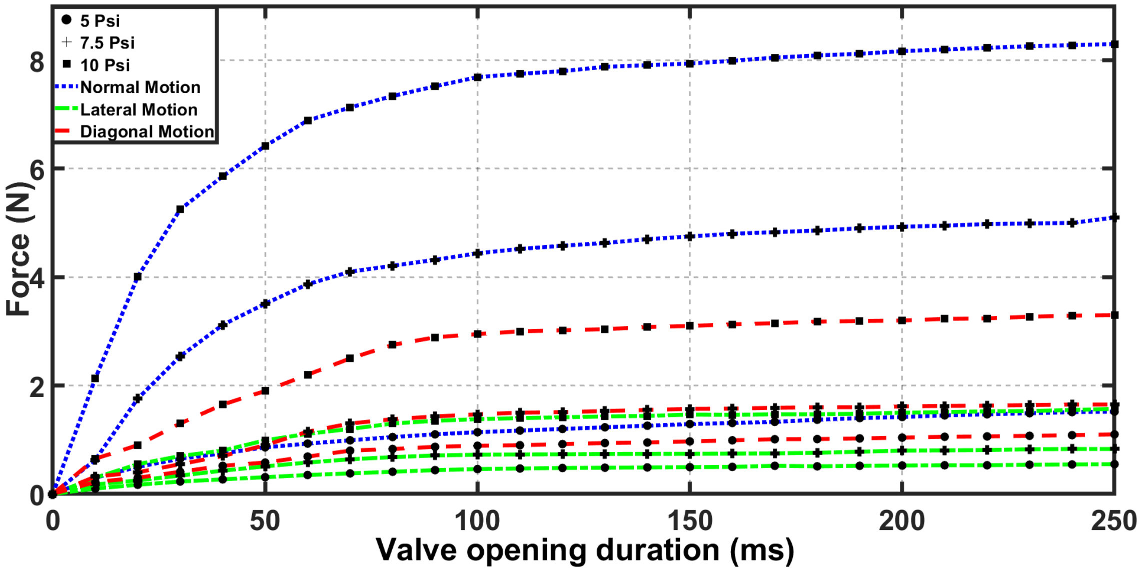

Figure 4.12: Force measurement against positive valve opening duration

The overall measurement experiment shows that the actuator's static output can be controlled with time delay input to the solenoid valve opening. Beyond static output, these time delays can also be controlled dynamically to render the dynamically changing output of the actuator. The dynamic output can be controlled by an algorithm where the time delay of the rendered signals can be stored/logged to measure how much force has been registered into the device already, and how much more time delay is needed to reach the targeted output force.

4.5.3 Lateral Motion

One of the key features of the device is its ability to guide the end effector laterally. Fig. 4.7 (e) depicts the mechanism of valve regulation for attaining this sideways movement. Through this mechanism, users can direct the end effector toward a particular path by managing the input pressure and the duration of a solenoid valve's opening. Further description of the position control process is discussed in the subsequent sections.

Measurement Procedure: In the process of lateral motion control, one solenoid valve introduces air, propelling the end effector to generate a linear shift. Simultaneously, its opposite solenoid valve delivers air to exert a counteracting force, thereby constraining the extent of the

Direction	Pressure (Psi)	Force Resolution (N)	Valve opening duration (ms)	Transient time (ms)
Lateral	5	0.02	5	90
	7.5	0.02	3	90
	10	0.03	2	90
Diagonal	5	0.02	2	70
	7.5	0.04	2	70
	10	0.06	2	70
Normal	5	0.02	2	90
	7.5	0.07	2	60
	10	0.11	2	60

Table 4.1: Force resolution w.r.t. different direction of actuation and minimum valve opening time during transient time phase

shift. The degree of displacement can be managed by adjusting the time delay of each solenoid valve's activation. To monitor the positional variation in the end effector, the activation delay for the solenoid valves was sequentially adjusted between 0 ms and 12 ms in increments of 3 ms. Displacement measurements were conducted using a dial calliper. The resolution of the slide calipper was 0.01 mm. The data for each positional variation was recorded five times and the rounded mean of the displacement was calculated. The pressure input was maintained at 10 psi during the measurement.

Results and discussion: Table 4.2 displays the results of the changes in position that took place upon manipulating a pair of solenoid valves situated in opposing directions, utilizing various combinations of time delays. Notably, the device achieved a displacement spanning 12 mm, implying a peak shift of 6 mm on either side from the central point with a standard deviation in the range of 0.18 mm. Straightforwardly, diagonal movement can be achieved by regulating all four APs, each with distinct time delays.

It's worth admitting that this assessment was specifically concentrated on the effect of valve control for lateral motion or force, not on the precise control of the end-effector's position. Open-loop travel distance control may not work under different lateral resistances caused by contact between the end-effector and the user's skin, which even changes under different normal direction pressures.

FAP valve opening (ms)	12	12	12	12	9	6	6	9	6	3	0
BAP valve opening (ms)	0	3	6	9	6	6	9	12	12	12	12
Distance (mm)	6	4.48	2.26	0.75	1.49	0	1.47	0.76	2.24	4.51	6
Standard deviation (mm)	0	0.18	0.12	0.07	0.1	0	0.1	0.08	0.12	0.17	0
	Backward Motion					**Center**	**Forward Motion**				

Table 4.2: Displacement measurement based on controlling a pair of valves. Data measured at a set pressure of 10 psi.

