MOBILE TOUCH

Responsive Wireless Tactile Communication for Portable Pneumatic Wearables

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Abstract

Pneumatic actuation is an effective method for recreating human touch sensations because it can apply pressure to the skin and has a natural softness. However, integrating this technology into fully wearable devices has proven to be difficult due to the lack of responsiveness with smaller pneumatic components, which limits the number of effective touches that can be portrayed.

Mobile Touch is a fully wearable system designed to deliver touch sensations to the wrist through a combination of pneumatic and vibrotactile actuation. By compensating for the inflation time of the pneumatic component with vibrations, the system's responsiveness is increased, allowing for the creation of more varied touch patterns. In addition, a wireless controller was developed that allows for programming touch patterns and directly transmitting touch wirelessly to the wearable device.

In the user study, the pneumatic-vibrotactile modality generally received significantly higher ratings for its similarity to human touch and pattern recognition by leveraging the strengths of each individual modality (n=35). Specifically, for longer touches, it was more effective due to its ability to mimic the softness of human skin and the pressure of a touch. For short taps, the vibrotactile component was clearer and enhanced the perceived realism.

This thesis delves deeper into the development of the device and the thought process behind it.

Wearable device offering pneumatic/vibrotactile touch feedback to the lower wrist.

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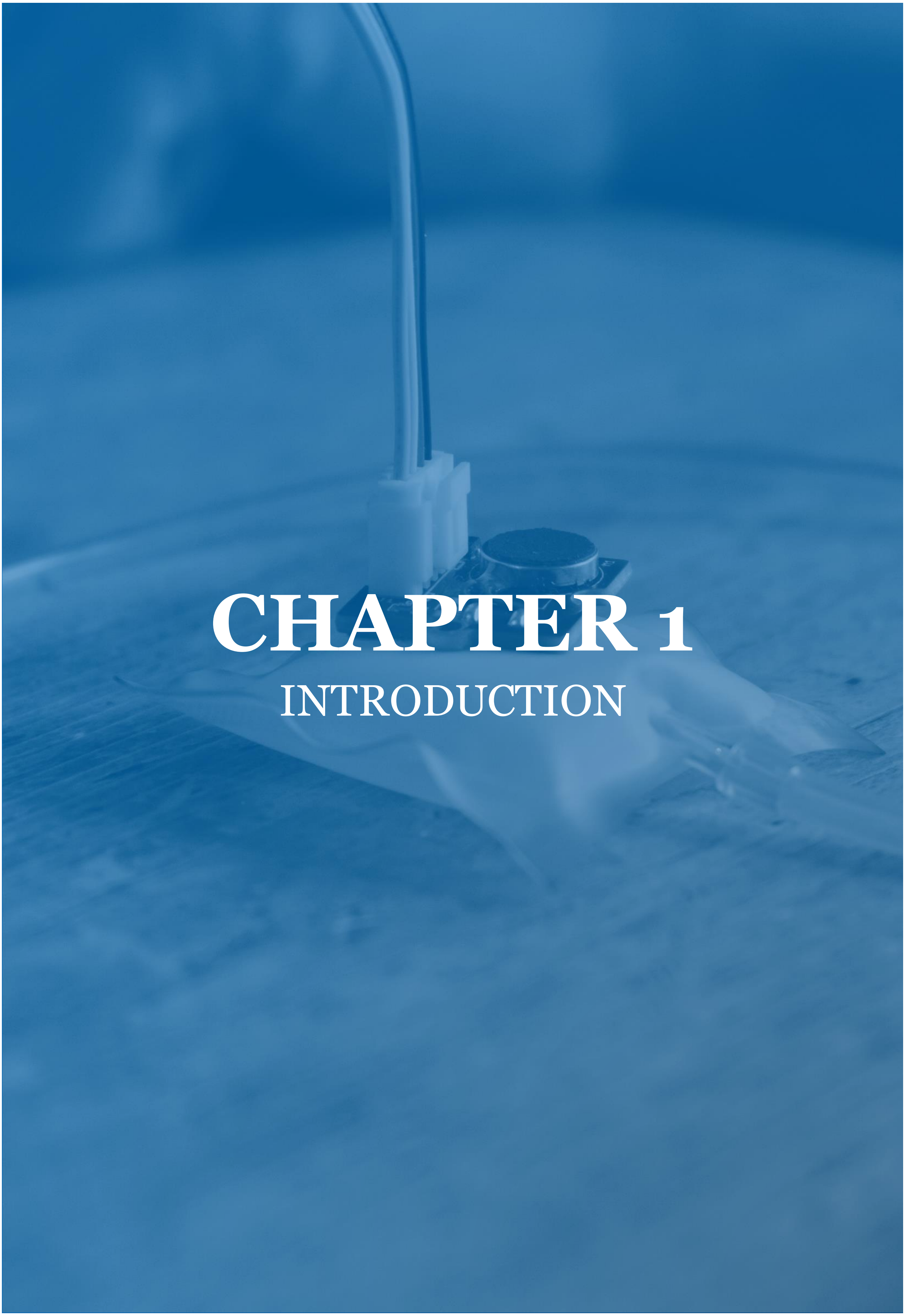

CHAPTER 1

INTRODUCTION

1. Introduction

1.1 Context

Wearable technology refers to electronic devices meant to be worn by individuals, ranging from smartwatches to hearing aids and beyond. These devices serve various purposes, from basic timekeeping to advanced functions like enhancing our surroundings through head-mounted displays. As wearable technology continues to advance rapidly, it creates new opportunities by enhancing portability and expanding into new markets.

One specific area that has captured the attention of researchers is haptic pneumatic wearable technology. Pneumatic technology utilises pressurised air for inflation or movement, offering flexibility, comfort, and versatility in wearables. Unlike many commercially available wearables that may feel rigid and unnatural over time, pneumatic technology enables more lifelike behaviour, such as mimicking touch or hugs.

Due to its characteristics, pneumatic technology is especially potent for use in affective touch applications; interpersonal touch to show affection and convey emotional support. This type of touch commonly uses gentle, fluid motions, suiting the characteristics of pneumatic systems. These possibilities open up a new design space for wearable technology that is more seamlessly integrated into how we humans live and interact with each other.

1.2 Project Brief

The initial objective of this thesis was to explore the possibilities of integrating pneumatic actuation with vibrations, a combination that has been underexplored yet holds significant promise. While pneumatic actuation typically involves gradual pressure application over time, vibrotactile actuation can be instant and provide localised feedback. By combining these two modalities, a unique set of technologies can be created, offering researchers and designers a novel platform for experimentation.

Building upon insights from Clint van Leeuwen's previous IDE Master's thesis, "Affective Air," which delved into pneumatic technology, this thesis aims to first explore the potential of both modalities, concluding in a new, more specific design direction that will be elaborated upon in detail.

Project brief (Chapter 2 – 4)

Exploring **Expressivity** through **Enriching Tactile Pneumatic Feedback** with **Vibrotactile Actuation** in **Wearables**

Design goal (Chapter 5 – 8)

“Creating the **Illusion** of a **Faster Responding Wearable Pneumatic System** through **Vibrotactile Enrichment**”

Target Group

The technology being developed in this report is intended to be used by two specific demographics: researchers and product designers. Researchers put their effort mostly towards developing the technology and exploring its potential, while product designers serve as intermediaries, bridging the gap between research discoveries and the end-user. The technology described in this report holds the capacity to benefit both target demographics, which is explained in Chapter 4.

1.3 Project Approach

Throughout this project, a research through design approach was taken. Early on, numerous smaller experiments were conducted to gain an understanding of the technologies used in this project and to explore new ideas. These experiments can be found in Chapter 3. Simultaneously, a thorough literature research (see Chapter 2) was conducted in order to obtain an understanding of what has been researched within the field of wearable HCI (Human Computer Interaction) and identify areas of novelty.

The insights gained from both types of research were essential in formulating the design direction, documented in Chapter 4. The same approach was carried through in the concept development (Chater 5) and the user testing stages (Chapter 7).

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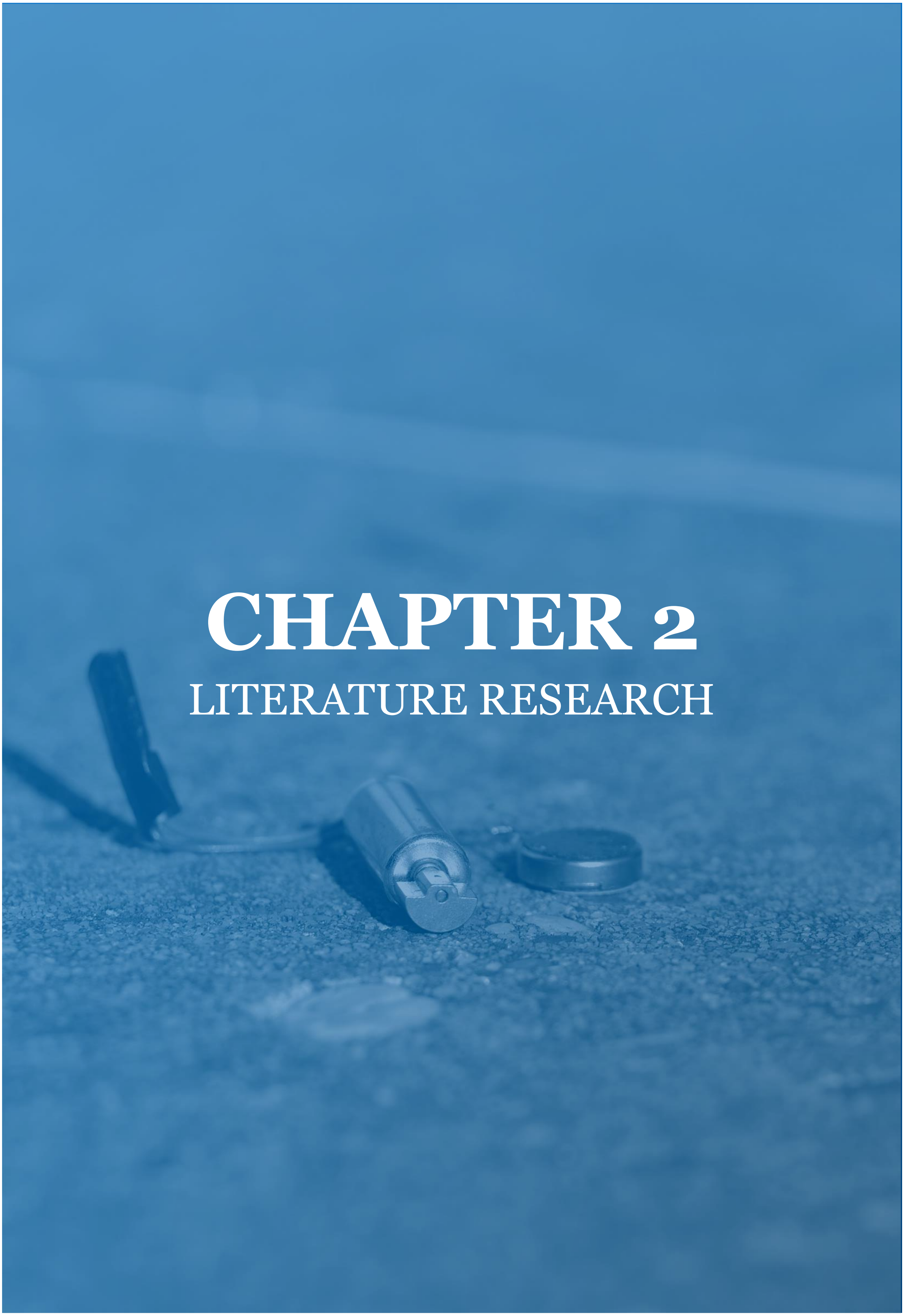


CHAPTER 2

LITERATURE RESEARCH

2. Literature Research

The literature research has been divided into several research topics to gain an overview of the research which has been conducted related to touch and wearable technology. This acts as the foundation for determining the exact research direction and learning about where the novelty lies.

2.1 Fundamentals of Touch

In this subchapter, the working of human touch is explored by first recognising the different touch modalities followed by the human sensory system and affective touch. As an essential part of wearable haptics, a fundamental understanding of the human somatic system, especially for receptors, is needed. Besides, affective touch benefits from pneumatic technology which is explored later in this Chapter.

2.1.1 Touch Modalities

Touch is a multifaceted sensory experience, commonly categorised into two modalities: kinaesthetic and cutaneous. Kinaesthetic feedback relates to the perception of positional changes, movements, and forces, whereas cutaneous feedback encompasses sensations experienced through the skin, including vibrations, pressure, and shear force (Culbertson et al., 2018).

2.1.2 Human Sensory System

Mechanoreceptors are used in detecting stimuli such as pressure and vibration (French & Torkkeli, 2009). The intricate workings of touch are regulated by three distinct types of sensory afferent nerves: the Aβ, Aδ, and C fibre groups (McGlone et al., 2014) (see Figure 1). The Aβ Fiber Group serves as the pathway for conveying haptic information, such as vibrations and pressure.

Contrarily, the low-threshold mechanoreceptors (C-tactile afferents, CT) within the C fibre group specialise in transmitting emotional touch, particularly characterised by low-force/velocity dynamics on hairy skin (refer to Figure 1).

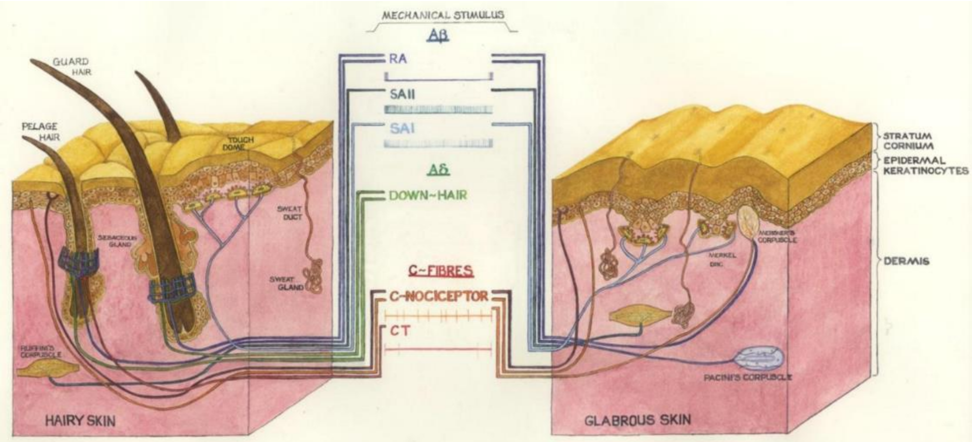


Figure 1: Mechanoreceptors and mechanical stimuli on glabrous and hairy skin (McGlone et al., 2014).

Touch communication relies on four low-threshold mechanoreceptors (LTMs): slowly adapting type 1 (SA1), slowly adapting type 2 (SA2), rapidly adapting (RA), and Pacinian units (PC). Each receptor type has a unique role in processing tactile stimuli. SA1 units, for instance, are sensitive to sustained pressure, while RA units detect low-frequency vibrations (under 40 Hz), and Pacinian corpuscles transmit high-frequency vibrations (above 40 Hz). These mechanoreceptors are commonly used in identifying textures (Purves et al., 2001). The definitions of pressure and vibrations can be found in Figure 2.

Pressure

Pressure, defined as the force exerted per unit area, plays a significant role in tactile perception. When a surface, such as a fingertip, makes contact with the skin, it exerts force over a specific area. Notably, substituting a finger with an object of smaller surface area, like a nail, intensifies the pressure exerted on the skin.

$$P = \frac{F}{A}$$

Vibrations

Vibrations are a repetitive oscillatory motion around an equilibrium point. Their characteristics are typically described in terms of frequency (the rate of oscillations per unit time) and amplitude (the maximum displacement).

Understanding these parameters is crucial in comprehending the diverse vibrational stimuli encountered in tactile perception.

Vibrations differ from pressure in the sense that they move the skin while pressure acts as an inward force (Pohl et al., 2017).

Figure 2: Definitions of pressure and vibrations.

2.1.3 Affective Touch

In addition to discriminative touch, which involves discerning between different tactile stimuli, there exists affective touch; a form of tactile interaction aimed at expressing affection. Affective touch can be transmitted through the wrist by simulating a squeezing or a stroking motion (X. Yang & Zhu, 2023). A brushing velocity between 1 and 10 cm s^{-1} was perceived to be most pleasant by subjects (Löken et al., 2009). Furthermore, CTs discharge preferably at a typical skin temperature (Ackerley et al., 2014), suggesting its importance for perceiving pleasantness in skin-to-skin contact and affective touch among humans

While CT afferents are often associated with affective touch in existing literature, it's noteworthy that research in this domain remains in its emerging stages, and other afferent pathways may also contribute to affective touch experiences (Schirmer et al., 2023).

Furthermore, it is important to highlight with affective touch is that it is culture-dependent and that affective touch is more acceptable in some cultures than others (Suvilehto et al. 2015).

2.2 Exploring Wearable Technologies

In this subchapter, an outline of current wearable technologies is provided, focusing particularly on pneumatic and vibrotactile actuation as they are essential to the research objectives. Initially, pneumatic actuation is examined, followed by an exploration of vibrotactile technologies and the advantages of the combination. Subsequently, suitable body locations for wearables are investigated in conjunction with existing haptic toolkits, offering insights to guide the exact direction of the research.

2.2.1 Pneumatic Actuation and Technologies

Many different types of tactile pneumatic actuation have been developed and researched. In this subchapter, they are categorized based on their actuation surface area, and underlying technology followed by a general overview of pneumatic air systems.

Localised Tactile Pneumatic Actuation

Local tactile pneumatic actuation has the advantage of quick response time due to its low volume. As was explored by Talhan et al. (2020), it is possible for pneumatic actuation to implement multiple types of actuation such as static, vibration and impact. This creates a unique set of characteristics able to simulate the properties of human touch.

Qi et al. (2023) developed the PneuIndenter, a haptic module able to indent a fingertip. By sandwiching two circle-shaped elastomer sheets between an air tube, pressure can be built up in between, which causes an indentation on the fingertip (see Figure 3). Furthermore, by controlling the pressure frequency, vibrations (10 – 170 Hz) can be simulated through this system.

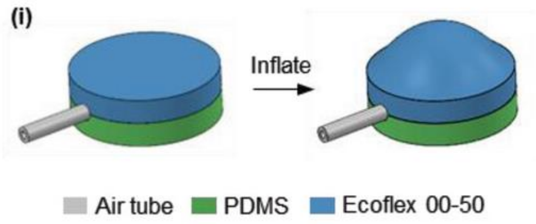
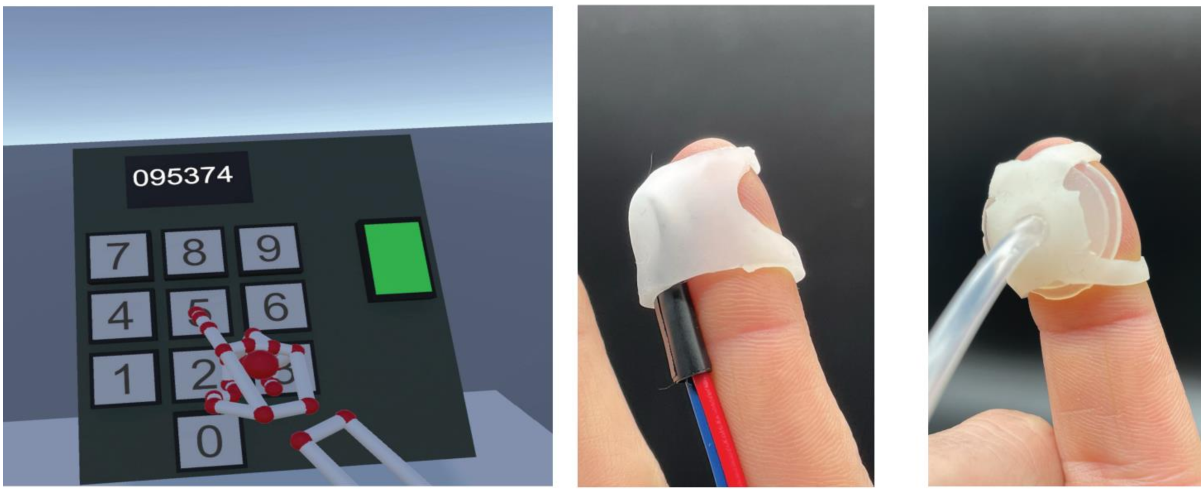


Figure 3: PneuIndenter (Qi et al., 2023)

Sonar and Paik (2016), created a closed-loop wearable device implementing both pneumatic and vibrotactile technologies. In this case, pneumatics were used to create a vibrotactile signal while a piezoelectric sensor was used to measure this signal. This sensor can detect external impacts such as a finger tap, also on contact release. Through this control loop, they were able to obtain consistent performance at 15 and 70 Hz.

Localised pneumatic feedback has been further explored by Van Beek et al. (2021) in which the feel of a pneumatic button press was simulated and compared to vibrotactile feedback (see Figure 4). There was no significant difference found in the time needed to complete the given task between the types, although participants preferred and experienced less stress with the pneumatic type.



(a) (b) (c)

Figure 4: Comparison between vibrotactile and pneumatic actuator in a VR-application (Van Beek et al., 2021).

Uniform Tactile Pneumatic Actuation

Uniform tactile pneumatic actuation encompasses a range of applications aimed at providing tactile feedback over extended areas or volumes. Pohl et al. (2015) introduced a pneumatic wearable designed to apply uniform pressure around the wrist, capable of delivering compression feedback varying from subtle to intense levels. Additionally, Delazio et al. (2018) developed the "Force Jacket," incorporating an array of pneumatically-actuated airbags to create a diverse library of sensations, such as a heartbeat or hug, enhancing immersive experiences.