4.5.4 System's Response Time

The actuation delay is a critical factor in pneumatic systems, directly affecting the quality of perceived haptic feedback. This section examines the response time of the proposed pneumatic system.

Measurement Procedure: The system's response time was determined by sending a step signal to the actuator and monitoring the acceleration response using the setup illustrated in Fig 4.8. The procedure involved activating the positive valve for 100 ms to generate a distinct impact, followed by a 100 ms activation of the negative valve to reset the actuator. Acceleration data was captured at a frequency of 1 kHz, and the delay between the initiation of the step signal and the onset of acceleration was calculated.

Results and Discussion: The response time, as shown in Fig. 4.13, indicated an approximate delay of 10 ms from the step signal to the start of acceleration. This response time is influenced by several components, including the reaction time of the electronic valves, the pressure of the air source, and the hose's physical attributes [15, 90, 91].

The rapid response time of the proposed actuator can be attributed to three key factors. First, the solenoid valve's minimal latency, notably 2 milliseconds, ensures swift control over the valve states. Second, the CO_2 tank's high-pressure gas facilitates rapid air movement through the hose, allowing the system to react promptly to actuation commands. Finally, the thin soft silicone air cell is designed for rapid actuation as soon as it is filled with air.

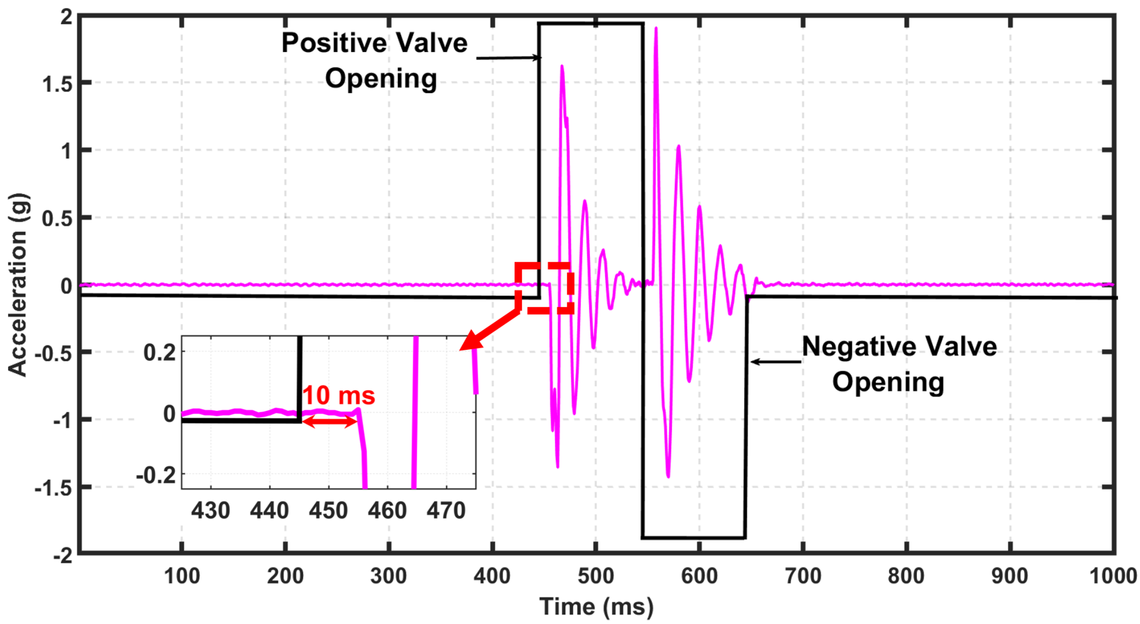

Figure 4.13: System's response time measurement result.

It is to be noted that a delay of 10 ms is imperceptible. For visual-tactile stimulation, the perception of temporal delay depends upon the sequence of stimulus presentation, whether visual or tactile stimuli are presented first. Research has shown that the perception threshold of temporal delay during a visual-tactile rendering event ranges from 27 ms to 71 ms [92, 93]. Hence, a 10 ms delay can be considered perceptually negligible in the presentation of visual-tactile stimuli.

4.5.5 Performance metrics comparison

The device's performance was assessed by evaluating its principal attributes and comparing them with those reported in similar research. The comparison focused on several key aspects: normal and shear forces, and vibration acceleration in both normal and lateral orientations. The presence of simultaneous actuation and the range of frequency bandwidth were also considered. Features that are absent in the compared studies are indicated as 'N/A' for not available. Meanwhile, features that are acknowledged by the reference study but lack any empirical characterization are marked as 'NR', which stands for not reported.

Table 4.3 presents a comparison of various tactile devices based on several performance metrics and characteristics. The proposed pneumatic actuator stands out with its capacity for simultaneous actuation and a wide frequency range of 1-250 Hz, matching the upper limit of Talhan et. al. [15] pneumatic actuator. It also shows a significant improvement in maximum output force with 8.3 N normal force and 3.3 N shear force, which is higher than any other pneumatic actuator listed. It's worth mentioning that the proposed device is comparatively heavier at 25 g than some actuators, however, all the lightweight actuators were not able to achieve higher performance in comparison to the proposed actuator.