Pneumatic actuators have the advantage that they are soft, versatile and almost lifelike making them suitable as a wearable technology (Chen et al., 2021). Poor portability hereby is generally an issue as the electronics needed for a pneumatic system (pumps, valves etc.) are often bulky to obtain a desired system responsiveness or pressure (Delazio et al., 2018; Choi et al., 2021; Günther et al., 2019).

Research in this domain also focuses on utilising pneumatic technologies for breathing regulation, which has been associated with reduced anxiety and blood pressure levels. Yu et al. (2021) introduced ViBreathe, a haptic interface tailored for practising slow breathing at work, leveraging heart rate variability (HRV) sensing to guide users' breathing patterns. Similarly, wrist-worn devices like the Affective Sleeve, developed by Papadopoulou et al. (2019), apply pressure and warmth to the lower wrist to promote calmness and reduce the feeling of anxiety

.

Mobile solutions such as Somnox, a sleeping robot capable of sensing and adjusting breathing rates by simulating a delayed biosignal (Tirtadji, 2022), and aSpire (see Figure 5)), a mobile breathing regulation device (Choi et al., 2021), offer further opportunities for breathing regulation in various contexts.

Figure 5: aSpire (Choi et al., 2021).

Furthermore, Cochrane et al. (2022) developed a wearable breathing scarf, able to support personalised emotional self-regulation strategies. This device redirects attention away from negative emotions by controlling breathing rate, and offering customization options to stimulate a sense of ownership and connection to the technology.

Moreover, pneumatic technologies can influence interoceptive signals, such as stimulating carotid baroreceptors, thereby modulating perceived emotional intensity (Jain et al., 2023).

Innovative Solutions and Technologies

One method for creating larger air bags involves ultrasonically bonding two sheets of polyurethane along with an air tube (Van Leeuwen, 2023). This technique enables the formation of air bags of varying sizes while maintaining a compact profile.

A common issue with pneumatic systems is their tendency to be bulky and generate noise. To address this issue, Smith et al. (2023) conducted experiments with a novel fluid fibre pump (see Figure 6). This pump operates silently, generating pressure internally within the fibres at a rate of 100 kPa/m and a displacement speed of 55 mm/min. This innovation holds the potential to eliminate the necessity for large external valves or pumps, but it currently lacks a sufficient flow rate for inflating or deflating larger pneumatic airbags.

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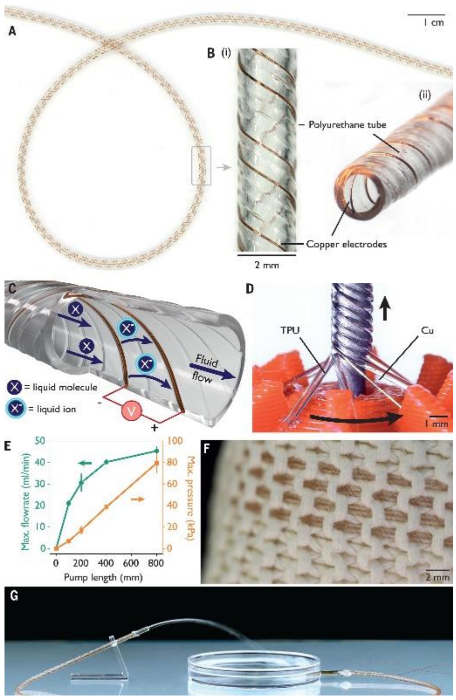

Figure 6: Fluid fibre pump developed by Smith et al. (2023).

Functioning of pneumatic air systems

Pneumatic air systems generally can be divided into two categories: pumps and valves. Pumps are commonly used to generate the pressure needed for a pneumatic-actuated system to operate, while valves are utilised to control the airflow. A diagram of such a system can be found in Figure 7, where two pumps and three valves are used to perform the actions of inflation, deflation/vacuum and pressure equalisation with the atmosphere.

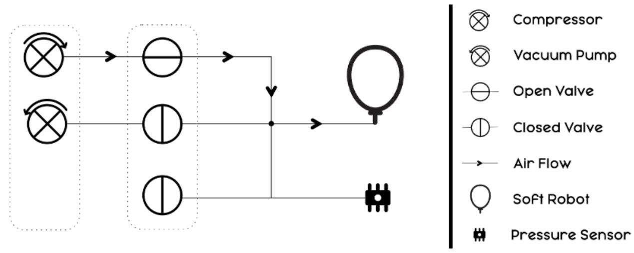

Figure 7: Schematic of the Programmable Air toolkit (Programmable Air, n.d.).

Air pumps and valves come in a variety of sizes. Larger sizes have been used in many research examples in the form of air compressors due to their improved airflow allowing a quick inflation time. However, smaller pneumatic actuators are more interesting for research on wearable technology as their compact dimensions and low power draw allow them to be wearable and untethered (see Figure 8), although this comes at the cost of a reduced flow rate (see Table 1).

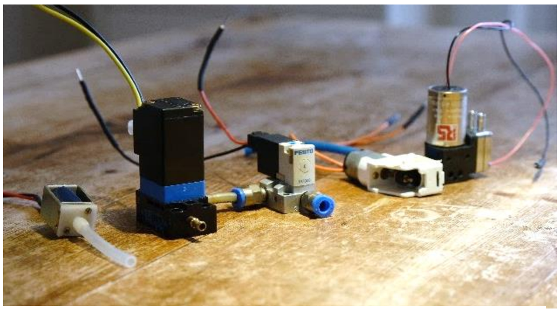

Figure 8: Air pumps and valves come in different sizes and shapes.

	Yimaker 370 Micro Air Pump ***(used in Programmable Air)***	**RS PRO Gas Compressor Pump 702-6898**	**CurieJet Piezo-electric Micropump Gas Pump GS9S**
Dimensions (mm)	58 x 30 x 30	38.5 x 27.9 x 17.0	16.5 x 16.5 x 3.8
Maximum Flow Rate (l/min)	2	0.4	0.12
Maximum Output Pressure (mBar)	500	800	400
Maximum Input Power (W)	1.35	0.6	<1.5
Sources	(Programmable-Air, n.d.) (AliExpress, n.d.)	(RS, n.d.)	(Taiwantrade, n.d.)

Table 1: Specifications of three different-sized, compact air pumps compared.

2.2.2 Vibrotactile Actuation and Technologies

Vibrotactile technology can be used in a variety of applications, particularly in the realms of sensory perception and affect regulation.

Despite vibrations being perceived through different mechanoreceptors (see Chapter 2.1.2), recent research suggests that the sensation of pressure could be imitated utilising vibrotactile actuation. For example, Huisman et al. (2013) demonstrated that vibrotactile feedback can simulate tactile experiences such as pressing and poking (see Figure 9). This is something commonly used by game developers for interactions with the environment. Expanding on this, Smith et al. (2022) found that multiple vibrotactile actuation could be used to simulate pressure, although a direct comparison between the two types of modalities remains to be explored.

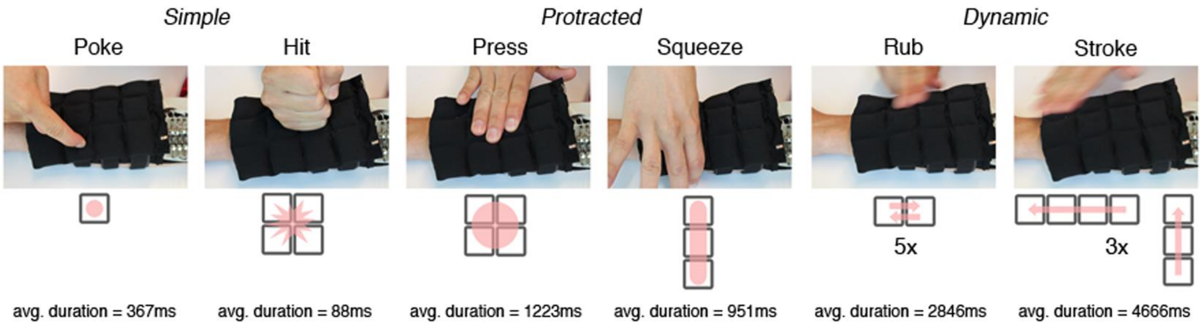

Figure 9: Vibrational patterns simulating different types of touch (Huisman et al., 2013).

A key area of interest in vibrotactile technology lies in affect regulation, with a particular focus on stress and anxiety reduction. Umair et al. (2021) found that low-frequency vibrations are particularly effective in this regard, indicating the importance of frequency modulation in designing vibrotactile interventions for affective regulation. Another way for affective regulation is to provide social support to a plush robot toy which is made more life-like through haptic vibrations (Isbister et al., 2021). Furthermore, subjective feelings can be communicated with one another through utilising vibrational feedback as was found by Ju et al. (2021).

Simulating a (lower) heart rate using vibrational haptic feedback can be used to physiologically relax and reduce the feeling of anxiety (Y. Zhou et al., 2020; Azevedo et al., 2017; Costa et al., 2016; Costa et al., 2019). Opposite effects such as increased anxiety and heart rate can be a consequence of presenting a fast heartbeat, which can feel more immersive (Wang et al., 2023; Ueoka & Almutawa, 2018).

Furthermore, the utilisation of arrays of vibrotactile actuators presents opportunities for generating virtual actuators (De Vlam et al., 2023). These arrays also facilitate the creation of dynamic vibrational patterns, which hold promise for affect regulation applications (Richard et al., 2023).

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Vibrotactile perception

As a general rule of thumb, lower sinusoidal vibrational frequencies need to have a higher amplitude in order to be detected by users (Ryu et al., 2010). Furthermore, a positive correlation between perceived intensity and amplitude; and perceived intensity and frequency (see Figure 10) were found, with amplitude having most effect on the perceived intensity.

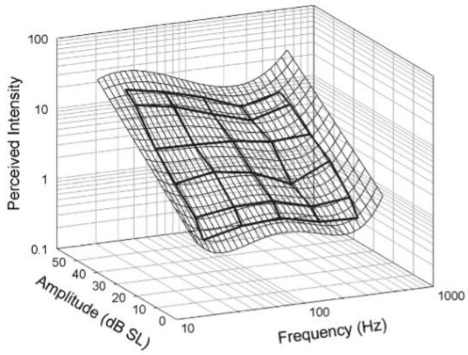

Figure 10: Perceived intensity plotted against amplitude and frequency for a vibrotactile actuator (Ryu et al., 2010)).

Satiety effects

However, a potential drawback of prolonged exposure to vibrotactile stimuli is adaptation (satiety), which could diminish its effectiveness over time (Pasquero, 2006). This is similar to exposure to affective stroking, which can result in tactile satiety with repeated exposures (Triscoli et al., 2014). Depending on the afferent type, adaptation and recovery rates differ (Leung et al., 2005). SA1 afferents adapt the fastest, whereas PC afferents adapt the slowest among tactile afferents. This suggests that sensitivity to high-frequency vibrations (over 40 Hz) can be sustained longer than sensitivity to pressures exerted on the skin. To mitigate this issue, one proposed solution is to selectively activate these actuators during moments of high arousal, as suggested by Raether et al. (2022).

Furthermore, human skin has a detection threshold of 1 mN and a response time of ~15 ms for detecting static forces (Chortos et al., 2016). Several current sensor types can detect smaller forces and respond more quickly, yet they lack the adaptive capabilities of human skin.

Overview of Vibrotactile Actuator Types

There are many different types of vibrotactile actuators. This subchapter explores the benefits and drawbacks of each to gain insights into which best suit the application of this research.

ERM (Eccentric Rotating Mass)

ERM motors are commonly used in devices such as smartphones and wearables. It works by spinning an eccentric mass which causes displacement of the device, a vibration (see Figure 11). The amplitude and frequency are linked with each other, as the faster the eccentric mass spins, the larger the resulting force.

There are many different sizes of ERM motors, ranging from smaller pancake-style actuators to more powerful, larger devices (see Figure 11).

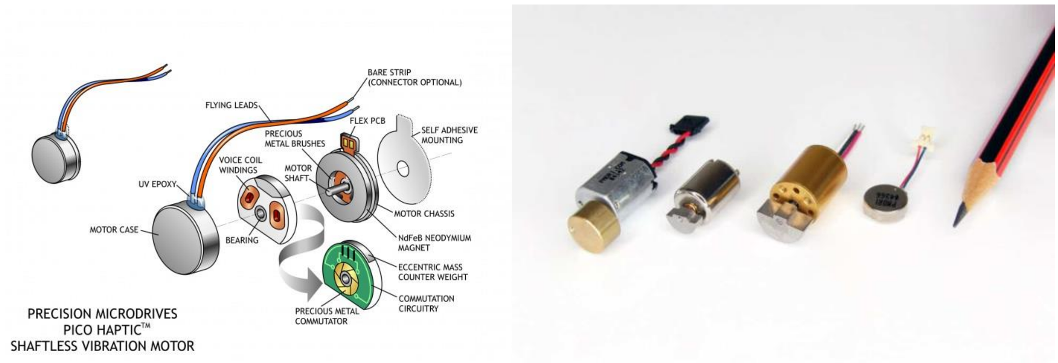

Figure 11: (Left) internals of an ERM. (Right) different types and sizes of ERMs (Precision Microdrives, n.d.-b).

LRA (Linear Resonant Actuator)

LRAs can look very similar to ERMs although they function differently. Similarly to ERMs, LRAs use a moving mass to create vibrations. Instead of spinning this mass around an axis, LRAs move the mass along one axis. This mass is placed between a spring and a voice-coil (see Figure 12) which are used to attain the resonant frequency of the spring.

The main advantage of an LRA is its improved response times over ERMs (Engineering Product Design, 2021), but they do require an AC signal to be driven (Precision Microdrives, n.d.-a), which can be created using a driver board (for example a DRV2605).

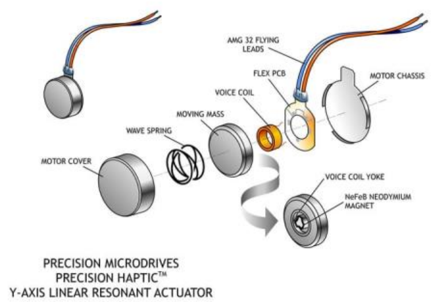

Figure 12: Internals of an LRA (Precision Microdrives, n.d.-a).

LMR (Linear Magnetic Ram)
Similarly to LRAs, LMRs use voice coils to create vibrations, only without the use of springs (see Figure 13). The mass which causes these vibrations is suspended through a magnetic field. This allows for a quick response time, high intensity and diverse frequency range. Furthermore, it makes it possible to simulate an impact.

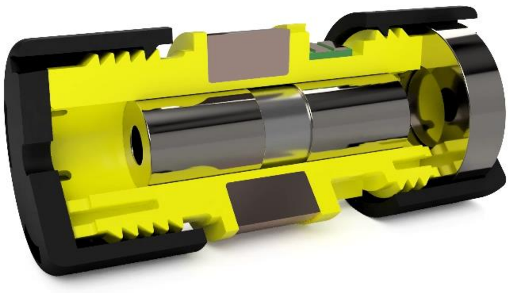

Figure 13: Internals of a LMR (TITAN Haptics, n.d.).

Piezo actuator
Piezo vibrational actuators work on the piezo effect; when placed on a high voltage the material contracts, which can be used to generate vibrations on a wide frequency spectrum. Of all vibrotactile actuators, piezo has the highest response times due to the absence of a moving mass (Boréas Technologies, 2022). As this is a less commonly used actuator type and the fact it requires a specially developed driver board, this option is more costly than the other options discussed in this Chapter.

Chapter 3.2 delves deeper into testing and evaluating the characteristics of the identified vibrotactile actuators to determine which one is most suitable for the chosen design direction (see Chapter 4.2)

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2.2.3 Benefits of Combining Pneumatic Feedback with Vibrotactile Actuation

The functioning of both individual types of feedback has been explored in previous subchapters. This subchapter explores the possibilities and potential of combining both types of actuation.

Both modalities can be used to simulate a multitude of sensations and semantics. Vibrotactile is particularly good at providing instant, localized feedback (such as raindrops) while pneumatic actuation excels in conveying affective sensations such as the feeling of a hug (Delazio et al., 2018; Haynes et al., 2022).

Each actuation type presents unique considerations regarding user experience and perception. Vibrotactile feedback, while effective, can sometimes be disruptive, especially when sustained over prolonged periods (Haller et al., 2011; Kaaresoja & Linjama, 2005). In contrast, pneumatic actuation offers varying levels of attention capture, with pressure exertion achieving different levels of user engagement (Zheng et al., 2013). Zheng and Morrell (2012) discovered that vibrations demand more attention compared to pressure and that user attention capture was significantly improved with devices with negative affect. Besides, Lower amplitude vibrations can result in a feeling of 'lightness', while higher amplitude feedback feels 'repulsive', which is also axis-dependant (Hwang & Hwang, 2009). As discussed in Chapter 2.2.2, satiety effects are likely to occur sooner with pressures than with high-frequency vibrations (> 40 Hz).

Moreover, pneumatic feedback holds potential advantages in terms of energy efficiency, as highlighted by Qi et al. (2023). However, this modality typically requires a longer duration to create perceptible effects compared to vibration motors due to the inflation of air bags and the time required for pressure feedback to manifest (Pohl et al., 2017). Additionally, individual variability in the threshold for sensing pneumatic actuation underscores the importance of personalisation in haptic interfaces (Pohl et al., 2017). Preferences regarding the intensity of both vibrotactile actuation and pneumatic pressure can vary significantly among users, influenced by personal preferences as well as external factors such as pressure applied from clothing (Hwang & Hwang, 2009; Zheng & Morrell, 2012).

These insights are essential in designing haptic interfaces based on individual preferences and optimising user experience. Understanding the potential of combining both modalities lays the foundation for further exploration, which can be found in Chapter 3.

2.2.4 Body Locations suitable for Wearables

This subchapter explores the most suitable locations for wearables, which will be identified in Chapter 4.

Zeagler (2017) identified the most likely position for wearables on a human's body by first identifying different body maps such as sensitivity to passive touch and sensor locations to measure human vitals. Layering these body maps results in a map showing the most likely places for wearables (see Figure 14).

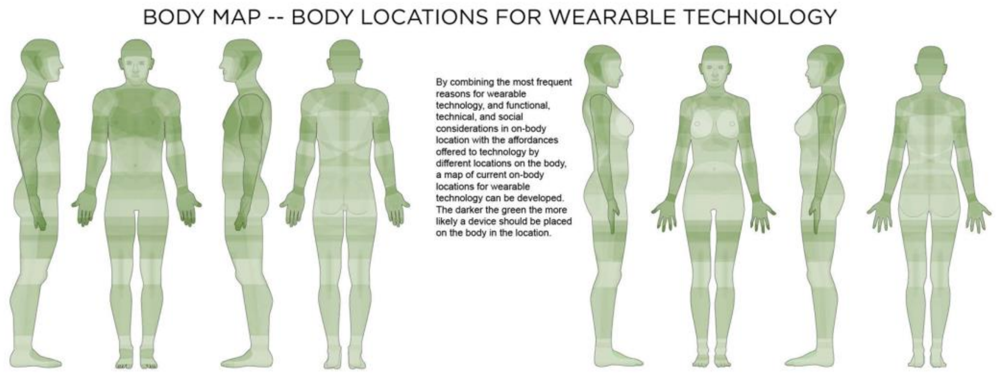


Figure 14: Body map showing the most likely positions for wearables (Zeagler 2017) .

Furthermore, humans perceive size differently based on where an object is placed on the body (proxemics). For example, objects placed on the hand are generally perceived to be larger than when placed on the waist. In case a wearable exceeds a human's body dimension, it can obstruct their movement. As was found by Zeagler et al. (2017), the least amount of weight (<.5lb) is wanted on the hands, arms and head before it starts becoming discomforting. This proves challenging for wearable technology, especially for the current pneumatic technology as was found in Chapter 2.2.1.

Wrist

The wrist is a commonly used area for wearable technology for various reasons. Multiple physiological measures can be monitored through the wrist such as heart rate, blood pressure and temperature. Moreover, its visibility allows for a quick response time in case of a visual cue (Zeagler, 2017). Additionally, this location can be utilised as well for regulating a user's heart rate (Choi & Ishii, 2020) and is more sensitive to touch than other limbs such as the shoulder, thigh and calf (Mancini et al., 2014).

The wrist is a suitable location for affective haptics. A stroking sensation on the wrist can be utilised to induce affective touch and lower state anxiety (Zhao et al., 2022). Furthermore, Suvilehto et al. (2015) identified the hands and arms as the most likely area for social touch, making the wrist a common site for such interactions (Huisman et al., 2013). Given its sensitivity to touch, different textures can be felt on the wrist and alter affective perception (X. Yang & Zhu, 2023).

2.2.5 Existing Haptic Toolkits

Haptic toolkits can be invaluable to designers for developing new technologies and conducting research. Through experimentation with these toolkits, new insights can be quickly gained as they offer a foundation for further development. Given the focus of this research on assisting designers and researchers in the creation of wearable technologies, this subchapter provides an overview of existing haptic toolkits and their utility.

HapLand allows researchers to use haptics on emotional regulation. This toolkit incorporates multiple sensor and actuator types to explore design parameters and body locations (Miri et al., 2017).

Compressables (Endow et al., 2021) is an open-source prototyping toolkit for creating haptic compression, which is done through pneumatics. This kit encourages users to develop their own custom inflatable silicone bladders that can be used on multiple body locations due to their customisability (see Figure 15).

Figure 15: Compressables (Endow et al., 2021).

Tractorbot is a toolkit developed by R. Zhou et al. (2023) which enables designers and researchers to develop their haptic patterns from a servo-driven arm. Through an open-source design, users can 3D print their parts and assemble the toolkit. A web application can be used to program the toolkit based on patterns (stroking, pressing etc.) and emotions.

Brocker et al. (2022) developed simulation software for soft robotic grippers. How these grippers bend often requires trial and error, however this tool allows the designer to preview the actuator movement. This makes the design and iteration process quicker.

[redacted]

Li et al. (2022) explored touch encoding, wireless transmission, and haptic reproduction using the e-skin device. This device enables interpersonal touch by deforming a sensor and utilising vibrations to create the perception of touch.

Modular toolkits have been developed as well, for example by Zhang & Sra (2021) in which pneumatic pressure and thermal cues can be applied to different body parts, allowing the creation of patterns (see Figure 16).

Figure 16: PneuMod (Zhang & Sra, 2021).

VibViz is an online library in which designers can navigate vibrational patterns (Seifi et al., 2015). As haptic collections are often difficult to navigate, a library was developed which allows users to sort using different organisational schemes to easily find the patterns suiting their needs.

Another example of a haptic toolkit to be used for haptic tabletop applications was developed by Ledo et al. (2012). Since developing haptic sensations is often cumbersome, the HapticTouch toolkit allows for easier programming and improves accessibility through a software-based interface. This interface has different levels of complexity, allowing designers to choose from several interfaces from very customizable towards more user-friendly, less customisable options.

2.3 Literature Research Conclusion

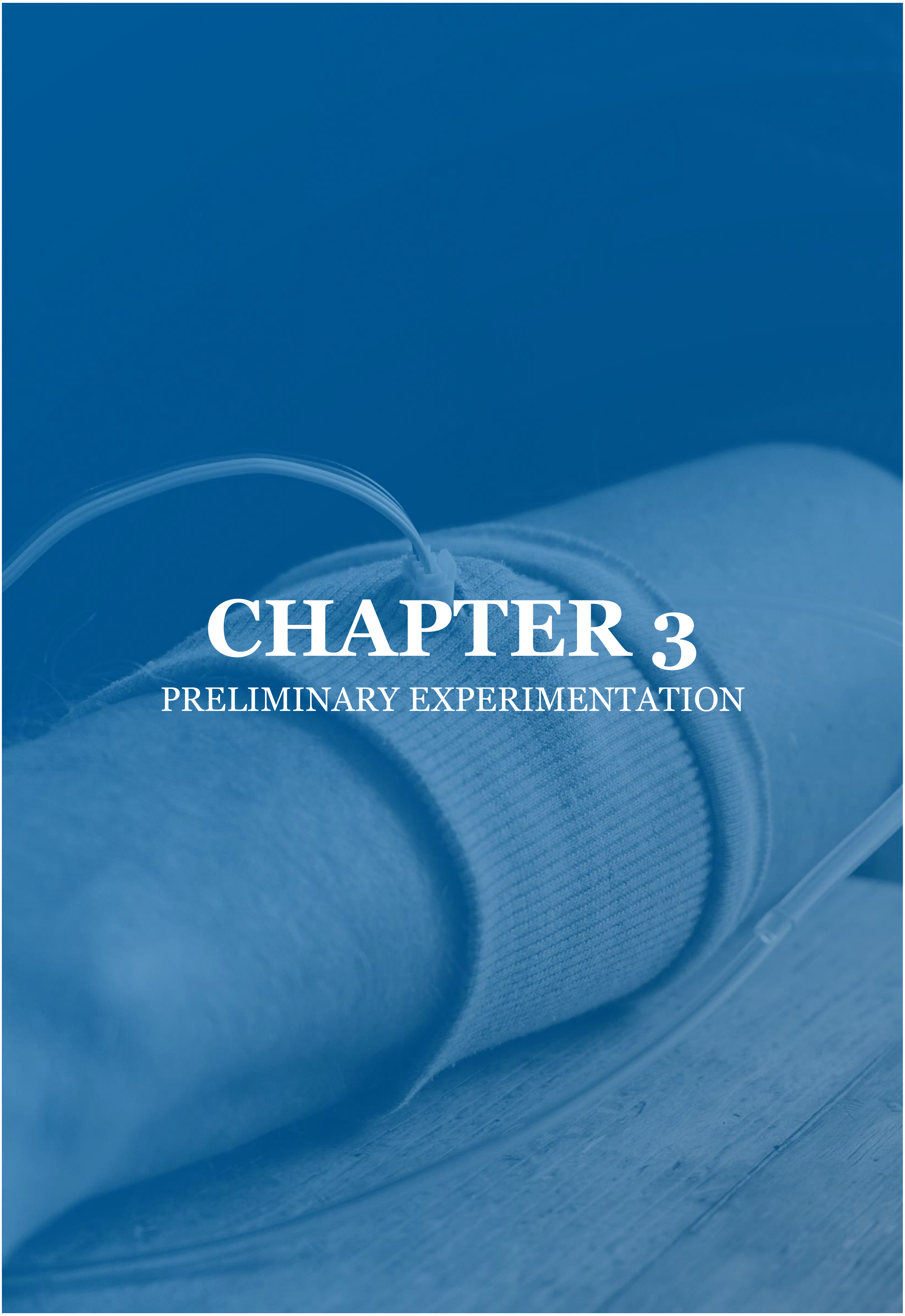
This chapter gives an overview of research in the field, providing a solid foundation for understanding important concepts and exploring new ideas. The insights obtained from this chapter are further discussed in the following chapters.

First, it covers the basics of touch, including different types of touch, how the human sensory system works, and the role of touch in emotions. This knowledge is essential for developing wearable devices that interact well with the human body and emotions.

Next, it looks at wearable technologies, focusing on two types: pneumatic systems and vibrotactile technologies. Pneumatic systems are soft and realistic, making them useful for things like calming and regulating breathing. Vibrotactile technologies provide quick, localised feedback, which can help reduce stress and regulate emotions.

Combining pneumatic and vibrotactile technologies opens up possibilities for creating a wide range of sensations, but it's important to consider how users will perceive these sensations. Also, where the wearable is placed on the body matters a lot, with the wrist being a popular choice due to its ability to monitor vital signs and its sensitivity to touch.

Lastly, existing haptic toolkits are highlighted as valuable resources for designers and researchers. These toolkits include everything from tools for emotional regulation to software for developing customised vibrational patterns, making them essential for moving the field forward.



CHAPTER 3

PRELIMINARY EXPERIMENTATION

3. Preliminary Experimentation

This Chapter focuses on the preliminary experiments conducted as part of the research. These experiments serve an exploratory purpose, as their outcomes are utilised in shaping the specific research direction discussed in Chapter 4. The sole purpose of these experiments is to give direction to the design process and identify opportunities to further study, not to draw strong conclusions, as the data points are limited and would require a more robust study setup. Additional experiments can be found in Appendix A.

3.1 Compensating for a Slow-Responding Pneumatic System using Vibrotactile Actuation

As was found in Chapter 2, wearable pneumatic systems can sometimes lack responsiveness due to using compact, but underpowered electronics. The experiment described in this subchapter was conducted to test if it is possible to compensate for a slow-responding pneumatic system using vibrotactile actuation.

Goal

To test if vibrotactile actuation (in the shape of an ERM-motor) can be used to compensate for the response time needed for a pneumatic system (to apply pressure). This actuator was chosen as they are commonly used in devices such as smartphones and wearables.

Method

A wrist-wearable prototype is created implementing both pneumatic and an ERM-motor (10 x 2.7 mm) (see Figure 17). For the pneumatic system, the Programmable-Air toolkit (Programmable-Air, n.d.) was used to inflate the 40 x 40 mm inflatable air bag produced by Van Leeuwen (2023). These were placed inside a textile sleeve to put around the wrist.

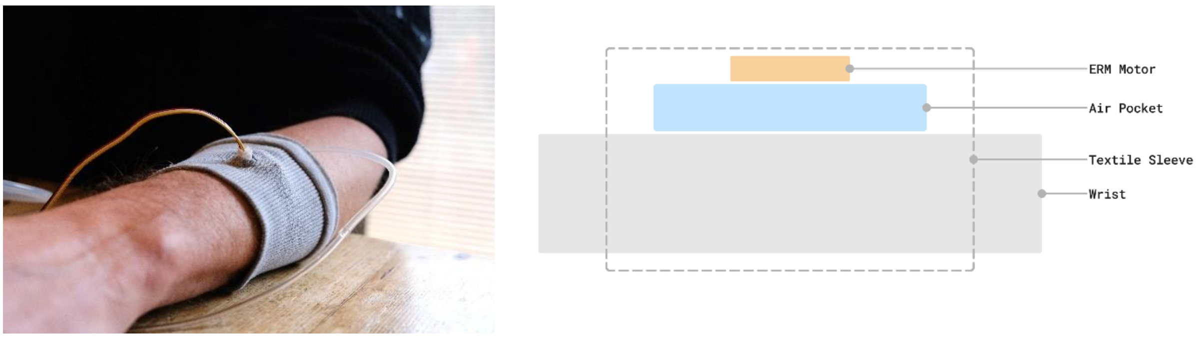


Figure 17: Wrist wearable prototype (left) and schematic (right).

One button on the Programmable-Air toolkit was used solely for the pneumatic feedback while the other is used for both pneumatic and vibrotactile feedback to easily compare both types of actuation. A 15% duty cycle of the compressor pump was used to simulate a slow inflation time (3 - 4 sec) and hold pressure.

The perceived response times for both inflation and deflation were tested with and without vibrotactile actuation. These results are entirely subjective, with the primary aim of this research being to quickly test new ideas and identify areas of interest for further study. Figure 18 shows the internal prototype before and after inflation. This prototype was tested on the researcher's wrist.

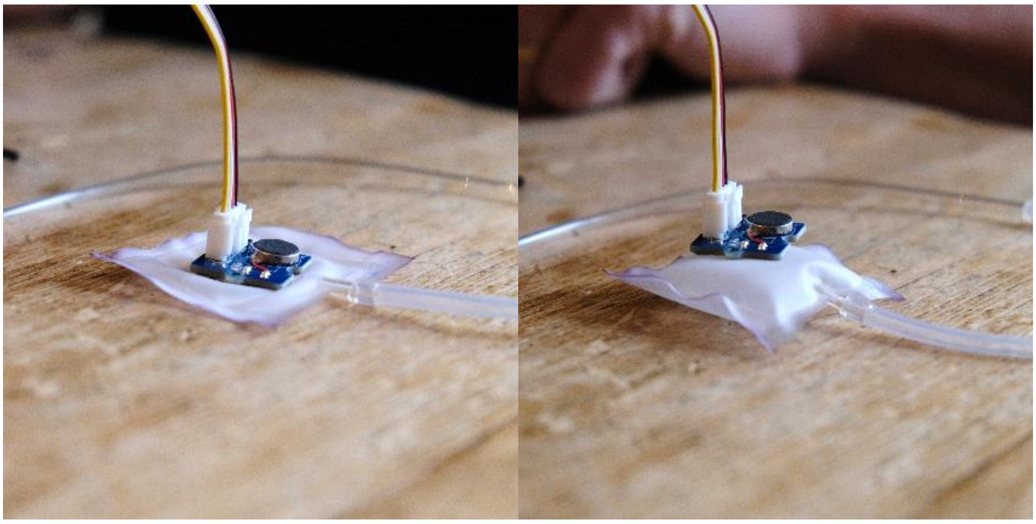


Figure 18: Vibrotactile-pneumatic system before and after inflation.

3.1.1 Inflation

To compensate for the lack of responsiveness during inflation, the duty cycle (DC) of the ERM motor starts at a PWM value of 20% and drops until the pressure from the air pouch takes over to compensate for the lack of pressure at the start (see Figure 19). Higher PWM values started feeling more intense and disproportionate to the actuation signal of the pneumatic system, which is why this value was chosen.

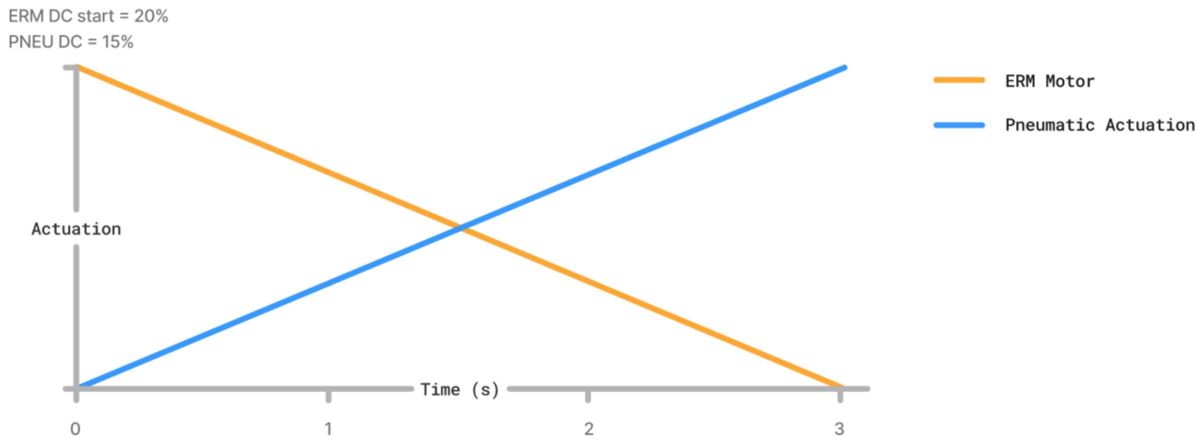


Figure 19: Actuation graph over time for both types of feedback during inflation.

Results

A clear difference was perceived between using the vibrotactile motor and not. When solely using pneumatic actuation, it is unclear whether the system is turned on or not at the beginning stages of the air bag inflating (neglecting the sounds the compressor pump produces). When the air bag starts to create pressure (around 3 seconds), the user starts to feel the system applying pressure to the wrist.

On the contrary, with vibrotactile actuation the user immediately feels the feedback created by the system, giving the illusion of a motor starting up. This vibration seamlessly goes over to pressure created by the pneumatic system. The ERM motor does feel different to the pneumatic actuation as it doesn't apply pressure but moves the skin tangentially, in line with the results found in Chapter 2.1.2. Furthermore, it was found that it takes a fraction of a second to spin up.

One observation found during the test was that for ERM motors there is a positive relation between amplitude and frequency (see Chapter 2.2.2). Other types of vibrotactile have been further explored in Chapter 3.2 to test whether different frequencies can feel closer to the feeling generated by pressure.

3.1.2 Deflation

The pressure drop is not instant during the deflation process, which is often limited by the tube diameters and valve through which the system needs to vent (see Figure 20). To compensate for this, a test was conducted in which the pressure drop was compensated for using an ERM motor with the same setup as described in Chapter 3.1.1.

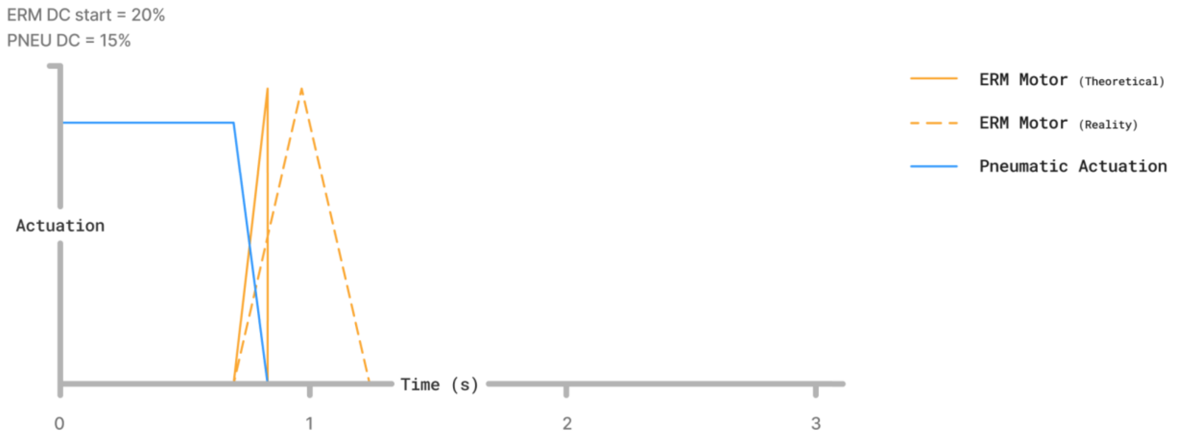


Figure 20: Actuation graph over time for both types of feedback during deflation.

Results

The system was perceived slightly more responsive when using the ERM motor compared to solely venting the pneumatic air bags, although this was less noticeable as compensation for inflation since it is much faster (estimated 0.5 s). One issue was that the ERM motor takes time to spin up and down which means it can't accurately compensate for the lack of pneumatic pressure in real-time. As can be found in Figure 20, the theoretically ideal actuation graph can't be obtained due to this.

3.1.3 Reflection

The compressor pump has been currently set at a 15% duty cycle to simulate a slow inflation time. When put at 100% power, the 40 x 40 mm pressurizes rapidly (estimated <0.5 s) for which vibrotactile compensation would not be necessary. An interesting opportunity would be systems which able to inflate larger volumes or utilise smaller electronics without losing responsiveness through the combination of pneumatic with vibrotactile actuation. This could result in improved wearability or reduced noise through the possibility of reducing the size and power output of pneumatic systems.

ERM motors can have a lack in responsiveness, as was experienced during the deflation stage of a pneumatic system. Other types of vibrotactile actuators are therefore interesting to research and to test whether they more closely resemble pressure actuation from a pneumatic system. The difference between the feeling of the two modalities could be explained by the different mechanoreceptors in the skin used to transmit vibrations and pressure (see Chapter 2.1).

3.2 Testing different Vibrotactile Actuators on Response Time and Feel

As was found in the previous subchapter, ERMs can lack responsiveness in certain circumstances, such as compensation for the inflation/deflation stages of a pneumatic system. This subchapter explores the different vibrotactile actuators as identified in Chapter 2.2.2 to test responsiveness and if one feels more similar to an applied pressure.

Goal

Testing what the perceived response time and feel to find which one is most suitable in a system for compensating pneumatic actuation.

Method

Three types of actuator types were used, an ERM, LRA and two LMRs (see Figure 21). The piezo-actuator was left out due to its high costs and rarity. A similar research setup as described in Chapter 3.1 was used, with the only difference being the switching between vibrotactile actuator types and it being directly placed on the skin underneath the air bag (see Figure 22). Instead of decreasing the vibrotactile actuation linearly, the internal air pressure signal was directly used to map the intensity for a more accurate response. A DRV2605L driver board was used to drive the LRA and LMR. The prototype was experienced by the researcher and two external participants who gave subjective feedback on intensity and feel.

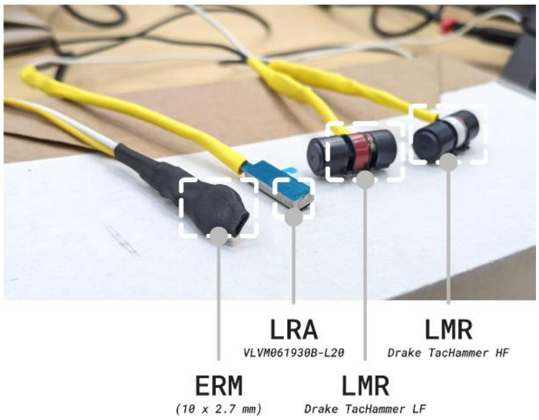


Figure 21: ERM, LRA and LMR vibrotactile actuators.

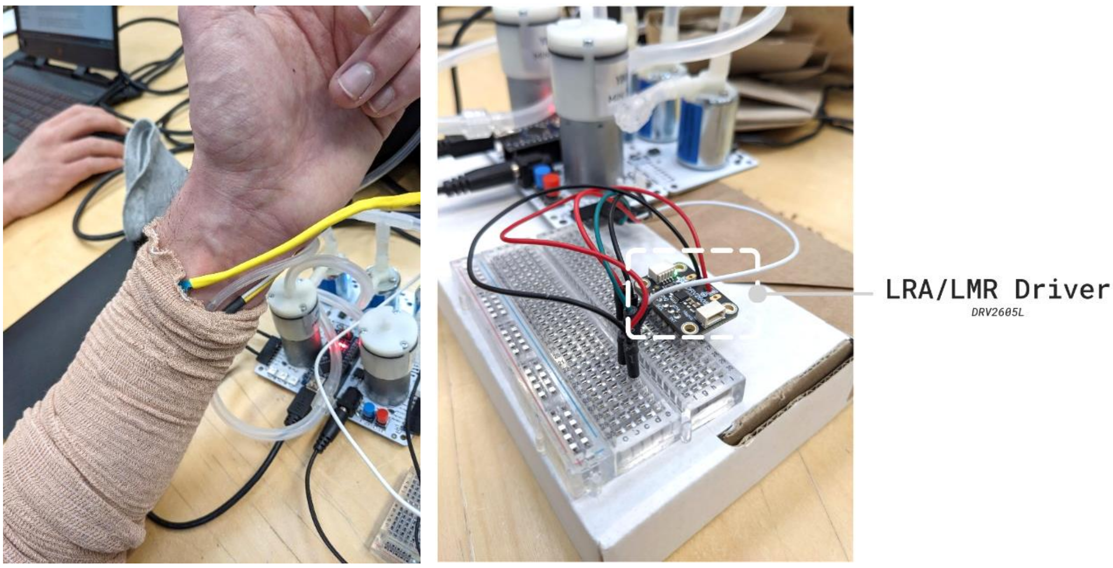


Figure 22: Vibrotactile and pneumatic actuator being placed inside a sleeve (left), DRV2605L driver (right).

Results

Noticeability and Feel

For all three participants, the ERM actuator was perceived more intense than the LRA actuators (see Figure 23). The LRA was difficult to notice, even while it was placed directly on the skin. LMRs were more noticeable than the LRA, although not as well as the ERM.