The ability to provide simultaneous actuation is a key feature that may enable more complex haptic feedback, and this feature is only present in two devices listed, including the proposed actuator. In terms of actuation method, pneumatic systems seem to dominate, except [34] and [94], which use DC motors, indicating a variation in the design approach to achieve tactile feedback. The proposed device provides a robust range of capabilities, suggesting that it might be better suited for applications requiring a more dynamic haptic response.

Study	Actuation	Form Factor		Simultaneous Actuations	Max Output				
		Size	**Weight**		**Normal Force**	**Shear Force**	**Normal Vibration**	**Lateral Vibration**	**Frequency Range**
Kanjanapas [35] (2019)	Pneumatic	48.8 x 48.8 (mm)	150 g	No	1 N	N/A	N/A	N/A	N/A
Yoshina [42] (2019)	Pneumatic and DC motor	113 mm diameter 30mm height	82 g	**Yes**	1.3 N	0.47 N	NR	NR	NR
Zhakypov [40] (2022)	Pneumatic	40 x 20 (mm)	13.7 g	No	7N	1.3N	NR	NR	1 - 64 Hz
Talhan [15] (2019)	Pneumatic	100 mm length	4.5 g	No	6.3 N	N/A	2.2 g	N/A	1-250 Hz
Pezent [34] (2022)	DC motor	50 x 30 x 15 (mm)	120 g	No	**15N**	1.2 N	NR	N/A	0-15 Hz
Thai [94] (2020)	DC motor	**12 mm diameter 2mm height**	**4.3 g**	No	N/A	1.8 N	N/A	N/A	N/A
Proposed	Pneumatic	55 x 55x 20 (mm)	25 g	**Yes**	8.3 N	**3.3 N**	**3.15 g**	**2.05 g**	**1 - 250 Hz**

Table 4.3: Performance comparison of the proposed work with the available state-of-the-art related works. (N/A: Not Available, NR: Not Reported)

4.6 User Perception experiment

In section 4.5, the device's performance is estimated with a series of measurement experiments. The device is found to be able to render strong lateral cues and vibrotactile feedback e. However, to confirm the effectiveness of this quantitative observation, a user perception experiment is designed. The main goal of this experiment is to identify if the users can easily identify the difference between lateral cues and vibration signals rendered with different frequencies.

4.6.1 Participants

A total of 15 participants (Thirteen males and two females) took part in the perception experiment. Their age ranged from 25 to 34 with an average of 29.06. All the participants were healthy and fit to take part in the experiment. An informed consent was also obtained for taking part in the experiment from each participant.

4.6.2 Procedure

The perception experiment was meticulously designed to assess the efficacy of lateral and vibration feedback mechanisms. Initially, participants were introduced to lateral cues in four distinct directions: forward, backward, right, and left, applied to the forearm. The device's attachment was precisely oriented to intuitively correspond with the user's body: forward towards the hand, backward towards the elbow, right towards the thumb, and left to the opposite side. This setup aimed to provide clear and distinguishable directional cues through the movement of the end-effector along specified paths.

In addition to lateral cues, the experiment evaluated vibration feedback through the presentation of three different signal frequencies: 40 Hz, 80 Hz, and 120 Hz. This component was designed to test participants' ability to discern variations in frequency, further contributing to our understanding of sensory perception under varying vibratory conditions.

The experimental setup was calibrated with specific attention to the input pressures and contact forces to ensure consistent delivery of stimuli while maintaining participant comfort. Lateral cues were administered with an input pressure of 10 psi and a normal contact force of 1 N, whereas

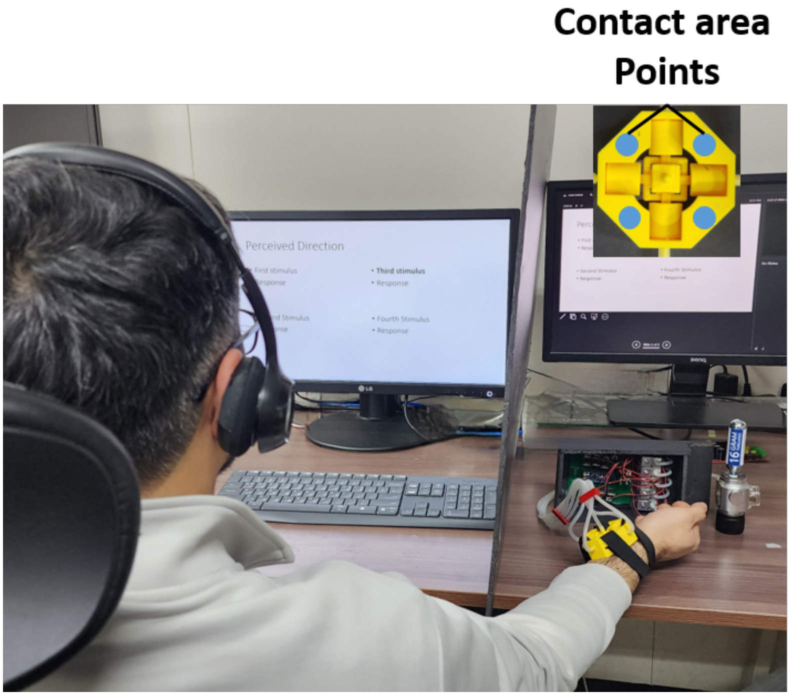

Figure 4.14: A participant taking part in the experiment. The contact area is also highlighted creating no contact force between the body site and the end-effector when attached to the body.

vibratory feedback was provided at a slightly reduced pressure of 7.5 psi. To prevent direct contact between the device's end-effector and the participant's skin, a contact area is integrated into the design, as shown in Fig 4.14. The depth of the contact area is higher than the end-effector, therefore, in rest condition the end-effector hovers just above the skin and not in contact.

Before the commencement of the experiment, participants underwent a comprehensive briefing session, accompanied by a practice session aimed at acquainting them with the haptic cues. This preparatory phase was essential for familiarizing participants with the experimental environment and ensuring accurate response collection. During the experiment, the lateral actuation point was pressurized by opening the valve for 150 ms and the cue was presented for 2 seconds, after which participants were asked to identify the cue's direction. To eliminate potential biases and ensure the reliability of responses, the presentation order of the cues was randomized, and participants were given the option to request a repetition of any cue. Following the lateral cues, participants were subjected to vibration stimuli, where they were asked to match a test stimulus with one of three subsequent stimuli in a similar randomized fashion. This methodology, encompassing a total of 105 trials across all participants, was employed to gather a dataset for analysis.

Figure 4.14 shows the experimental environment. The participants wore headphones with white noise to remove environmental noise. The forearm attached with actuation was rested on a table, and a visual barrier was introduced between the participant's vision and arm so that the participant could focus only on the instructions and the stimulus presented.

4.6.3 Results and discussion

The results, shown in Fig 4.15, clearly show that all the participants showed 100% accuracy for vibration feedback. This explains why the participants were able to feel the difference between the presented stimuli. On the other hand, for lateral cues, the overall perception accuracy for identifying lateral cues was 88.33%. The highest and lowest individual accuracy from the participants were found 100% and 50% respectively. While the majority of the participants were able to recognize the lateral cue accurately.

In the experiment, higher accuracy was achieved possibly due to the lateral housing as it guides the inflation of air cell and converts all the pressure into linear translation. Additionally, the end-effector stays in stable contact with the skin when the lateral cue is rendered. In haptic literature, it is found that the perception of tangential force increases as the magnitude of applied normal force as an analysis was conducted on the perceived magnitude of shear force between 0.1 N to 0.7 N [95]. Kanjanapas et al. reported that a shear force of 0.23N applied on the user's forearm with just 1 mm displacement allows users to perceive the direction of lateral stimulus [35]. During the perception experiment, the lateral cues were rendered at around 1.7 N shear force, which is quite higher than the human perception range and helped to achieve accurate user response.

4.7 User Experience Study

To evaluate the effectiveness of the developed haptic device and its integration in real-world scenarios, we conducted a study focusing on the subjective experiences of users. This study involved participants who interacted with the device in a gaming environment.

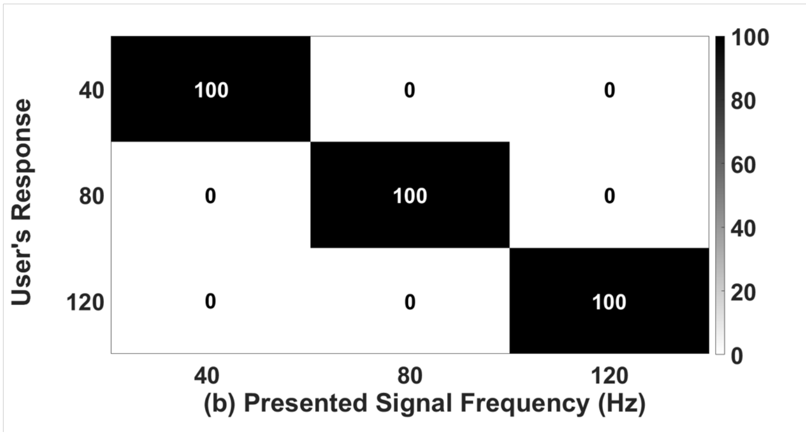

Figure 4.15: Confusion matrix showing results for (a) Direction Classification and (b) vibration classification

4.7.1 Participants

The study comprised 15 individuals (twelve males and three females), with an average age of 28.75 years (ranging from 26 to 33 years). None of the participants reported any physical impairments that could affect their ability to participate in the experiment. Before participating, all individuals were provided with a detailed explanation of the study's nature and objectives. Informed consent was obtained from each participant, ensuring they understood the procedures and their rights.

Figure 4.16: Subjective experiment scenario: A participant playing a game while the proposed device is attached to the wrist

4.7.2 Procedure

The study utilized a first-person shooter (FPS) game scenario created in Unity3D to assess the device's performance and compare it with conventional gameplay experiences. The participants were asked to use a mouse to control the gun and shoot the targets present in the scene. The device was attached to each participant's wrist using a Velcro strap. To ensure an immersive experience and minimize external distractions, participants were provided with headphones to block outside noise. The evaluation environment is shown in Fig. 4.16.

Three different gameplay modes were presented: 1) Audio-Visual (AV) feedback, 2) Audio-Visual with single Haptic (AVSH) feedback, and 3) Audio-Visual with Multi-modal Haptic (AVMH) feedback. In the AV mode, participants experienced the game with standard audio-visual feedback. The AVSH mode added single-impact feedback from NAU upon firing a gun, simulating the gunshot impact. The AVMH mode provided combined haptic feedback; impact from the NAU and short burst lateral motion effect from the two LAUs mimicking the gun's recoil effect. The order of these modes was randomized for each participant to reduce any potential bias.