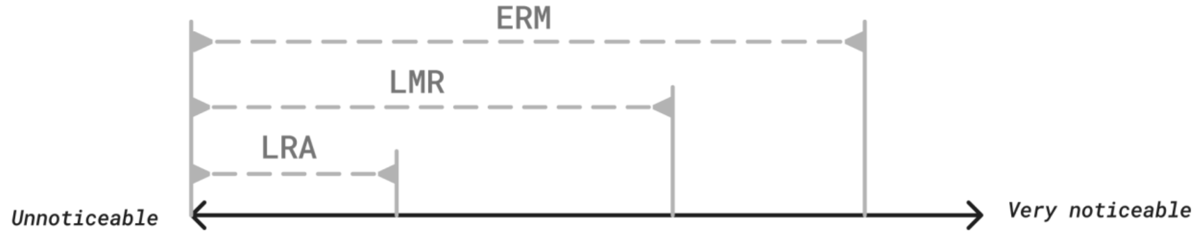


Figure 23: Perceived intensities between the different vibrotactile actuator types (N=3).

LMR actuators have higher frequencies than ERM and LRA actuators (300 Hz,183 Hz and 180 Hz respectively). One did not feel more similar to pressure than the other. With ERMs, the amplitude and frequency are attached towards one another, while with LRA and LRM actuators the frequency stays the same but the amplitude differs.

Directionality between actuators cannot be sensed. Furthermore, it was found that the ERM is more compact than the LMR types and lies flat automatically.

Reaction time

The LRA and LMR actuators react instantly. The ERM actuator takes a fraction of a second to speed up. This is most noticeable at lower voltages, although at maximum PWM power, this delay is difficult to sense, which was not done in previous experiments (see Chapter 3.1).

Reflection

The compact form factor, and intensity are all factors in favour of the ERM actuator. A slower response time could potentially be accounted for with programming where a maximum voltage is initially applied to ramp up the motor quickly, before settling to the desired intensity. This is further researched in Chapter 5.1.4.

One advantage the other types have over ERM motors is their instant response times, which allows the creation of different patterns such as a pulse and impact. These will be further investigated in Chapter 3.4.4 alongside orientation of LMRs using these patterns.

3.3 Testing Response Time and Perception for different Vibrotactile Patterns

Goal

The main goal of this experiment is to test the effect of different patterns between pneumatic and vibrotactile actuation on reaction time and feeling of responsiveness, urgency and comfort.

This research is in line with the experiment of Chapter 3.1, only with responsiveness being quantified through measuring reaction time adjacent to perceived urgency and comfort. It was found in Chapter 2 that vibrotactile actuators often convey an urgent message while pneumatics are more associated with comfort. Therefore, it is hypothesized that different patterns could be used to simulate different states of urgency and comfort.

Method

This study is divided into two parts. The initial part consists of a reaction game in which a pattern is played and users are asked to press a button when they feel it actuating to measure reaction time. Hereby it is tested whether more vibrotactile-orientated actuation can be quicker perceived and which pattern combinations are best for this.

Every pattern was tested three times and after each button press, the pattern was changed to prevent participants from getting accustomed to the pattern or the stimulation. The researcher actuated the system randomly after which he noted down the response time. During a preliminary experiment, it was found that the sound of the opening of the valve can trigger users into thinking the device is actuated. To solve this, users were asked to wear headphones during the study besides looking away from their arm ensuring the actuation is only felt, not seen or heard.

The second part of this study consists of how the different patterns are perceived, specifically on responsiveness, urgency and comfort. For this, a survey was created in which participants could quantify how they perceived each variable on a scale from one to seven.

A similar research setup as Chapter 3.2 was used where a vibrotactile actuator was placed inside a sleeve below a 40 x 40 mm pneumatically actuated air bag (see Figure 24). An ERM was chosen as it was most noticeable of all the actuator types tested in Chapter 3.2.

[redacted]

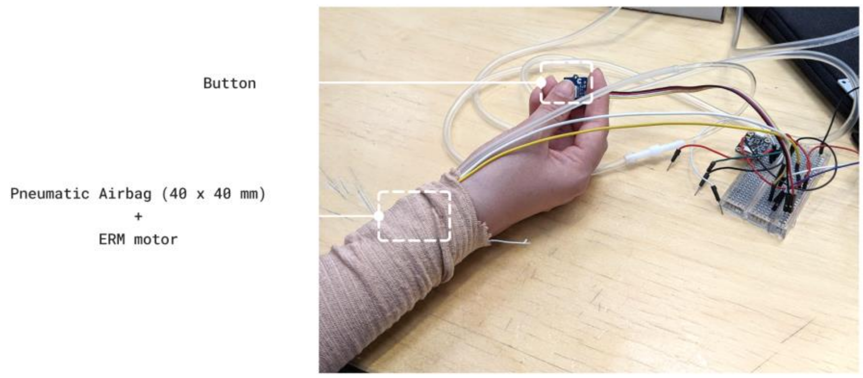


Figure 24: Research setup with a user holding the button to measure reaction time.

A total of six patterns were programmed using an Arduino. A visual representation of these can be found in Figure 25.

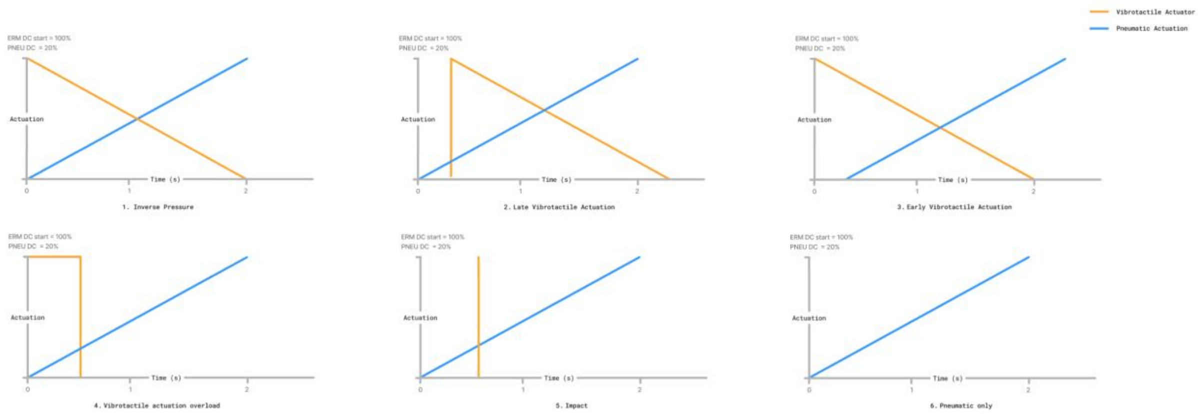


Figure 25: Six programmed vibrotactile-pneumatic patterns.

1. Inverse Pressure
Directly inverting air pressure readings from the programmable air toolkit. These values are used as actuation signals for the vibrotactile actuator. As pressure increases, vibrotactile actuation decreases. This pneumatic behaviour was applied to every pattern to only test the influence of vibrotactile actuation on the system as a whole.

2. Late Vibrotactile Actuation
Late reaction time of the vibrotactile system (300 ms delay), to accommodate for later reacting pneumatic system as it takes a fraction of a second to inflate and apply pressure to the wrist.

3. Early Vibrotactile Actuation
Before the pneumatic actuation starts, the vibrotactile actuation starts (300 ms delay).

4. Vibrotactile actuation overload
Creates an intense vibrotactile actuation for 300 ms at the start before pneumatic actuation takes over.

5. Impact
Creating an impact sensation after 300 ms for 100 ms.

6. Pneumatic only
Only use the pneumatic system to see how when users can feel the feedback.

Parameters:	
ERM duty cycle:	100%
Pump duty cycle:	20%
Inflation time:	~2 s

Results

A total of four participants participated in this study. The results regarding the reaction time per pattern and the perceived responsiveness, urgency and comfort per pattern can be found in Figure 26.

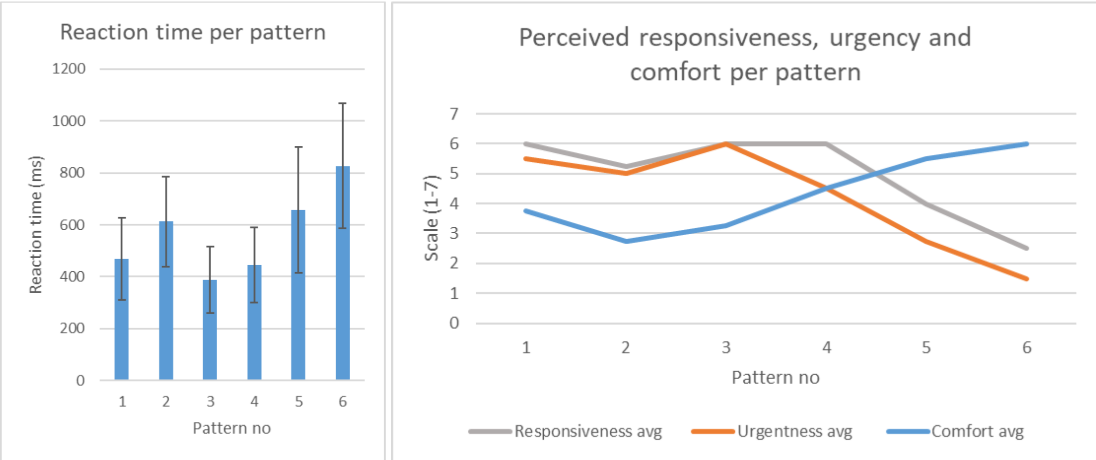


Figure 26: Reaction time per pattern and perceived responsiveness, urgency and comfort per pattern.

The data shows that pattern 3 had the shortest average reaction time (388 ms), followed by pattern 4 (447 ms) and 1 (468 ms) (see Table 2). The slowest pattern was number 6 (827 ms) followed by pattern 5 (657 ms). This data is reflected in the results of the perceived responsiveness here patterns 1, 3 and 4 were perceived as most responsive (6.0 / 7.0) and pattern 6 the least responsive (2.5 / 7.0) followed by pattern 5 (4.0 / 7.0).

Patterns 1 to 3 were found to be the least comfortable and most urgent. Patterns 5 and 6 showed opposite results and were more comfortable and perceived as less urgent.

Descriptives

Reaction time avg (ms)

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1	12	467.75	157.922	45.588	367.41	568.09	294	772
2	12	611.92	174.611	50.406	500.97	722.86	289	932
3	12	388.00	127.005	36.663	307.30	468.70	191	660
4	12	446.67	145.499	42.002	354.22	539.11	246	693
5	12	656.67	242.873	70.112	502.35	810.98	253	957
6	12	826.83	241.029	69.579	673.69	979.98	337	1193
Total	72	566.31	234.827	27.675	511.12	621.49	191	1193

Table 2: Descriptive data on the reaction times per pattern.

Reflection

Reaction time

The patterns utilising more intense vibrotactile actuation at the start (1 - 4) yielded faster response times. Pattern 6 which utilised only pneumatic actuation was over twice as slow to notice than the fastest pattern, pattern 3 (827 ms compared to 388 ms).

Patterns 1 to 3 are very similar as their vibrational pattern remained the same but is delayed for pattern 2 and advanced for pattern 3. Pattern 3 was found to be most responsive which could suggest that solely using vibrational actuation is most responsive or that pneumatic actuation could interfere with responsiveness.

Pattern 5 actuated with the same delay as pattern 2 with the difference being simulating an impact as opposed to a slow decrease in vibrotactile actuation. This was perceived slightly later (657 ms compared to 612 ms). However, the standard deviation (see Table 2) for pattern 5 was found to be larger than pattern 2 (243 ms as opposed to 175 ms), which could suggest impact actuation is less clear.

Perceived responsiveness, urgency and comfort

The perceived responsiveness was closely aligned with the measured reaction times suggesting the moment they feel a system actuate, feels directly more responsive.

This research aligns with results from Chapter 2.2.3, in which vibrotactile association was more associated with urgency while pneumatic actuation feels more comfortable. This means that these patterns could be utilised in a device able to convey a range of notifications from more subtle to more alerting ones depending on the application.

Improvements and Future Research

Some users were able to identify the sounds of the button press and valve opening even though headphones were worn. For future research, ear protection would be needed to cancel unwanted sounds that could trigger actuation to solely focus on tactile perception.

During the experimentation, the air pumps were set at the same power level. External variables such as wrist circumference and tightness of the sleeve could influence the results, which is why for future research a way of verifying is needed to ensure the actuation remains the same or to compensate for the difference. Internal pressure measurements can be recorded during the research or externally applied pressure measurements at the wrist using a Force Sensitive Resistor (FSR).

As was found in Chapter 2.1.2, users perceive vibrations and pressure intensities differently from one another. A way to accommodate for these differences in perception could be something to implement in future research to gain more accurate insights. Furthermore, different intensities of vibrotactile and pneumatic actuation could also be explored.

3.4 Preliminary Experimentation Conclusion

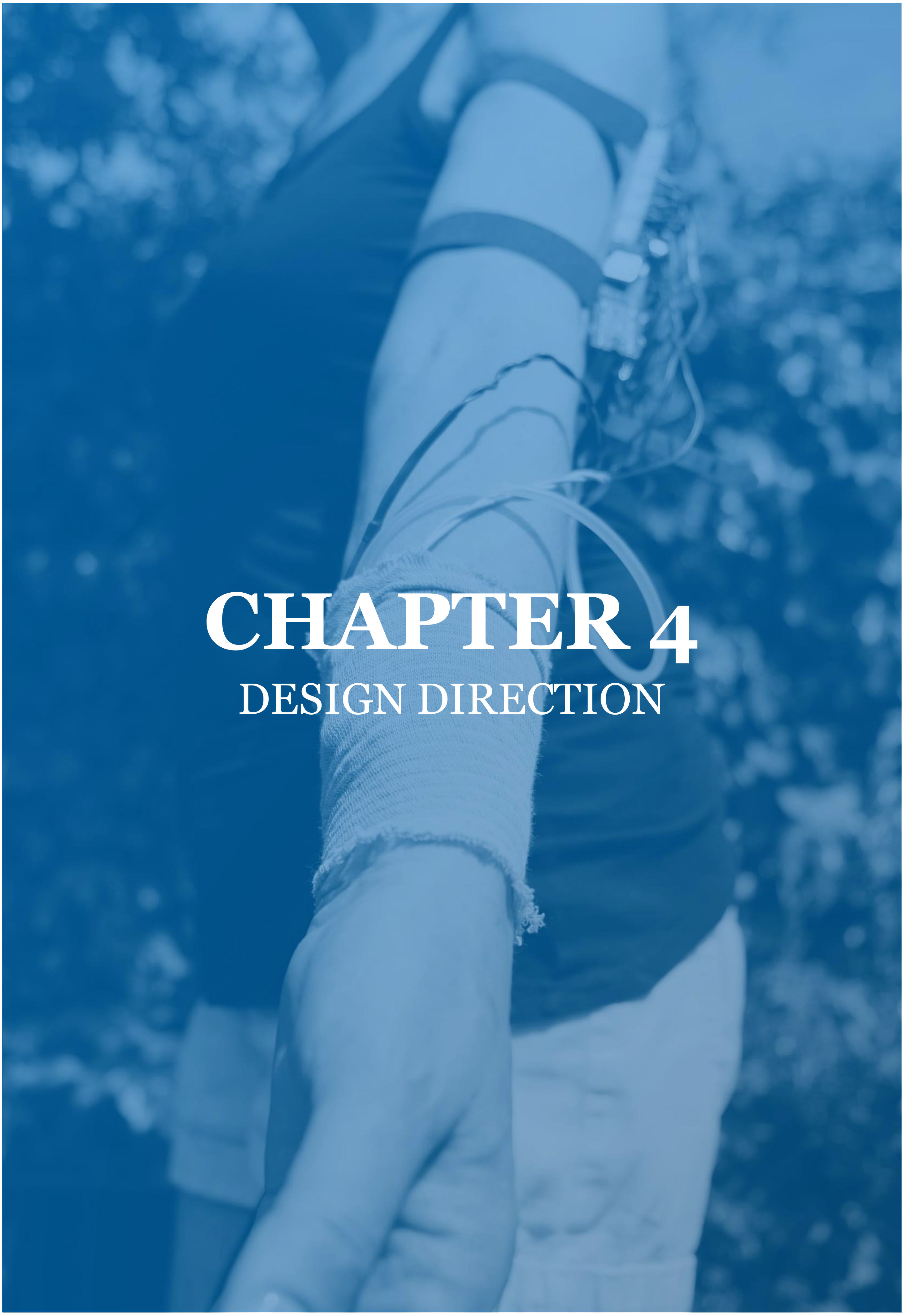
The preliminary experimentation conducted in this Chapter aimed to explore the potential of using vibrotactile actuation to compensate for the slow response times of pneumatic systems in wearable devices and test on feel. The experiments focused on two main areas: compensating for slow inflation time of smaller, potentially wearable, pneumatic systems using vibrotactile actuators, and testing different vibrotactile patterns to understand their impact on responsiveness, urgency, and comfort.

In the first set of experiments, it was observed that incorporating vibrotactile actuation alongside pneumatic systems improved user perception of system responsiveness during both the inflation and deflation stages. Vibrotactile actuation provided users with immediate feedback, creating the illusion of faster response from the pneumatic system.

Several different types of vibrational actuators have been evaluated based on responsiveness and feel. The evaluation of vibrotactile actuators for compensating pneumatic actuation showed that ERMs offer high intensity but slower response times compared to LRAs and LMRs. While ERMs are compact and intense, LRAs and LMRs react instantly, allowing for dynamic patterns.

Further experimentation involved testing different vibrotactile patterns to evaluate their impact on user perception. Patterns incorporating intense vibrotactile actuation at the beginning were found to bring out faster response times from users, suggesting that more intense initial vibrational feedback enhances perceived responsiveness. Additionally, the perceived urgency and comfort varied among different patterns, with vibrational patterns being perceived as more urgent but less comfortable.

Several insights were gained from additional experiments, including the influence of actuator location and size on user perception, as well as the effect of orientation on the feel of vibrotactile actuators (see Appendix A). These experiments provided valuable information for optimising the design of wearable devices.



CHAPTER 4

DESIGN DIRECTION

4. Design Direction

This Chapter concludes the main insights gathered from the previous literature research and preliminary exploration Chapters and the explorative part of the research as a whole. It goes in-depth into the main benefits of combining pneumatic actuation with vibrotactile feedback (see Figure 27) after which the project direction is defined.

4.1 Main Benefits of Combining Pneumatic Actuation with Vibrotactile Feedback

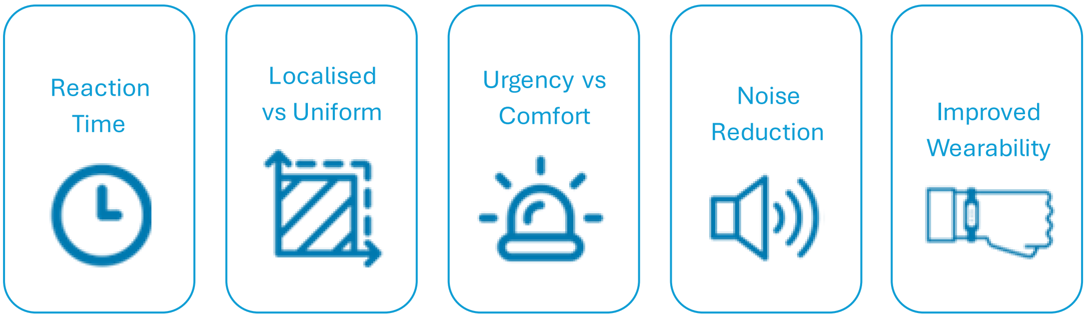


Figure 27: Overview of the potential areas of combining pneumatic actuation with vibrotactile feedback.

4.1.1 Reaction Time

Vibrotactile actuation has a fast reaction time. Pneumatics can have a short reaction time as well, although large compressor pumps are needed to achieve this. This is especially the case for larger pneumatic airbags, which are commonly used in research examples regarding affective touch. Some examples include the "Force Jacket" (Delazio et al., 2018) and "aSpire" (Choi et al., 2021), both utilising large air compressors which reduces the mobility of the participant and the amount of scenarios which can be explored.

Vibrotactile actuation can be used to compensate for this loss in reaction time of smaller pneumatic systems by providing a stimulus during the inflation/deflation. This was found to be effective in Chapter 3.1 and 3.3.

4.1.2 Localised vs Uniform stimuli

Vibrotactile actuation can give a very localised stimuli as the surface area can be very small. Pneumatics can have this as well, as was found in Chapter 2.2.1 and in some cases mimic vibrations. However, as was found in Appendix A.2, these were more difficult to notice than larger air bags and come at the cost of comfort. A solution would be to have multiple air valves to control an array of smaller airbags after which pressure from a larger size takes over to increase comfort, although this will result in a more bulky, complex system.

Vibrotactile feedback was clearly noticeable, dependant on the type of actuator (see Chapter 3.2), where comfort could be improved by increasing its surface area (see Appendix A.2). Thus, combining pneumatic and vibrotactile actuation can portray a range from very localised to more uniform stimuli.

4.1.3 Urgent vs Comforting stimuli

As was found in Chapter 2.2.3, pneumatic actuation can be more comfortably sustained for a longer time than vibrotactile stimuli. Furthermore, vibrotactile feedback can better suggest a feeling of urgency than pneumatic actuation. This was in later experiments confirmed (see Chapter 3.3) whereby a vibrotactile-pneumatic stimulus was applied to the lower wrist and the more vibrational-focused patterns were perceived more urgent and less comfortable than the pneumatic-focused patterns.

This showcases interesting opportunities for combining both types of modalities, for example for notification design or touch translation, as a range of intensities can be explored.

4.1.4 Reduction in Noise

As was found in Chapter 2.2.1, noise is a common issue in pneumatic wearable design. In case the responsiveness of a pneumatic can be compensated for through vibrotactile actuation, it might be possible to run pneumatic pumps at a lower power output, reducing volume. Besides, flow-rate becomes of less importance which opens-up new possibilities for choosing pneumatic actuators.

4.1.5 Improved wearability

Following up on the point of improved responsiveness (4.1.1), this allows designers and researchers to develop smaller, more wearable pneumatic systems. This opens up a new design space in which researchers can better explore real-world testing while making these devices better integrated into our daily lives by being less obtrusive. This can be especially true for body locations in which one would like to minimise mass and size, such as the arms.

Furthermore, this allows product designers to explore soft wearable devices making use of affective touch, a key advantage of pneumatics as outlined in Chapter 2.2.1.

[redacted]

4.2 Project Direction

After identifying multiple possibilities regarding the benefits of combining pneumatic with vibrotactile feedback in wearables the decision was made to focus on creating the illusion of a faster-responding pneumatic system by combining it with different modalities.

This is quite a novel approach as it would mean the pneumatic systems can be comfortably, and wirelessly worn as the system can be downsized. This would enable researchers to better test in real-world scenarios where users are asked to wear a prototype for longer periods and aid in product development, ensuring comfortable wearability and seamless integration with human movement patterns.

“Creating the **Illusion** of a **Faster Responding Wearable Pneumatic System** through **Vibrotactile Enrichment**”

Other decisions include opting for testing discriminative touch instead of affective touch. Affective touch is usually connected with stroking at specific speeds (see Chapter 2.1.3) while discriminative touch can be more reactive and instant. Although a major benefit of pneumatic technology is its potential in affective touch, for validating the effectiveness of the technology and quickness of actuation discriminative touch is better suitable.

To further showcase the potential of this technology, the lower wrist was chosen as the location to test. As was found in Chapter 2.2.4, the wrist is a suitable location for wearables as it is a sensitive area and allows for measuring bio signals such as heart rate, blood pressure and temperature. Besides, this location allows for larger air bags, which are commonly difficult to react quickly with small pneumatic systems, and is usable in affective touch applications. As the system surrounds the wrist, this can be easily translated into other body locations such as the arms or waist, exemplified in Chapter 2.2.5.

4.3 Potential User Scenarios

Accommodating the chosen project direction in the previous subchapter, two potential user scenario were presented acting as potential use cases for this technology.

4.3.1 Interpersonal Touch

To demonstrate the potential of this design concept, a scenario is presented in which users can wirelessly communicate different tactile sensations to one another (see Figure 28). By utilising pressure data, a touch can be translated into pneumatic and/or vibrotactile actuation, mimicking the sensation of somebody touching. This opens up possibilities to explore various types of touches, ranging from soft and gentle to firmer ones, as well as touch and hold interactions.

The novelty lies in translating touch into both actuation types and having systems which are wearable and tetherless, allowing freedom of movement while retaining responsiveness. For the sake of this research, only one actuator of each type is explored to reduce the amount of variables. However it is suggested for future research to experiment with adding more actuators to simulate more affective behaviour.

Ultimately, this scenario acts as a proof-of-concept of this technology and as a step-up towards novel applications such as wireless VR/AR communication and portable affective wearables which can be integrated into our daily lives.

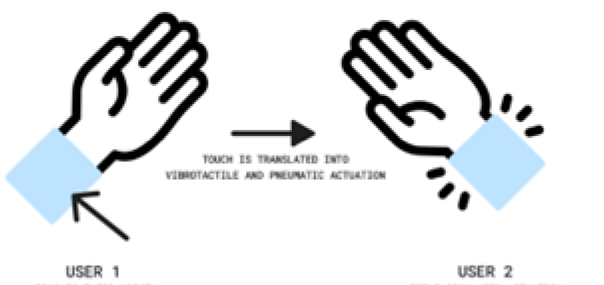


Figure 28: Wireless interpersonal touch translation.

[redacted]

4.3.2 Simulating a Wrist Touch/Hold in a Virtual Reality Environment

Coping with stressful situations can be difficult at times. Virtual reality (VR) provides an outcome as these situations can be simulated and experienced by users from an environment where they feel safe and by taking small steps at a time. Most VR setups are limited in the sense they focus mainly on visualising an environment and have limited haptic feedback (mostly vibrational feedback from a hand-held controller). A mobile device, able to simulate a touch on the wrist could provide an outcome for a more immersive experience. For example, a firm grip on the wrist can be used to guide users in an environment in which they don't feel confident and need to overcome fear. On the other hand, a softer actuation could be used in an affective manner, soothing the user and providing emotional support.

Guidance in VR-applications was found to improve effectiveness in obtaining operative skills (J. Yang et al., 2022; Bucher et al., 2018), although there is a lack in research for emotional support of wrist guidance.

This is especially valuable for VR exposure therapy to overcome phobias. VR is hereby used to simulate a controlled environment in which patients are subjected to their fear in a gradual, and controlled manner (Rosen, n.d.). VR was discovered to enhance effectiveness in treating anxiety disorders when compared to in-person or imagined exposure techniques (Boeldt et al., 2019). A lack of immersion was found by Benbow & Anderson (2019) to be the most common reason for dropping out of VR exposure therapy, suggesting a need for solutions offering improved realism.

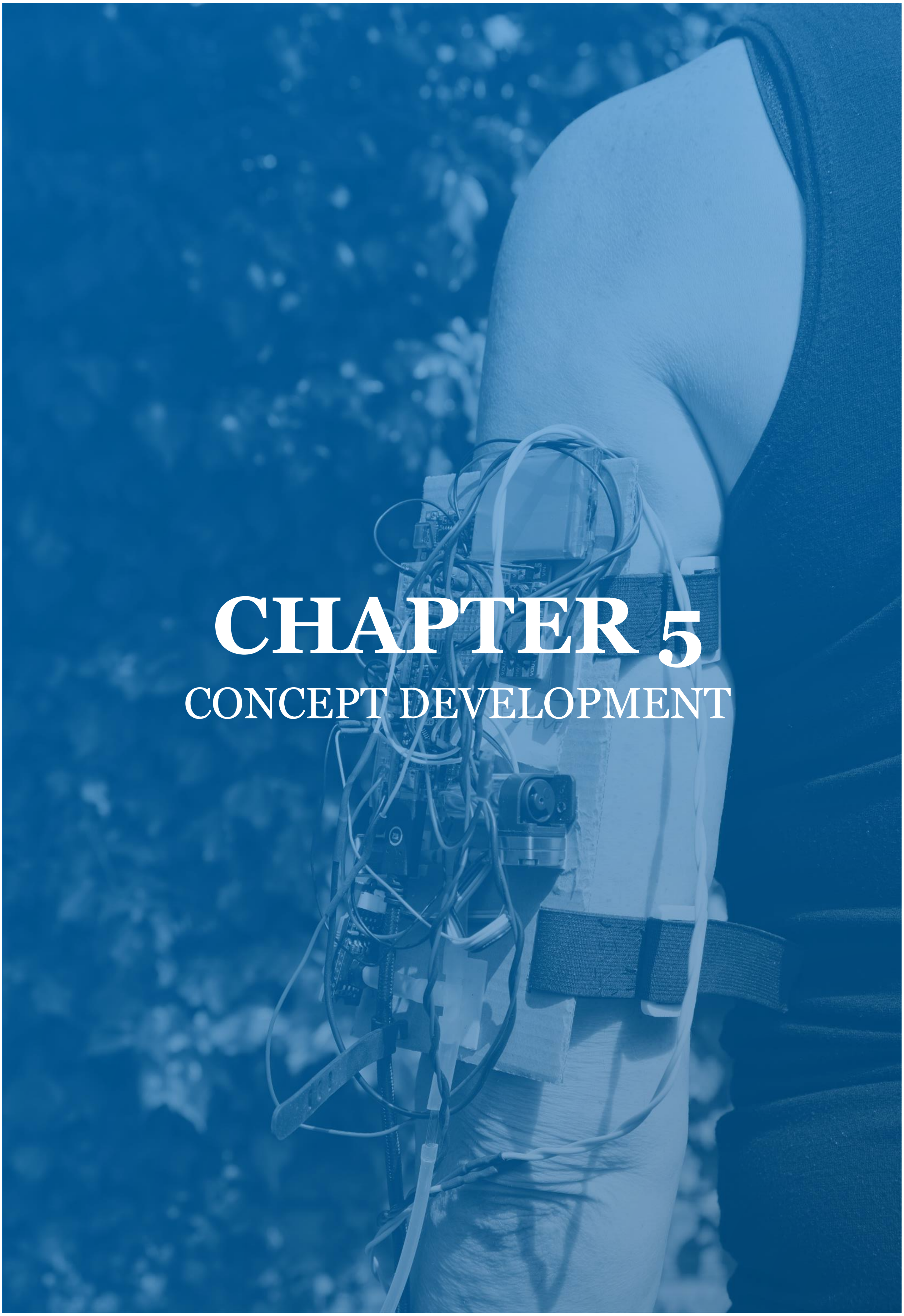
A wrist hold (see Figure 29) was found to relax the user and decrease their heart rate

Figure 29: Wrist hold (photograph: Du Preez, 2018).

(Eckstein et al., 2020). Similarly, as was found in Chapter 2.2.4, affective touch can be conveyed through the wrist via simulated squeezing or stroking motions (X. Yang & Zhu, 2023).

Other potential application areas include: [redacted]

- Facilitate emotional regulation in the wild (Miri et al., 2018).
- Utilise for breathing regulation and to reduce anxiety (Miri et al., 2020).
- Wireless hand rehabilitation device (Du et al., 2022).



CHAPTER 5
CONCEPT DEVELOPMENT

5. Concept Development

The device proposed in Chapter 4.2, can be divided into four subparts. Firstly, the primary device needs to be able to sense a human touch on the wrist. Secondly, the raw data from this sensor needs to be translated into a pneumatic/vibrotactile actuation signal to accurately represent the input signal (touch). Thirdly, this signal would need to be wirelessly communicated to the secondary device. Finally, the secondary device needs to actuate giving the impression of a human touch. An overview can be found in Figure 30.

This Chapter delves into the concept development phase of the device proposed in Chapter 4.2 and the underlying technologies behind it.

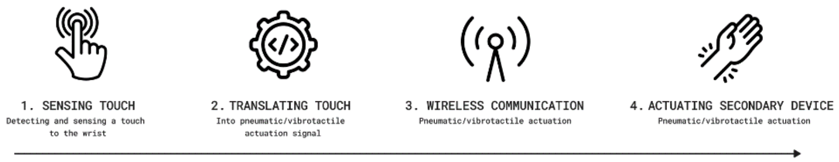


Figure 30: Overview of the steps needed to translate touch on the wrist and actuate a simulated touch on a secondary device.

5.1 Design Requirements

A series of design requirements were made to guide the design process. The have been categorised into three categories: wearability, system performance and usability. These are further described in this Chapter.

1. **Wearability**
    - 1.1. Freedom of Movement
        - 1.1.1. Low Weight: Device weight should be less than 0.2 kg (Zeagler, 2017).
        - 1.1.2. Compact Size:
            - 1.1.2.1. Lower arm dimensions: 6 mm – 13 mm (Zeagler, 2017).
            - 1.1.2.2. Upper arm dimensions: 25 mm – 51 mm (Zeagler, 2017).
        - 1.1.3. Wireless Touch Reception: Device must be capable of receiving touch signals wirelessly.
        - 1.1.4. Tetherless Operation: Device must function without being tethered to an external system.
    - 1.2. Ease of Use
        - 1.2.1. Device should be wearable on the wrist within 20 seconds.

2. **System Performance**
    - 2.1. Touch Imitation
        - 2.1.1. Quick Response: Device should respond to touch within 0.1 seconds.
        - 2.1.2. Comfort: Device should feel more comfortable over time compared to solely using vibrotactile actuation.
    - 2.2. Integrated Actuators
        - 2.2.1. Device should incorporate both vibrotactile and pneumatic actuators on the lower wrist
    - 2.3. Reliable Wireless Operation
        - 2.3.1. System should reliably receive touch data wirelessly and actuate accordingly.

3. **Usability**
    - 3.1. Programming and Experimentation
        - 3.1.1. Device should facilitate easy programming and experimentation with different touch patterns and settings.
    - 3.2. Calibration
        - 3.2.1. Device should allow for calibration of the vibrotactile actuator based on user preferences.

5.2 Initial Prototype: Reducing Form Factor

In the initial experiments described in Chapter 3, the Programmable Air toolkit was employed. However, its bulkiness and power requirements make it challenging to use as a fully wearable system. To demonstrate the potential of the pneumatic/vibrotactile technology, a smaller, mobile prototype was created. This new prototype maintained responsiveness despite using smaller, low-power pneumatics. This Chapter delves into the process of reducing the form factor and the technology underlying this initial prototype.

5.2.1 Reducing Functionality and Improving Form Factor

First, the essential functions of the pneumatic system were identified to reduce its form factor. As shown in Figure 31, the Programmable Air toolkit includes functions for inflation, equalising pressure, and vacuum. The vacuum function, however, is not necessary for simulating touch. By excluding this function and the valve in front of the compressor pump, a more compact system can be achieved. This adjustment allows for the use of a single valve and compressor instead of three valves and two pumps to imitate touch functionality.

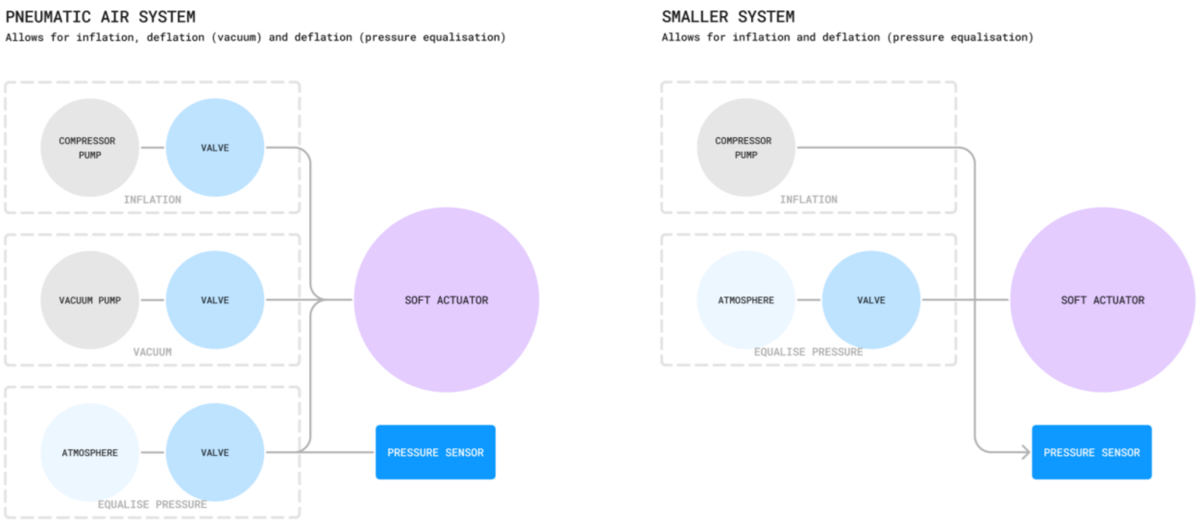


Figure 31: Programmable Air toolkit (left), customised compact system (right).

Compact System

The next step is to test the functionality of the described system. For this, a small cardboard template was used to lay out all the components and assess their functionality (see Figure 32). A simplified version of the wiring circuit, along with power draw estimations, is shown in Figure 33.

In this new design, a small air pump (RS PRO Gas Compressor Pump 702-6898) and a valve (DC 5V One Way Exhaust Valve) were used (see Figure 33 for a system overview). To establish wireless communication for transmitting touch, an NRF24L01 module integrated with an Arduino Nano was utilised. An air pressure sensor was used to measure the internal air pressure, preventing the system from over-inflating. Additionally, to make the device completely wireless, it is powered by an 800 mAh Li-Po battery, which can be recharged using a TP4056 USB-C module. The battery (3.7 V) powers the Arduino by raising its voltage to 5 V using an MT3068 step-up module.

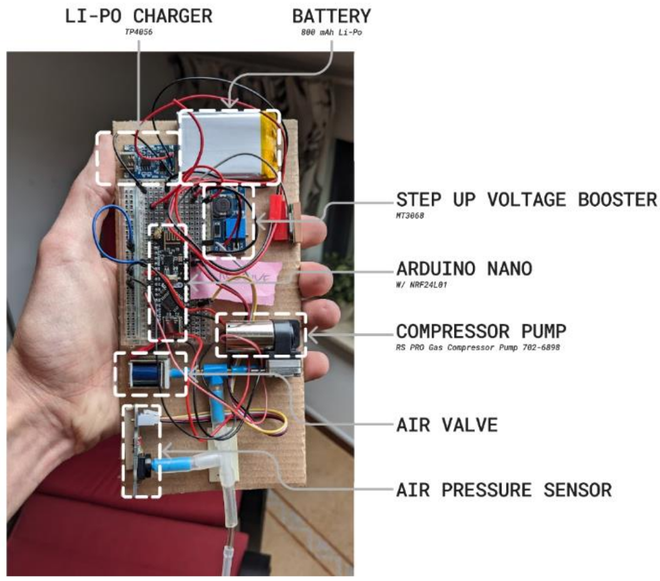


Figure 32: Mobile pneumatic/vibrotactile system.

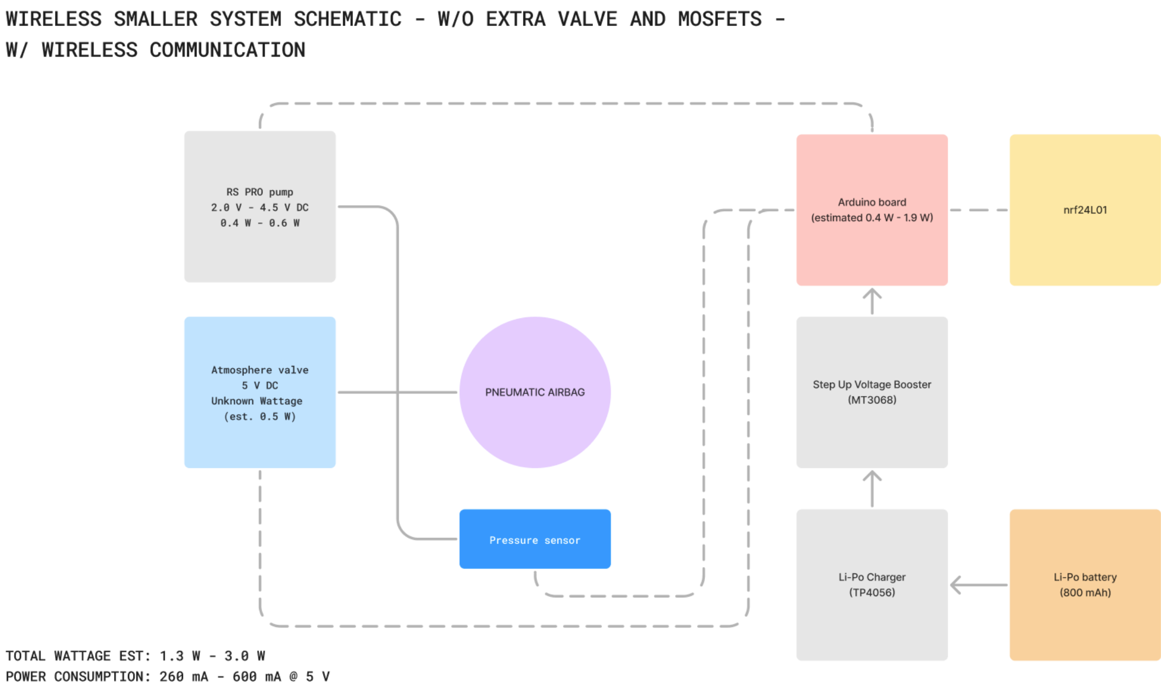


Figure 33: Detailed wiring schematic of the proposed system.