4.7.3 Feedback Questionnaire

The study aimed to evaluate various aspects such as the quality of feedback, user experience, and device response time. The questionnaire was designed based on the guidelines from standardized tools for assessing game and haptic experiences [96, 97]. It included six questions, three of which focused on feedback quality, addressing immersion, sensory and imaginative (S & I) feedback, and expressivity. Two questions explored user engagement and experience enhancement during gameplay. The final question assessed the flow of the game in different modes to gauge the system's response time. Participants rated their responses on a Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree). Additionally, they were given the opportunity to provide general feedback about their experience. The factors with descriptions presented to the participants in the feedback questionnaire are shown in Table 4.4.

For this experiment, a 15% mean difference between two conditions was considered sufficient to demonstrate statistical significance, as determined by our pilot study. The standard deviation was set at 7% for this analysis. To verify the adequacy of the participant count for this study, we conducted the previously described power analysis using Equation 3.1. A mean difference of 15 between the conditions was presumed adequate to achieve statistical significance. For the current experiment, the standard deviation (σ) was approximately 7. All other parameters remained consistent with those specified in the formula. The power analysis indicated that a minimum of 11.28 participants would be required. Consequently, recruiting 15 participants was deemed sufficient for the experimental needs.

4.7.4 Results and discussion

Participant feedback was aggregated and assessed by computing the mean of the Likert scale scores for all factors within each experimental condition. The outcomes of this assessment are shown in Fig. 4.17. In this figure, the bar graph illustrates the average scores participants assigned on the Likert Scale, while the accompanying error bars represent the standard deviation of these scores. It is evident from the graph that the device's AVMH mode (mode 3) outperformed other modes across most of the individual factors. To further examine the data, a one-way analysis of variance (ANOVA) was employed to determine both the mean values and the statistical disparities

Sr.	Factors	Description
1.	**Immersion:**	The gameplay helped me to focus on the task
2.	**Sensory and Imaginative Feedback:**	The feedback received helped in visualizing and experiencing the game's environment more intensely.
3.	**Expressivity:**	The gameplay helped me distinguish what was going on.
4.	**Experience:**	The feedback provided by the game improved my overall experience
5.	**Engagement:**	I felt connected to the game's actions
6.	**Flow:**	I experienced a smooth progression of game activities.
7.	**General Comments:**	

Table 4.4: The psychophysical experiment's factors and corresponding descriptions were presented to participants during the evaluation.

across the different conditions. This was complemented by a post hoc pairwise comparison test applying the Tukey-Kramer method to analyze specific differences.

The analysis showed that the modes incorporating haptic feedback (AVSH and AVMH) were statistically significantly ($p < 0.05$) better than conventional gameplay systems in all individual factors, except *Flow*. It should be noted that the lack of statistical difference ($p > 0.05$) for the factor *Flow* confirmed that the participants found the proposed device's actuation was well connected with the user's actions while playing the game with AV feedback. For all other factors, the data indicated a clear preference among users for the multimodal haptic feedback, as it appeared to enrich their gameplay experience. In addition to quantitative data, qualitative feedback was also gathered. One participant commented, ”This particular feedback (referred to as mode 3) felt better and I enjoyed it while playing the game”. Another participant commented, ”I prefer playing games with special effects (mode 3) generated by the device than the other modes”

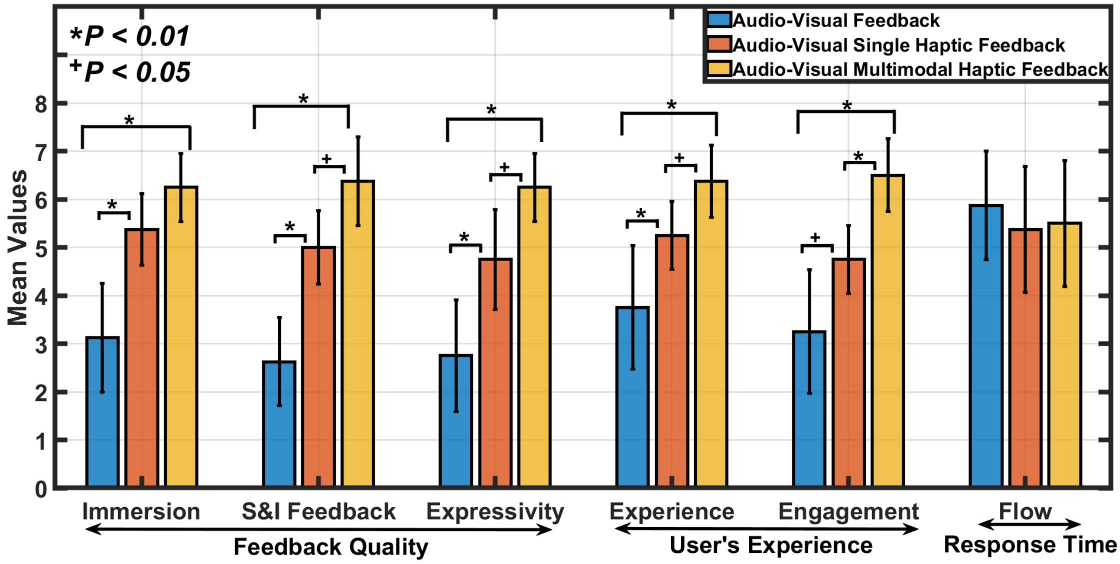

Figure 4.17: Psychophysical Evaluation Result. The audio-visual feedback didn't have any haptic sensation. In the audio-visual single haptic feedback, impact feedback was rendered upon firing bullets from a gun, while in audio-visual multimodal haptic feedback, the impact feedback along with a lateral motion to mimic the firing of the bullets along with the gun's recoil effect