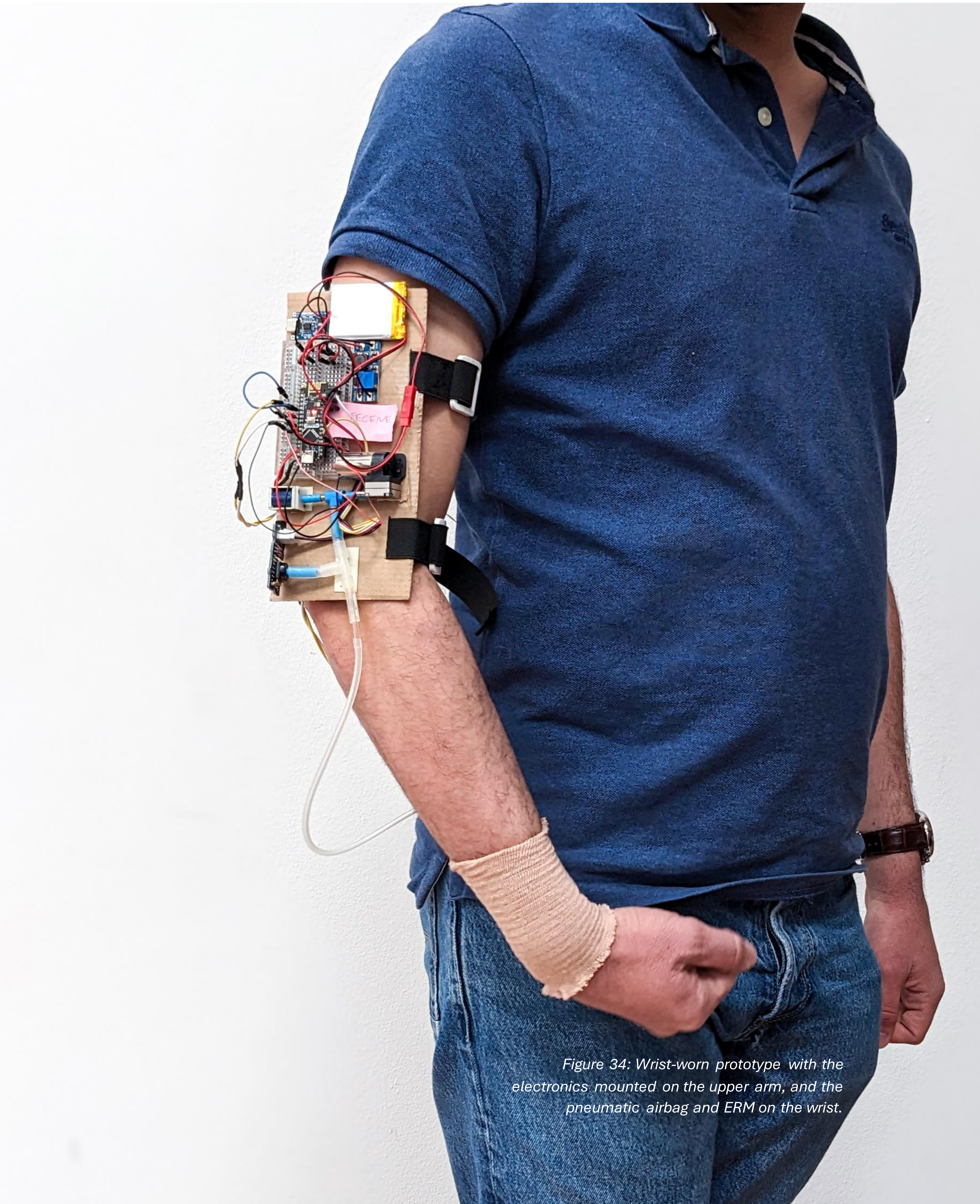


Figure 34: Wrist-worn prototype with the electronics mounted on the upper arm, and the pneumatic airbag and ERM on the wrist.

5.2.2 Sensing Touch

To effectively communicate touch and create touch patterns, the first step is to sense the touch. Two options were experimented with: an FSR sensor and an air pressure sensor.

Force Sensitive Resistor (FSR)
Force-sensitive resistors change their resistance when an external force is applied. Since a touch on the wrist applies pressure, an FSR can be used to translate this pressure into a digital signal suitable for computing and wireless communication. For instance, Huisman et al. (2013) utilised conductive wool in their "Tactile Sleeve," which acted as an FSR, effectively converting touch into a digital signal.

Air Pressure Sensor
An air pressure sensor can measure touch by detecting changes in the internal pressure of a pre-inflated pneumatic airbag within an airtight system when it is pressed.

Comparing an FSR to an Air Pressure sensor.
The FSR reliably recreated touch forces when pressure was applied to the sensor (see Figure 35). Typically, FSRs exhibit a linear correlation between resistance and force when plotted on a log/log scale (see Figure 36), enabling direct calculation of applied force.

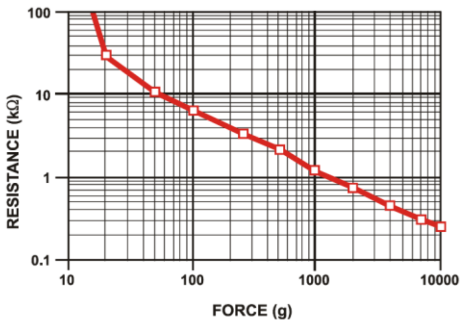


Figure 36: Resistance plotted against force of an FSR (Interlink Electronics, n.d.).

In contrast, the air pressure sensor also recreated touch, but required partial inflation of the airbag to obtain a reading. Additionally, its readings were more influenced by factors such as wrist circumference and pressure from clothing or sleeves than FSRs. Due to these complexities, an FSR sensor was preferred over an air pressure sensor to translate touch force into a digital signal.

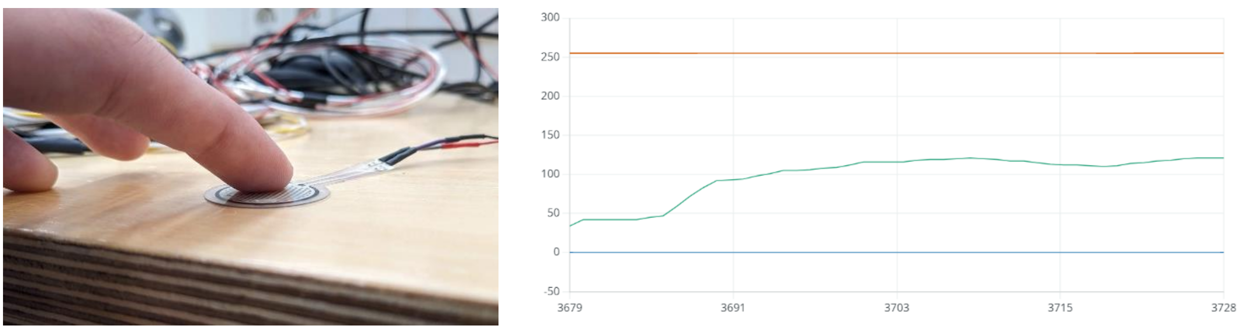


Figure 35: Touching an FSR (left) and the resulting 8-bit digital signal (right).

Depending on the chosen pull-down resistor in a voltage divider circuit, the sensitivity of the sensor can be adjusted (see Figure 37). This effect was validated through own experimentation using a 40 mm x 40 mm FSR sensor (see Figure 38). In practical testing, the FSR successfully detected forces ranging from 0.1 N to 2.3 N.

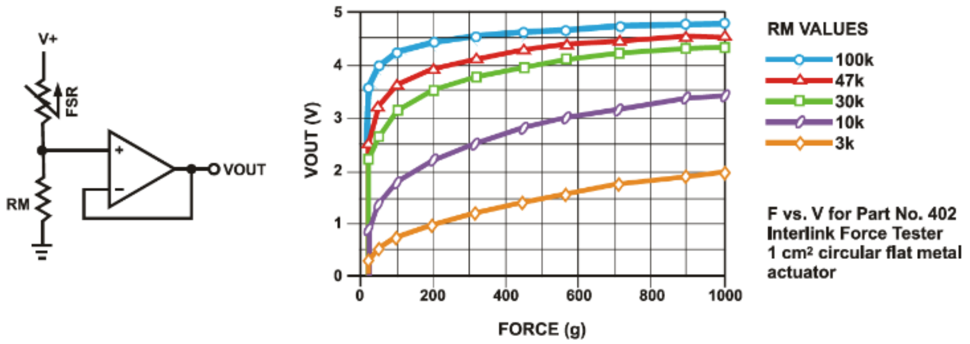


Figure 37: Different pull-down resistors in a voltage divider circuit result in different sensitivities (Interlink Electronics, n.d.)

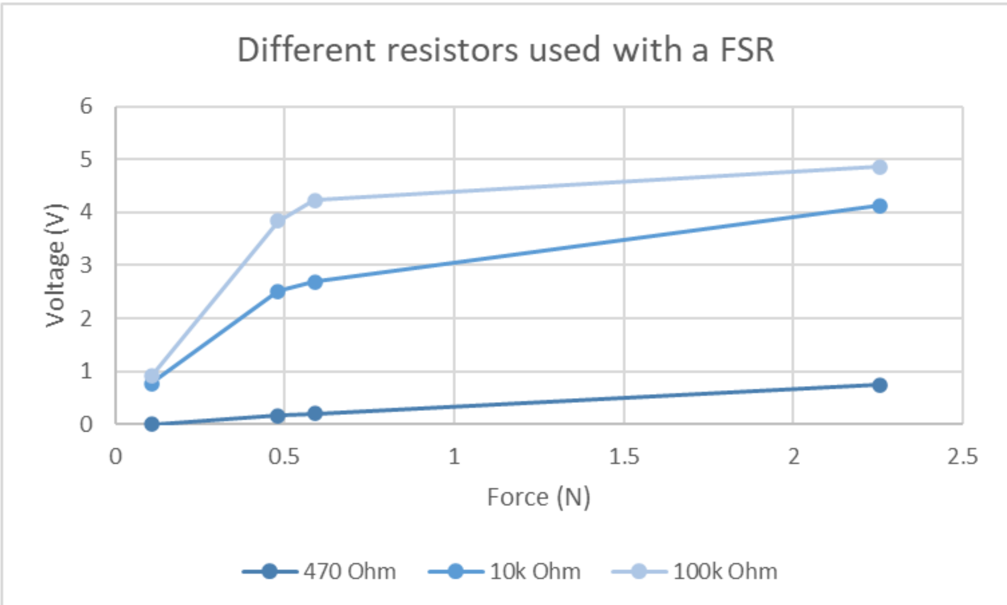


Figure 38: Experimentation with different pull-down resistors on an FSR.

5.2.3 Creating a Reliable Inverse Signal of Pressure Increase from the Pneumatic Airbag

In previous experiments (refer to Chapter 3.3), an attempt was made to use the inverse air pressure signal to actuate the ERM motor. However, further testing (see Chapter 5.2.2) revealed that this approach produced unreliable results for precise ERM actuation. Therefore, an FSR positioned between the pneumatic airbag and the skin is now employed to sense the pressure exerted on the skin.

To calibrate the FSR, an initial calibration code measures the resistance of the FSR under minimal pressure (when the pneumatic airbag is deflated) and maximum pressure (when the pneumatic airbag is inflated) while worn (see Figure 39). This calibration range is then used to map the intensities of the ERM, compensating for the slower response of the pneumatic system.

One issue encountered with the 40 mm x 40 mm FSR sensor was its sensitivity to wrist movement, leading to inconsistent readings. To address this, a smaller round FSR sensor (10 mm diameter) was adopted, which, although less accurate, remained stable during movement. Consequently, the pull-up resistor was adjusted from 10k Ω to 470k Ω to improve sensitivity (see Chapter 5.2.2).

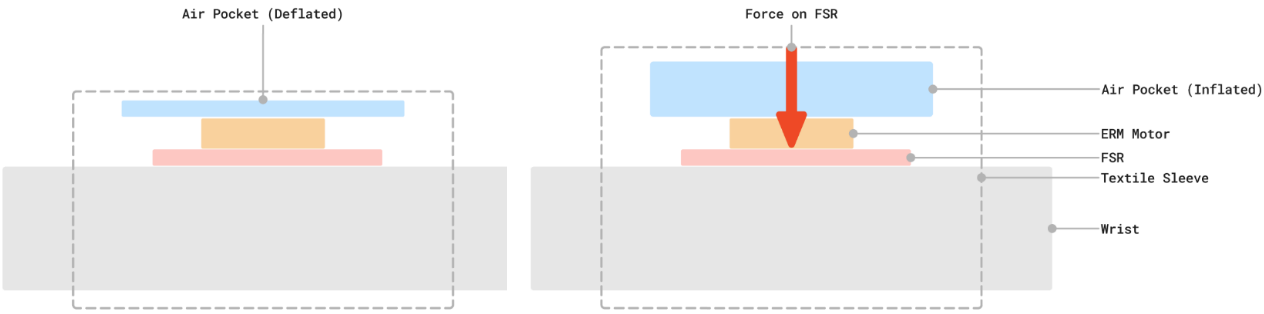


Figure 39: Force acting on FSR when air bag is inflated, which is used to drive a vibrotactile signal

5.2.4 Improving ERM Responsiveness

As discovered in Chapter 3.2, vibrations are perceived slower by ERMs at lower voltages. To address this, a code was developed that initially exceeds the desired value to rapidly ramp up the ERM (see Figure 40). This approach enhances responsiveness, eliminating the need for faster actuators like an LRA or LMR, as detailed in Chapter 3.2.

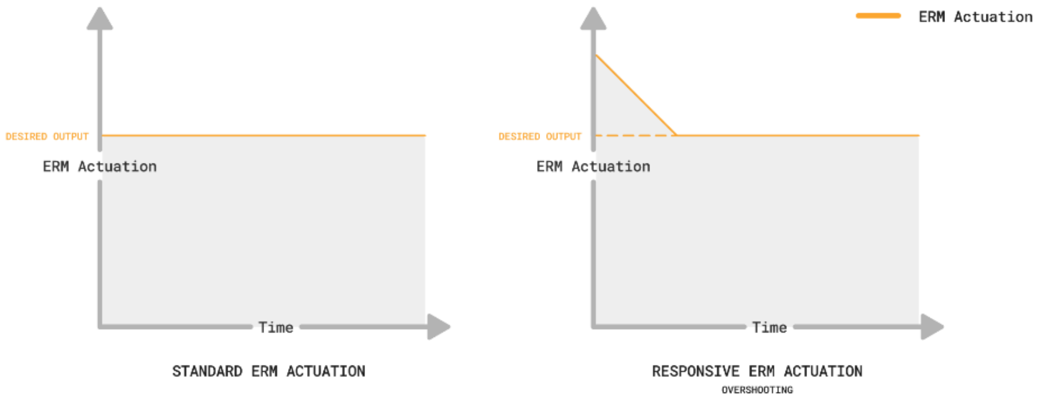


Figure 40: Regular ERM driving signal (left) and more responsive driving signal (right).

5.2.5 Calibration of FSR and Satiety

As observed in Chapter 2.2.3, human sensitivity varies for pressure and vibrations among individuals. To address this variability, adjustments are necessary to align the intensity of the vibrotactile actuator with that of the pneumatic actuator. An initial calibration process allows users to match the intensity of the vibrotactile actuator to the pneumatic inflation of the airbag using a potentiometer (see Figure 41).

In an initial experiment with a participant, it was challenging for them to accurately sense and adjust the intensity to match that of the pneumatic actuated airbag, potentially due to satiety effects (similar to findings in Chapter 2.2.2). This issue was later resolved in Chapter 5.3.2 by implementing periodic inflation and deflation intervals to regain sensitivity to pressures.

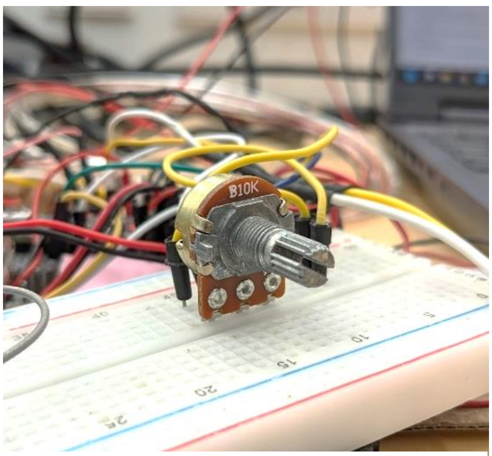


Figure 41: Potentiometer to be used to set the desired vibrotactile intensity.

[redacted]

5.2.6 Experimentation with Pneumatic Airbag Designs

Various types of pneumatic airbags were tested using the fabrication method described by Van Leeuwen (2023), with the modification of ensuring an airtight seal using superglue. One approach involved developing an airbag where both sidewalls were joined in the middle to achieve a more uniform distribution of pressure (see Figure 42). However, in practice, this modification was hardly noticeable, as the airbag could not expand as effectively, leading to less direct actuation.

Another design variation involved using a round shape instead of a square one, but similarly, this alteration did not yield noticeable improvements in performance.

Figure 42: Ultrasonic sewing on PE-film to create airtight airbags (left), airbags produced (right).

5.3 Second Prototype: Enhancing Form Factor, Reliability, and Programmability

5.3.1 Wearable Device

For the second prototype, similar components as those described in Chapter 5.1 were utilised, but focused on optimising space efficiency to enhance portability. The reduced footprint enabled comfortable wearing on the wrist rather than the upper arm (see Figure 43).

In addition to form factor improvements, ensuring device reliability was essential for practical use. To achieve this, all connections were securely soldered onto a protoboard, in addition to metal core wires, which do not break easily at the connections to the protoboard. Furthermore, a custom PLA housing was 3D printed to securely encase and protect the internal components, while keeping its footprint to a minimum.

Other modifications include an on/off switch for the battery, a quick disconnect for the battery components and header pins to easily replace Arduino boards in case one fries (don't ask). Hereby it is important to disconnect the battery components during programming and when the Arduino is directly powered from the USB-cable.

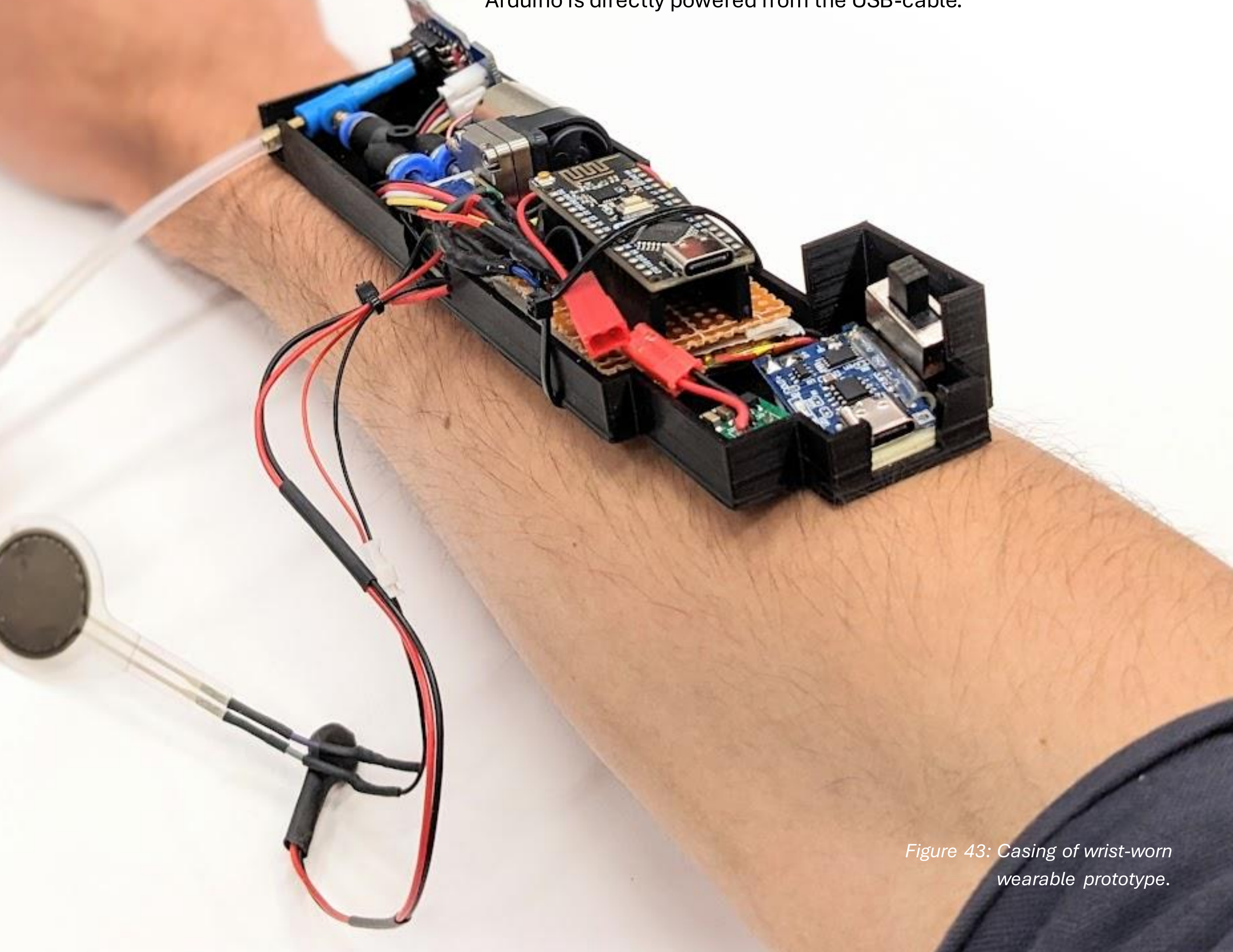


Figure 43: Casing of wrist-worn wearable prototype.

5.3.2 Wireless Controller

The decision was made to also develop a wireless controller to facilitate in user testing and future experiments (see Figure 44). This device allows for skipping calibration phases (adjusting vibrotactile feedback and calibrating FSR), programming and replaying touch patterns, selecting between pneumatic, vibrotactile, or combined modes, and activating the patterns.

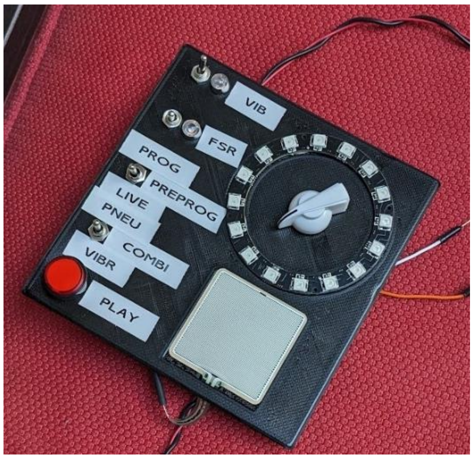


Figure 44: Control Box interface prototype.

```
0 0 0 1 0 2 5
0 0 0 1 0 2 12
0 0 0 1 0 2 24
0 0 0 1 0 2 16
0 0 0 1 0 2 7
0 0 0 1 0 2 18
0 0 0 1 0 2 28
```

Figure 45: Array of switch positions and FSR

Wireless communication between control box and wearble device
Both Arduinos utilized in this setup feature an integrated NRF24L01 module, enabling wireless communication between them on the 2.4GHz RF band. The transmitter continuously sends an array of numbers to indicate the state of each switch (see Figure 45). Due to the limited data package size, some values are temporarily substituted with others to ensure all critical data is successfully transmitted to the receiver. An overview of this wireless connection can be found in Figure 46.