4.8 General Discussion

Chapter 4 details the development and implementation of a concurrent multimodal feedback actuator, representing a notable progression in haptic technology. This actuator enables the simultaneous delivery of multiple types of tactile stimuli, allowing for the emulation of complex real-world interactions more effectively than prior technologies. By integrating pressure, vibration, and shear feedback into a single device, it offers an immersive user experience that enhances virtual environments for applications ranging from professional training to interactive entertainment.

The primary objective of the work was to render different types of haptic feedback through a single end-effector. As explained in Section 4.5, the actuator's characterization showed its ability to deliver diverse tactile sensations, a capability further affirmed by the user perception experiment. This experiment, designed to determine users' ability to differentiate between lateral cues and vibration frequencies, validated the actuator's effectiveness in providing distinct tactile feedback.

The actuator's design enables simultaneous actuation from all the APs, which are controlled independently. This feature is important in rendering multimodal tactile feedback effectively. The results from the subjective evaluations further support the success of the actuator in achieving its intended purpose. Participants in the study consistently reported that the AVMH feedback significantly enhanced their interactive experiences. We particularly note that the higher scores in the factor *expressivity* confirm that the multiple feedback added a significant level of detail to their in-game actions. These positive responses from the participants show the potential of the actuator.

The integration of this technology into virtual reality systems has demonstrated substantial improvements in user performance and satisfaction. By providing nuanced feedback that can replicate the texture, temperature, and resistance of virtual objects, users can perform tasks with greater precision and confidence. This has profound implications for professional training environments, where realistic tactile feedback is essential for skill acquisition and error reduction.

In summary, the advancements discussed in Chapter 4 not only demonstrate the feasibility and versatility of the developed multimodal actuator but also highlight its potential to revolutionize the way we interact with and through digital interfaces. These developments contribute significantly to the broader adoption of sophisticated haptic technologies across a range of practical applications, setting a new benchmark for immersive and interactive systems.

4.8.1 Limitations of our study

Despite the notable advancements detailed in Chapter 4, the development and implementation of the concurrent multimodal feedback actuator come with several limitations and challenges that need to be addressed to fully realize its potential.

The reliance on pneumatic systems, while effective, introduces complexity in the control mechanisms necessary to achieve precise and reliable tactile feedback. The size and noise associated with pneumatic components can detract from the overall user experience, potentially limiting the actuator's use in settings where discretion and portability are critical. Therefore, optimizing these systems to minimize their impact on user comfort and device portability will be crucial in enhancing the practical application of the actuator in various environments.

While the actuator is designed to be ergonomic, prolonged use could still lead to discomfort or fatigue, particularly in sensitive body areas [98]. The current design may not fully account for the wide variability in individual user anatomy and personal sensitivity, which can affect the effectiveness of the haptic feedback and overall user experience. Continuous ergonomic improvements are necessary to ensure the actuator is comfortable for a broader user base and suitable for long-term use.

Although the actuator is capable of providing complex tactile feedback, there is still a gap between the simulated sensations and real-world tactile experiences. The fidelity of feedback, particularly in terms of simulating textures and fine tactile nuances, remains a significant challenge. Enhancing the realism of feedback without overly complicating the device will require innovative approaches to tactile sensation simulation and may involve the development of new materials or actuation technologies.

The long-term psychological effects of continuous exposure to artificial tactile stimuli have not been fully explored. Issues such as sensory adaptation, where users become desensitized to haptic feedback, or psychological discomfort associated with artificial sensations, need thorough investigation [99–102]. These aspects are crucial for ensuring that the actuator does not inadvertently reduce user engagement or effectiveness over time.

To overcome these challenges and maximize the actuator's potential, future research should focus on miniaturizing the pneumatic components to reduce noise and increase portability. Additionally, expanding the actuator's adaptability to various body sites and interaction types through adjustable and more ergonomic designs will enhance its practicality and user acceptance. By addressing these challenges, the next iterations of the multimodal actuator can achieve broader applicability and user acceptance, paving the way for more immersive and realistic interactive digital experiences.

Chapter 5

Conclusions and Future Directions

In this section, we conclude our contribution and provide future research directions.

5.1 Conclusions

This thesis has greatly improved haptic technology by enhancing how users interact with digital systems through advanced tactile feedback. It started with a thorough review of the existing state of haptic technologies, identifying important gaps and limitations in providing high-quality tactile feedback in virtual and augmented reality environments. This review showed the need for haptic systems that are more flexible, scalable, and engaging, and which can be integrated smoothly into different digital interfaces without compromising user comfort or system ease of use. The creation of modular tactile actuating units and a new multimodal actuating device marks a major step forward in creating complex tactile sensations, which are key to making virtual interactions more realistic.