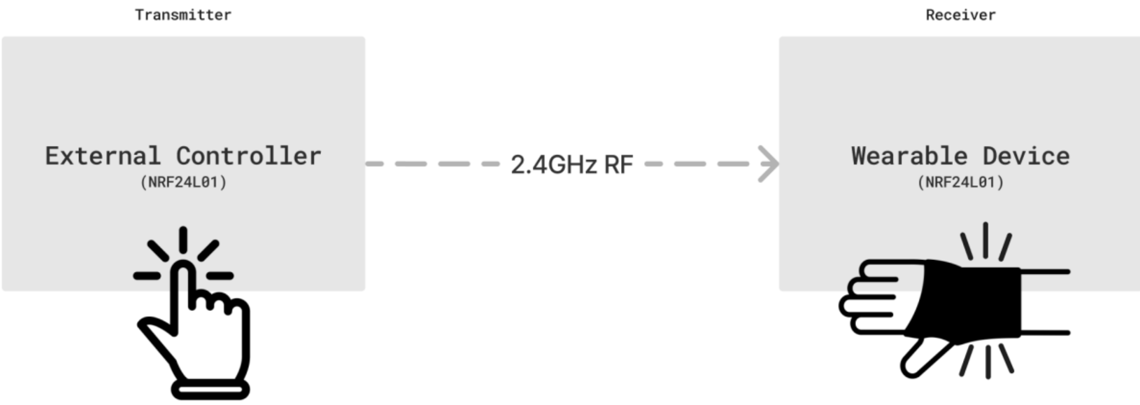


Figure 46: Schematic of data connection between the wireless controller and wearable device.

Calibrating the vibrotactile actuator

As was found in Chapter 5.1.5, the effects of satiety occurred when trying to match the vibrotactile intensity to the pneumatic intensity since after a certain moment, you cannot feel the pressure exerted by the pneumatic airbag. To compensate for this, instead of matching the vibrations to the always-on pneumatic pressure, the airbag inflates at an interval (see Figure 47). This allows participants to regain pressure sensations, making it easier to match both modalities.

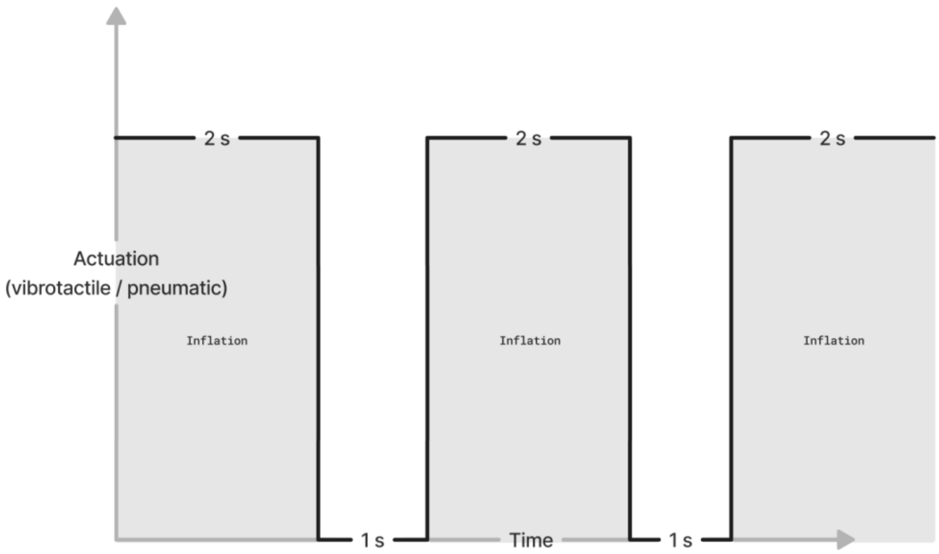
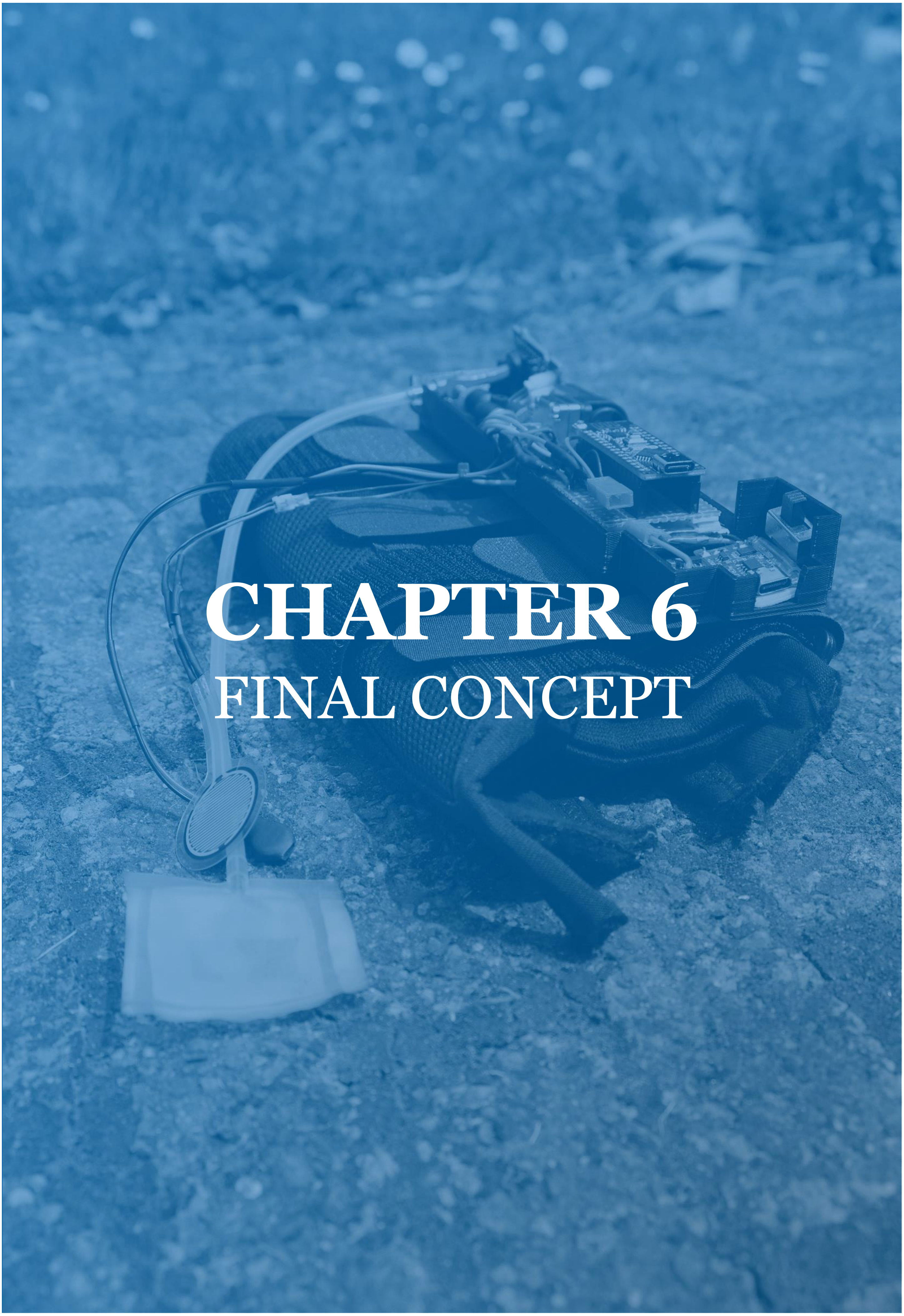


Figure 47: Inflation interval to regain sensitivity and prevent satiety.

Pre-programming Touch Patterns

The touch patterns can be directly programmed into the wireless controller using its integrated FSR sensor. These patterns are normalised, written, and stored in the internal EEPROM memory of the Arduino Nano. This process involves dividing the internal memory into four parts where the FSR values are recorded. To determine the duration needed to read a pattern, the first line of code in each segment is set to the total length of the pattern. This allows the microcontroller to read this line first, informing it of the duration required to read the entire sequence of values for that specific pattern.



CHAPTER 6
FINAL CONCEPT

6. Final Concept

The final concept includes two devices: the wrist-wearable device and an wireless controller. This Chapter provides an overview of the final concept and its features, building on the earlier prototypes described in Chapter 5.

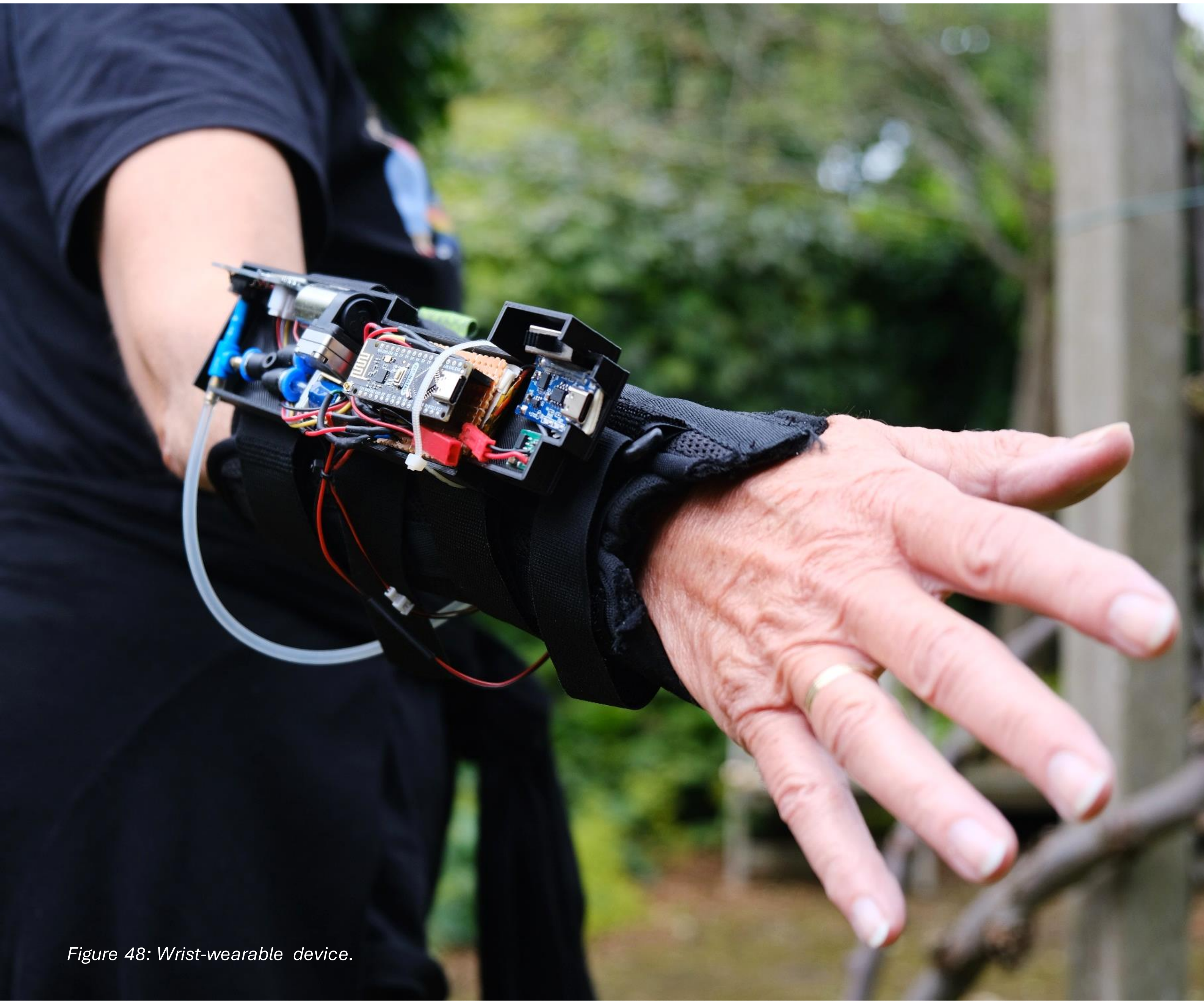


Figure 48: Wrist-wearable device.

6.1 Wrist-Worn Wearable Device

For the final concept, the wrist-worn wearable device has been further developed from the prototypes described in Chapter 5 (see Figure 49, 50). The primary improvement is that the casing is now integrated into a wrist brace, which securely holds the prototype and incorporates the sensors and actuators on the inside of the wrist.

This design is similar to the prototype discussed in Chapter 5.1.1; however, the downsized electronics now allow it to fully fit on the wrist and more reliable through as the connections are soldered. Additionally, the brace material is sturdier than the previously used fabric (see Chapter 3.2), increasing the effectiveness of the pneumatic pressure by providing a higher counterforce.

Figure 49: Wrist-worn wearable device

Another advantage of using a brace is that it already incorporates an adjustment system in the form of velcro straps. This ensures that users can adjut the strap tension based on their personal preferences and wrist dimensions.

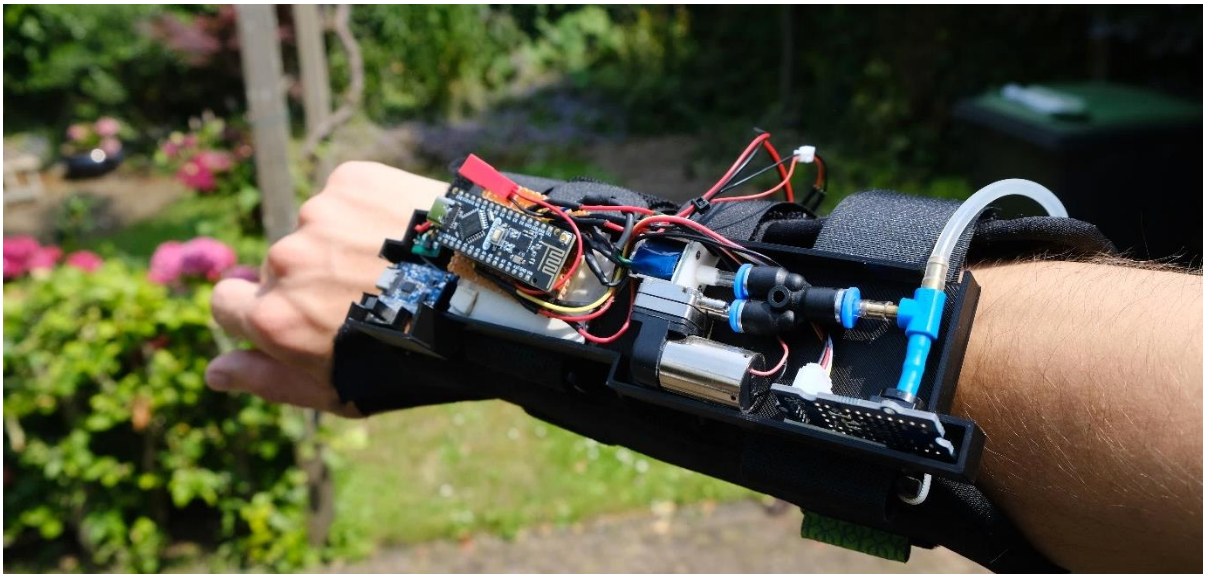


Figure 50: Wrist-worn wearable device incorporated into a brace.

Casing

A protective casing was developed to protect the electronics from accidental bumps (see Figure 51, 52). Using Rhino Grasshopper, a Voronoi lattice structure could be parametrically generated on a modelled surface. This allows the internal components to still be visible while wearing.

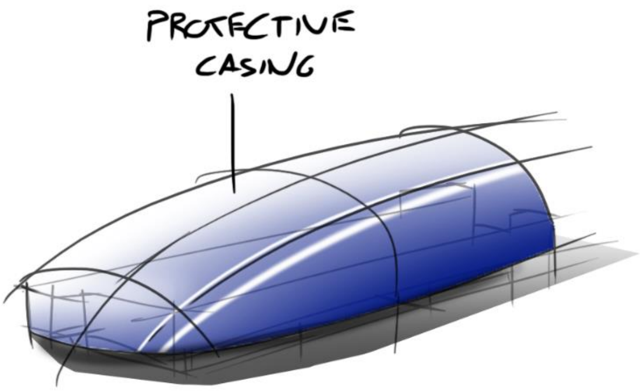


Figure 51: Initial sketch of a protective casing.

Figure 52: Wrist-wearable device with casing

6.2 Wireless Controller

The primary function of the wireless controller is to accommodate for easy programming and experimentation with wireless touch transmission, serving as a toolkit for designers and researchers. The final design of the wireless controller builds upon the design introduced in Chapter 5.2.2. This concept features lasercut plywood parts joined together using finger joints (see Figure 53, 54), with the user interface remaining unchanged.

This wireless controller offers a variety of programs and features, which will be particularly valuable in Chapter 7 for user testing and future research. An explanation of each feature is provided below.

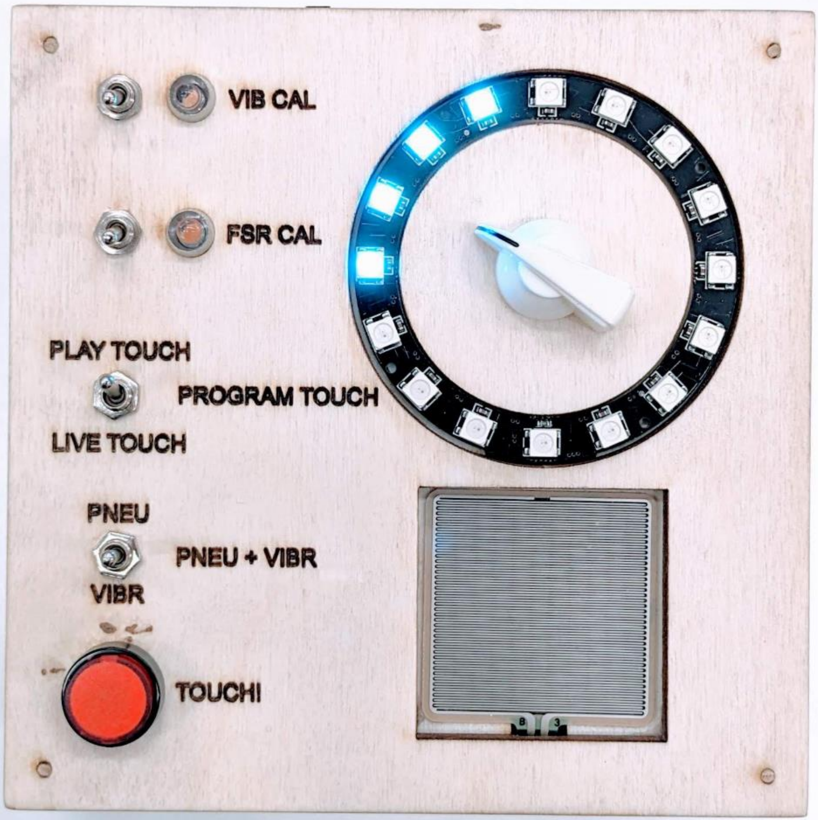


Figure 53: Wireless controller top view.

Vibration Calibration

As described in Chapter 5.2.5, users initially adjust the vibrotactile intensity to match the pneumatic intensity using a potentiometer.

To counteract the effects of satiety from constant pneumatic pressure, the system operates in pulses. For the first two seconds, both the pneumatic and vibrotactile systems activate, followed by a one-second deactivation period to allow for sensitivity recovery (see Chapter 5.3.2). This pattern repeats in a loop. Once the switch is deactivated, the selected vibrotactile intensity is stored in the internal memory.

FSR Calibration

As described in Chapter 5.2.3, an FSR is used to sense the external pressure applied by the pneumatic system to create an inverse ERM signal. Calibration is required to map the minimum and maximum FSR values during deflation and inflation. This calibration process can be initiated using the switch on the wireless controller.

Program Settings
The wireless controller offers three program modes: play, program touch, and live touch. In brief, the play mode plays the selected pattern, program touch is used to create a touch pattern, and live touch allows the user to directly simulate a touch.