The first goal of this research is to design and validate modular tactile actuating units capable of delivering versatile and customizable tactile feedback. These units should be easy to configure and adaptable to various body sites and interaction scenarios, providing users with personalized tactile experiences. This development includes the creation of modular units that can be easily integrated or reconfigured depending on specific application needs, from virtual reality (VR) environments to physical rehabilitation tools.

The second goal focuses on the development of a novel multimodal actuating device that can provide complex tactile feedback through a single end-effector. This device aims to seamlessly integrate multiple types of tactile feedback, such as pressure, shear, and vibration, to simulate realistic physical interactions. The challenge is to engineer a solution that maintains high fidelity and responsiveness without compromising the compactness and ergonomics of the design.

A critical aim of this thesis is to use the developed haptic technologies to enhance the realism and immersion of user interactions within digital environments. This goal involves conducting extensive user studies to validate and refine the haptic feedback systems, ensuring they effectively enhance user engagement and overall experience. These studies will help determine the systems' success in improving the authenticity and sensory richness of virtual environments.

Lastly, the research seeks to explore the broader applications and scalability of the developed haptic technologies. This includes investigating the potential integration of these systems into various sectors such as safety training, entertainment, etc. An important aspect of this goal is to assess the adaptability of the technology to different use cases.

In summary, the advancements made through this research greatly enhance the field of haptic technology, paving the way for more interactive and engaging VR experiences. As the use of haptic interfaces expands to include training, education, entertainment, and more, the contributions of this thesis focus on making digital interactions richer and more lifelike, thereby setting the stage for the future of human-computer interaction in VR and beyond.

5.2 Future Research Direction

This thesis has made significant progress in advancing haptic technology, yet, like any pioneering research, it introduces new questions and avenues for further exploration. This section outlines potential future research directions that could address the existing limitations and expand upon the foundation laid by this work.

Performance Evaluation and Dynamic Interaction Scenarios: One of the primary limitations of the current research is the evaluation of the custom-designed pneumatic actuator under static conditions only. Future research should focus on rigorous performance evaluations of the actuator in dynamic interaction scenarios. For instance, the actuator's force output was assessed straightforwardly by inflating and deflating the silicon air cell. Further studies should explore scenarios where the air cell is pre-inflated—examining how additional pressure affects the force output and the system's response time. Such detailed examination will help understand the actuator's behaviour under varied operational conditions, ensuring the delivery of realistic feedback across diverse application scenarios.

Tailoring Actuator Settings for Body Site Specificity Current user study assessed the performance of the actuator when placed on the wrist. The design of the actuator incorporates a velcro strap, which allows for its application to various parts of the body. If the actuator is positioned in different locations such as the leg or neck, the resultant sensory experience may vary due to the unique vibratory thresholds and considerations of comfort at each site. Therefore, it is crucial to tailor the actuator's settings to each particular location to achieve the intended sensory feedback. However, except for the human hand, which displays an increased sensitivity compared to other regions, the tactile sensitivity across various body sites tends to show a comparable level of perception [74, 103, 104]. This uniformity in sensitivity suggests that the standardization of input parameters is feasible, simplifying the process of calibrating the actuator for different body parts.

Optimization of Control Systems: The current setup uses several components that are shared across all modules, presenting an opportunity for optimization. Future efforts should aim to develop a unified control strategy tailored for each module to streamline operations and improve efficiency. This approach would simplify the control landscape, allowing for seamless operation of all actuating modules under a unified system. Advances in control technology could significantly enhance the performance consistency and integration of tactile modules, broadening their potential applications in digital interactions.

Advancements in Air Supply Systems: The existing control setup relies on an air tank to provide a continuous air supply, akin to a battery. While effective, this system requires periodic replacement. An intriguing line of investigation would be the integration of digitally controllable high-performance air pumps that could maintain consistent pressure without compromising response times. Such advancements could revolutionize the control setup, making it more efficient and less reliant on external air supply sources.

Comprehensive User Experience Studies: Although the current actuating modules have been evaluated through user experience studies, these have only scratched the surface of their potential. Future research should involve more comprehensive studies that place or present haptic cues in varied formations. This would allow researchers to fine-tune how users perceive and react to different tactile sensations under varied circumstances. Expanding user studies could provide deeper insights into the practical applications of the modules, enhancing user interaction and realism.

Exploration of Complex Perceptual Effects and Illusionary Tactile Effects: Building on the initial user studies, there is ample scope to explore complex perceptual effects such as tactile summation and spatial masking within the modularized actuating setup. Future research could delve into how different modules can be synchronized to create immersive experiences that mimic real-world interactions authentically. This could lead to the discovery of innovative perceptual effects, enhancing the versatility and applicability of the modular solutions in creating convincing and engaging user experiences.

By addressing these areas, future research can significantly expand the capabilities and applications of modular haptic systems, continuing to push the boundaries of what is possible in haptic technology.

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Appendix A

List of Publications

International Journal Papers:

[1] **Ahsan Raza,** Waseem Hassan, and Seokhee Jeon. ”Pneumatically Controlled Wearable Tactile Actuator for Multi-Modal Haptic Feedback.” IEEE Access (2024). **[IF 3.9]**

[2] Waseem Hassan, **Ahsan Raza**, Abdullah, M., Hashem, M. S., and Seokhee Jeon. ”HapWheel: Bringing In-Car Controls to Driver’s Fingertips by Embedding Ubiquitous Haptic Displays into a Steering Wheel.” IEEE transactions on intelligent transportation systems, 23(10), 18526-18534. **[IF 8.5]**

[3] **Ahsan Raza**, Waseem Hassan, Tatyana Ogay, Inwook Hwang, and Seokhee Jeon. “Perceptually correct haptic rendering in mid-air using ultrasound phased array.” IEEE Transactions on Industrial Electronics 67, no. 1 (2019): 736-745. **[IF 8.235]**

[4] Joolekha Bibi Joolee, **Ahsan Raza**, Muhammad Abdullah, and Seokhee Jeon. ”Tracking of flexible brush tip on real canvas: silhouette-based and deep ensemble network-based approaches”. IEEE access, 8, 115778-115788. **[IF 3.9]**

[5] **Ahsan Raza**, MS Hashem, and Seokhee Jeon. “Perceptual Characterization and Evaluation of Modularized Tactile Actuators for Wearable Haptic Application.” IEEE Transactions on Haptics (**Submission Ready**). **[IF 2.9]**

[6] MS Hashem, **Ahsan Raza,** Seokhee Jeon, ”Pneumatic Multi-mode Silicone Actuator with Localized Active Cold Thermal Feedback” IEEE Transactions on Multimedia. **[Submission Ready] [IF 7.3]**

[7] Waseem Hassan, Mudassir Ibrahim Awan, **Ahsan Raza,** and Seokhee Jeon, ”Haptic Perception of Force Profiles: A Data-Driven Approach to Quantifying Human Interaction with Car Doors” IEEE Transactions on intelligent transportation systems. **[Submission Ready] [IF 8.5]**

Patent:

[1] **Ahsan Raza,** Waseem Hassan, Abdullah, M., Jeon, S., “Apparatus for controlling electronic function module in the vehicle using steering wheel with dual ubiquitous haptic sensor(듀얼 유비쿼터스 햅틱 센서가 적용된 스티어링 휠을 이용한 차량 내 전장제어 장치).” South Korean patent 1022757610000, registered July 5, 2021.

[2] **Ahsan Raza,** MS Hashem, Jeon, S., “물속을 걷는 듯한 역감을 제공할 수 있는 햅틱 댐핑 신발.” South Korean patent. **(Submitted)**

International Conference Papers:

[1] Awan, Mudassir Ibrahim*, **Ahsan Raza*,** and Seokhee Jeon. ”DroneHaptics: Encountered-Type Haptic Interface Using Dome-Shaped Drone for 3-DoF Force Feedback.” In 2023 20th International Conference on Ubiquitous Robots (UR), pp. 195-200. IEEE, 2023.

[2] **Ahsan Raza** Muhammad Abdullah, Waseem Hassan, Arsen Abdulali, Aishwari Talhan, and Seokhee Jeon. “Painting Skill Transfer Through Haptic Channel.” In International AsiaHaptics conference, pp. 66-68. Springer, Singapore, 2019.

[3] Talhan, Aishwari, Hwangil Kim, Sanjeet Kumar, **Ahsan Raza**, and Seokhee Jeon. ”Pneumatic actuated haptic glove to interact with the virtual human.” In Haptic Interaction: Perception, Devices and Algorithms 3, pp. 213-215. Springer Singapore, 2019.

[4] Abdullah, Muhammad, **Ahsan Raza,** Yoshihiro Kuroda, and Seokhee Jeon. ”Drone Based Kinesthetic Haptic Interface for Virtual Reality Applications.” In Haptic Interaction: Perception, Devices and Algorithms 3, pp. 210-212. Springer Singapore, 2019.

[5] Abdullah, Muhammad, Waseem Hassan, **Ahsan Raza**, and Seokhee Jeon. “Haptic Logos: Insight into the feasibility of digital haptic branding.” In International conference on human haptic sensing and touch enabled computer applications, pp. 696-708. Springer, Cham, 2018.

International Conference: Non-refereed Papers/ Posters/Demonstrations:

[1] Waseem Hassan, **Ahsan Raza,** Abdullah, M., Jeon, S., “Friction Wheel: Bringing in-Car Controls to Driver’s Fingertips by Embedding Dual Ubiquitous Haptic Friction Displays into a Steering Wheel.” Student innovation challenge, World Haptics conference 2019. **[Best Student Innovation Challenge Award]**

Domestic Conference Papers:

[1] **Ahsan Raza,** and Seokhee Jeon. ”Active Vibration Control for Haptic Augmented Reality: An Initial Study.” 한국정보과학회 학술발표논문집 (2023): 1433-1435. **[Best Paper Award]**

[2] Hashem, Mohammad Shadman, **Ahsan Raza,** Mudassir Ibrahim Awan, and Seokhee Jeon. ”Pulsating Feedback: Render Human wrist Pulse via soft pneumatic actuator.” 한국정보과학회 학술발표논문집 (2023): 1439-1441.

[3] **Ahsan Raza,** Hwang Inwook, Jeongil Seo, and Seokhee Jeon. ”An Analysis of Haptic Based Image Classification.” 한국정보과학회 학술발표논문집 (2017): 1346-1348 **[Best Paper Award]**