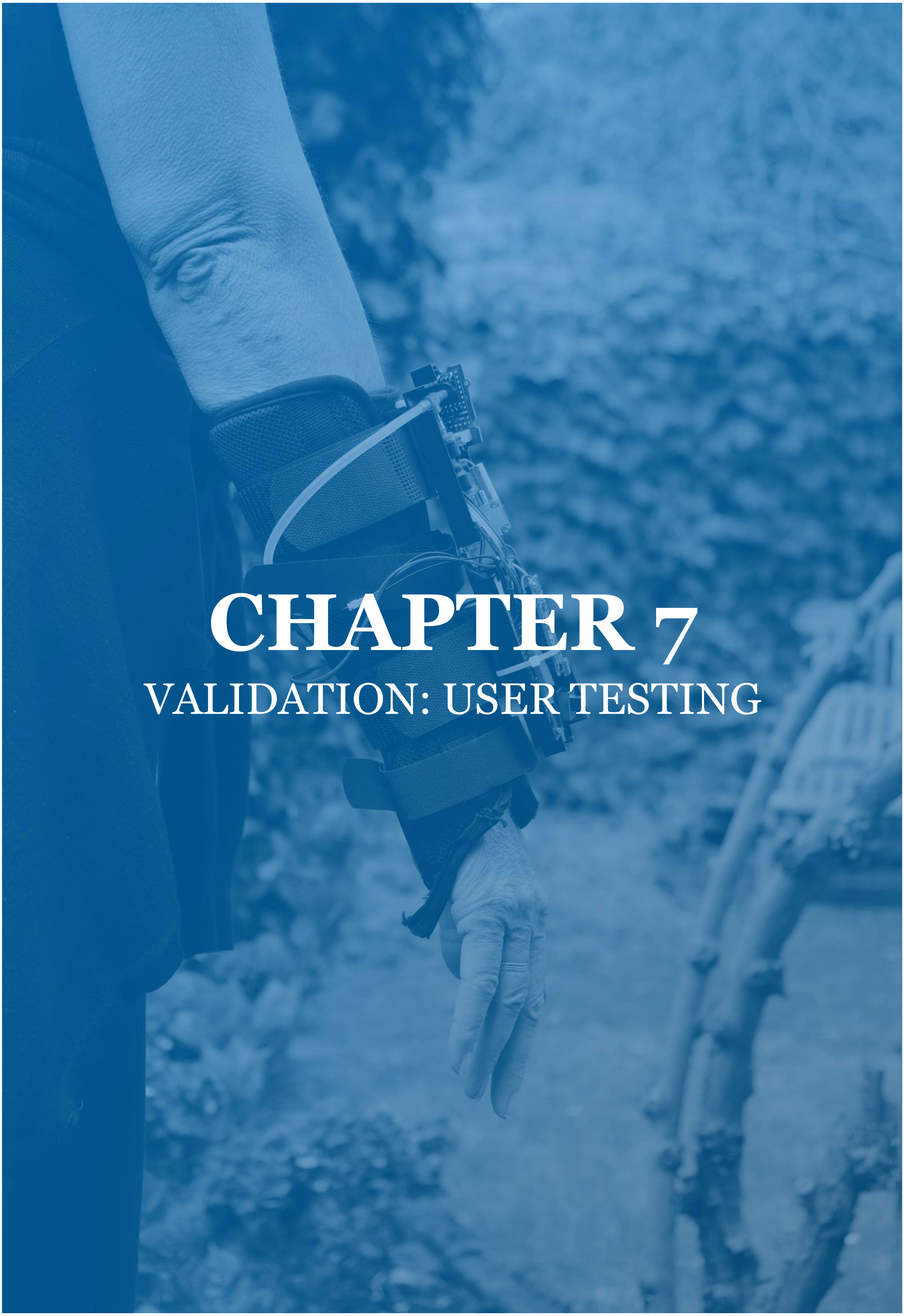
In the play mode, the potentiometer is used to select one of four touch patterns, as indicated by the segmented display. Pressing the red touch button wirelessly transmits the selected pattern to the wrist-worn wearable device, where it is played. The play mode also has a secondary function activated by turning the knob fully clockwise. This mode overwrites the four default patterns with those used in the user tests described in Chapter 7. When the red knob is pressed in this mode, these touch patterns are transmitted in a counterbalanced order, simplifying the execution of user tests.

The program touch mode allows manual input of a touch pattern. Similar to the play mode, the potentiometer is used to select the storage location in the Arduino's internal memory. When the user presses the FSR sensor on the wireless controller, the FSR values are stored in one of these four locations and can be retrieved later through the play mode.

Lastly, the live touch mode enables direct wireless transmission of a touch from the controller to the wrist-worn wearable device by pressing the FSR sensor.

Modalities
Finally, the lower switch allows users to choose from three different modalities: pneumatic only, pneumatic plus vibrotactile, and vibrotactile only. This enables users to experience the various modalities offered by the system.

Figure 54: Wireless controller.



CHAPTER 7
VALIDATION: USER TESTING

7. Evaluation: Touch Pattern Recognition and Simulation for a Pneumatic and Vibrotactile/Pneumatic Wearable System

In order to measure how well the system proposed in Chapter 6 performs regarding imitation of human touch, a user study was conducted. In this study is measured how realistic, comforting and accurate the three modalities (pneumatic only, vibrotactile only and the pneumatic-vibrotactile combination) performed for four different touch patterns.

Hypothesis
A fully wearable pneumatic system enhanced with vibrotactile feedback can better represent human touch patterns.

Variables
Type of touch representation -
pneumatic only, vibrotactile only and the pneumatic-vibrotactile combination

7.1 Study Design

7.1.1 Design

A within-subjects study design was used to evaluate system performance regarding imitation of human touch. A range of four types of touches, commonly used in daily-life situations, were presented and experienced by the participants:

- *Short touch (1s)*
- *Long touch (3s)*
- *Tap (0.1s)*
- *Double tap (2 x 0.1s with a 0.1s interval)*

As independent variables, three modalities were tested: 1) vibrotactile, 2) pneumatic, and 3) vibrotactile + pneumatic haptics. The dependent variables chosen were the level of perceived accuracy to the type of touch presented; the type of touch simulated; and valence, arousal, comfort and intensity of the actuation.

The following questions were asked:

1. *How similar would you rate the actuation felt to the type of touch presented in the video?*
2. *Which touch did you just feel?*
3. *How would you rate the valence, arousal and comfort of the actuation?*

A 7-point Likert scale ranging from not similar at all to very similar was used to rate accuracy. For the second part, participants can choose between four types of touches. Similarly to the first question, valence, arousal, comfort and intensity are rated on a 7-point Likert scale from very unpleasant to very pleasant, very calm to very excited, very uncomfortable to very comfortable and from very calm to very intense respectively. In case participants did not feel the system was acting, the option “I did not feel a touch” could be chosen. All conditions were repeated twice and at any time the participants could request to repeat a touch.

Participant recruitment
Participants were recruited from personal contacts. The testing location was varying but had similar properties to one another (removing any distractions and being in a quiet, isolated environment).

7.1.2 Setup

After introducing participants to the device, they were asked to sign a consent form and fill in a demographic questionnaire including age, gender and experience with smartwatches and vibrational notifications. They are then aided in putting the device on their right wrist and adjusting the strap tension to fit comfortably. Then, they are asked to adjust the vibrational intensity using the potentiometer on the wireless controller so they can feel both pneumatic and vibrational actuation, ensuring the effective functioning of the vibrotactile + pneumatic modality. This adjustment is done in 2s intervals, preventing satiety effects from occurring, as was found in previous experiments (see Chapter 5.3.2). The informed consent form and results of a pilot study can be found in Appendix B & C.

Afterwards, the FSR values of the deflated and inflated pneumatic airbag are stored to effectively create an inverse ERM signal for the vibrotactile + pneumatic modality. Before the study starts, participants are asked to wear headphones playing white noise to eliminate any sounds from the device and a random set of touch patterns and modalities are played for the participants to get accustomed to the device.

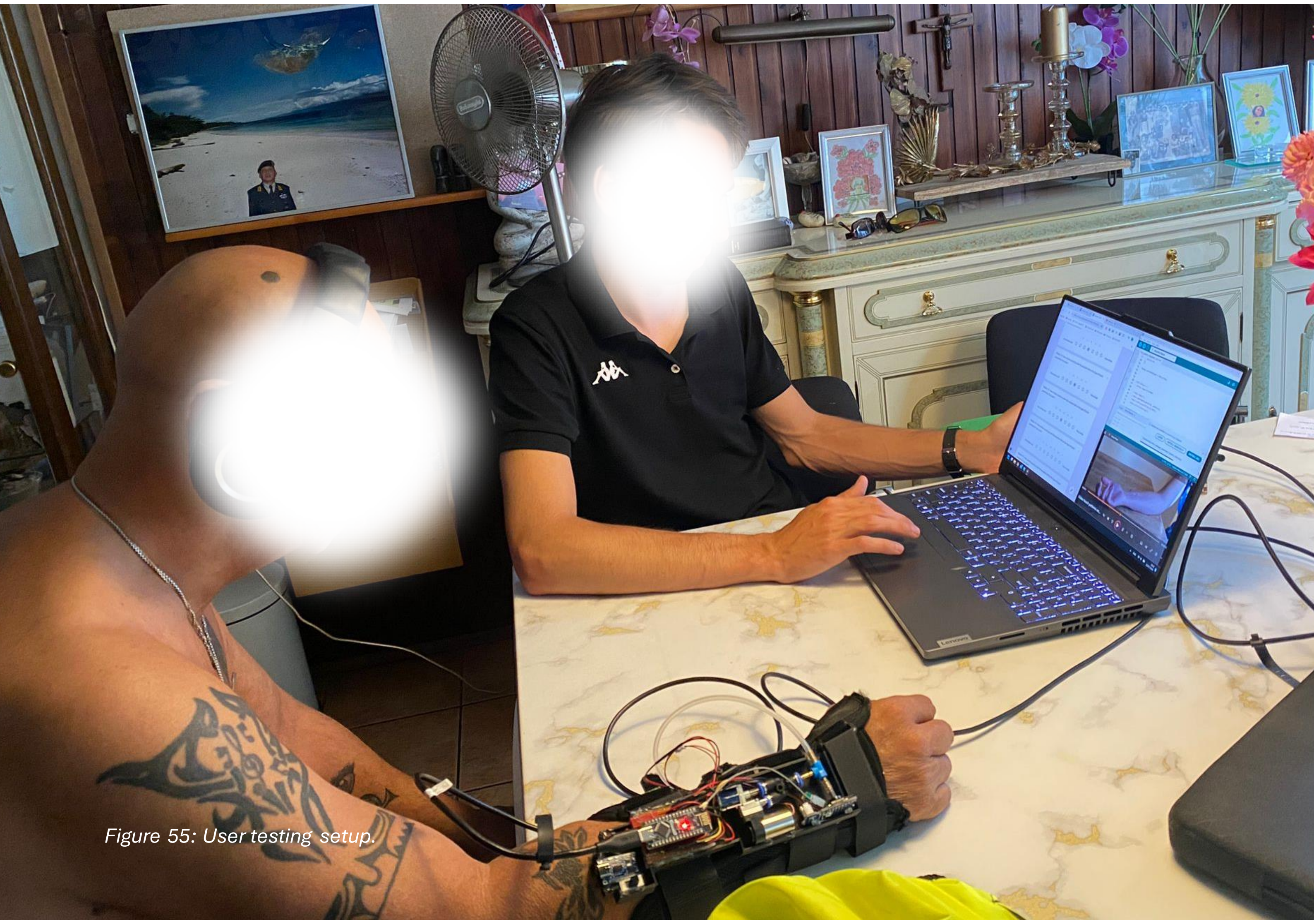


Figure 55: User testing setup.

7.1.3 Procedure

Part 1: Similarity to human touch

For the first part of the study, participants watch a video (see Figure 56) depicting the type of touch being simulated (a hand touching the wrist for the four touch patterns used in the previous section):

These patterns showcase the varying types of touches this system can present and the benefits of combining both modalities. For instance, a 0.1s touch would be difficult to sense using solely the pneumatic system, while a long touch (3s) would likely feel less comfortable using only vibrotactile actuation (see Chapter 2.2.3). The touch pressure in the video remained the same for all touches.

Figure 56: Screenshot of video simulating touch.

Following this, their wrist is subjected to the three modalities, and are then asked to rate the accuracy of each simulated touch compared to what they saw in the video, using a 1 – 7 Likert scale. This is repeated twice for a total of 24 touch pattern actuations (4 patterns x 3 modalities x 2).

Part 2: Pattern recognition

Participants are presented with the four touch patterns across the three modalities. Each pattern is presented in a randomised and counterbalanced order. After each simulation, participants select the pattern they believe was just presented. This process is repeated twice for each pattern, resulting in a total of 24 patterns being actuated (4 patterns x 3 modalities x 2). Participants also rate each touch pattern's valence, arousal, comfort and intensity level on a 1-7 Likert scale.

Part 3: CRS & interview questions

Finally, participants are asked a few questions regarding their experience of the device itself and the perceived touches. To assess the device's comfort, the Comfort Rating Scale (Knight et al., 2002) is used, which is followed by the questions listed below.

- *What is your overall impression of the device?*
- *What is your overall impression of the simulated touches you just experienced?*
- *Did the actuation feel like a human touch, and why?*
- *How was the noticeability of the patterns?*
- *Did you find a difference between the vibrotactile, pneumatic and vibrotactile + pneumatic modalities? If yes, how did you perceive these differences? What did you like / dislike?*
- *What did you think of the pneumatic actuation?*
- *What did you think of the vibrotactile actuation?*
- *Which type of touch (1s, 3s etc.) did you find most similar to a real human touch?*
- *For which (future) use cases do you think this technology would be useful? For which body parts could you see this technology being used for?*
- *Any other comments or suggestions?*

7.2 Results

A total of 35 participants between 18 and 78 years (M=41, SD=21, 21 male, 14 female) were recruited. 15 of them had previous experience with smartwatch technology of which 4 used smartwatch technology daily. Participants chose a range of vibrotactile intensity from 1.5 V to 3.7 V (M=2.4, SD=0.5) to be able to sense both vibrotactile and pneumatic actuation. A more detailed analysis can be found in Appendix D.

7.2.1 Similarity to human touch

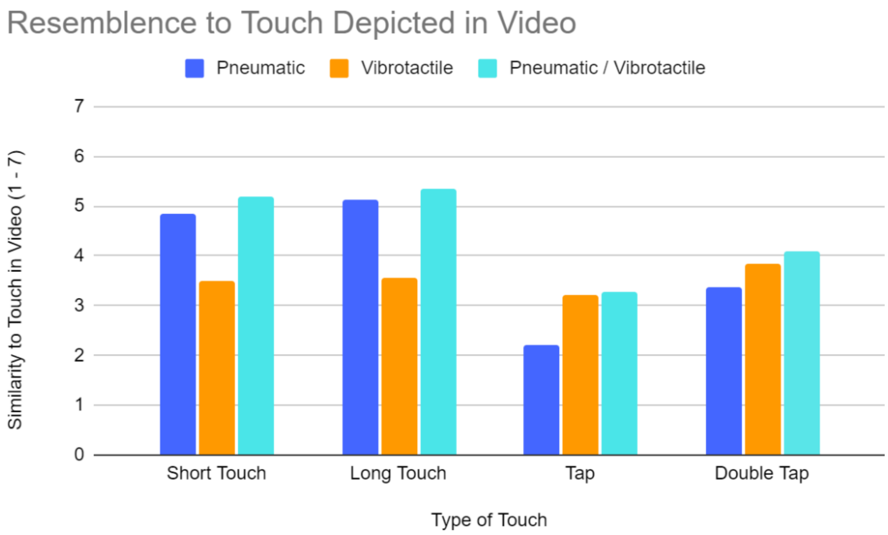


Figure 57: Resemblence to touch depicted in video for four touches and three modalities.

Results

Short Touch (ST)

For the short touch, both pneumatic (Mdn = 5.0, p < .001) and the pneumatic/vibrotactile (Mdn = 5.0, p < .001) modalities were significantly more similar to the touch depicted in the video than the vibrotactile (Mdn = 3.0). There was no significant difference found between the pneumatic and pneumatic/vibrotactile modalities (p = 0.027).

Long Touch (LT)

Similar results to the short touch were found with the long touch where a significant difference was found between the pneumatic (Mdn = 5.0, p < .001) and the pneumatic/vibrotactile (Mdn = 5.5, p < .001) modalities compared to vibrotactile (Mdn = 3.5).

Tap (TAP)

For the tap, a significant difference was found between the vibrotactile (Mdn = 3.0, p = .001) and the pneumatic/vibrotactile (Mdn = 3.0, p < .001) modalities compared to the pneumatic modality (Mdn = 1.0).

Double Tap (DTAP)

For the double tap, there was only a significant difference found between the pneumatic/vibrotactile (Mdn = 4.0) and the pneumatic modality (Mdn = 3.5, p = 0.009).

Analysis

For all four touches the pneumatic/vibrotactile modality performed best compared to the other two modalities (see Figure 57). It is not strange that for the short and long touch (1s and 3s respectively) the pneumatic and vibrotactile/pneumatic modalities performed best as the air cushion feels most similar to the press of a human touch (see Chapter 2.2.1 and 2.2.3). Hereby the vibrotactile actuation in the combined modality is solely used for generating a faster response time, although a significant difference between the pneumatic and pneumatic/vibrotactile modalities was not found.

For the tap (0.1s), both the vibrotactile and combined modalities performed were perceived as more similar to human touch than the pneumatic modality. These results are as expected since the pneumatic modality was for most participants barely noticeable. For the double tap only the combined modality was found to be significantly more similar to the touch in the video than the pneumatic modality. Interestingly, all modalities performed better than the single tap. This could be caused by the initial actuation of the double tap, preparing the user for a consequent actuation. Another possible reason for this difference is that confusion regarding if a touch is played can be reduced by repeating the actuation.

Looking at the data, the vibrotactile modality can be seen around the same values (around 3.5) for the four touches suggesting that similarity to human touch is independent of the touch length. For when the pneumatic touch was most clearly perceivable (short and long touch) it outperformed the vibrotactile modality likely due to its softness and being more similar to human touch.

Overall, the pneumatic/vibrotactile modality often outperformed or matched other modalities, suggesting it may offer a more versatile or realistic simulation of different touch lengths. Its effectiveness depends on the perception of the pneumatic modality and consequently the duration of touch.

7.2.2 Touch pattern recognition

Results (ST = short touch, LT = long touch, TAP = tap, DTAP = double tap)

		Actual (pneumatic)			
		ST	LT	TAP	DTAP
Perceived (pneumatic)	ST	42	12	3	7
	LT	25	57	0	0
	TAP	1	0	44	16
	DTAP	1	1	0	40
	NOT SENSED	1	0	23	7

		Actual (vibrotactile)			
		ST	LT	TAP	DTAP
Perceived (vibrotactile)	ST	47	2	10	1
	LT	22	66	0	0
	TAP	1	0	58	2
	DTAP	0	0	0	65
	NOT SENSED	0	2	2	2

		Actual (pneumatic / vibrotactile)			
		ST	LT	TAP	DTAP
Perceived (pneumatic / vibrotactile)	ST	40	4	10	5
	LT	27	64	0	0
	TAP	0	0	58	1
	DTAP	3	2	0	64
	NOT SENSED	0	0	2	0

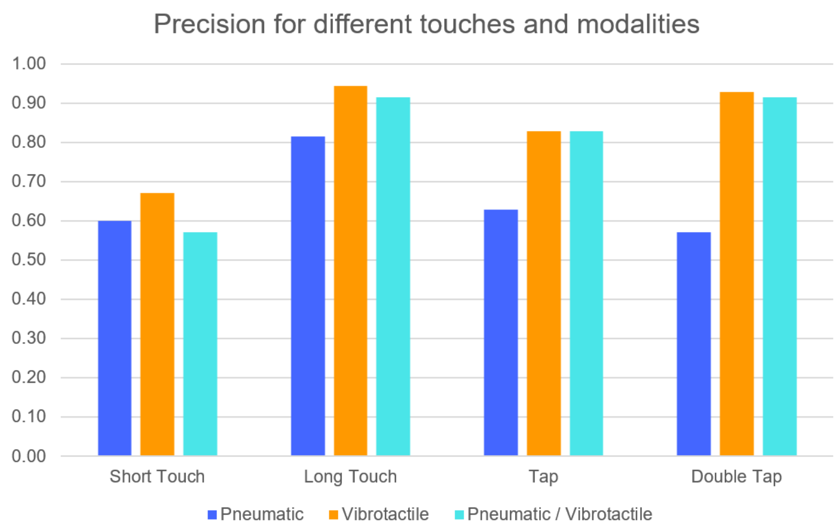


Figure 58: Confusion matrix of the presented and perceived touches per modality (top) and precision rating for each type of touch and modality (bottom).

Analysis

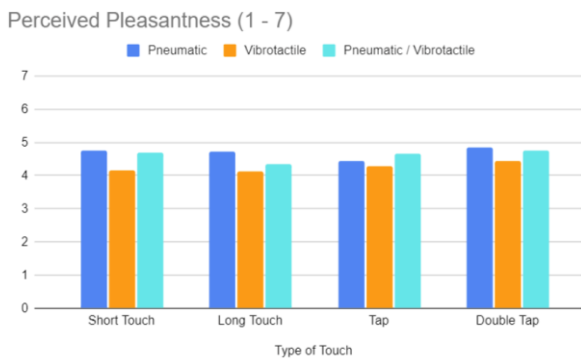
As can be seen in the data (see Figure 58), the vibrotactile and pneumatic/vibrotactile modalities performed best and were very closely aligned in terms of touch pattern recognition. More variation was found for the pneumatic modality, namely regarding the tap and double tap touches. As these were more difficult to sense, more participants did not feel the touch being played or guessed in case they felt something but were unsure of the touch duration, which sometimes resulted in giving a wrong answer.

Interestingly, many participants had difficulty in guessing the length of a touch, which can be seen for the short touches where participants often guessed they experienced a long touch.

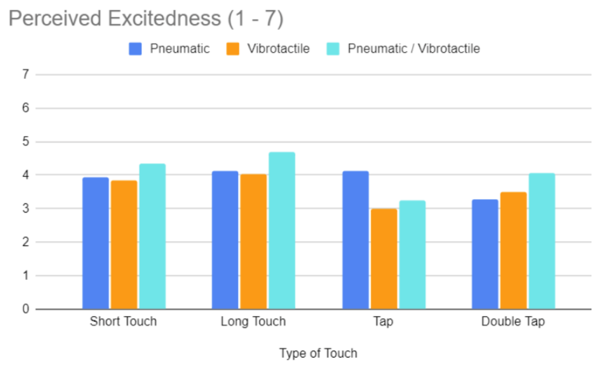
Looking at the precision chart per touch and modality (Σ True Positives / Σ False Positives), the vibrotactile and pneumatic/vibrotactile modality performed best. Similar to the results of part 1, the pneumatic modality performed worst on the tap and double tap caused by confusion or not being sensed.

7.2.3 Perceived pleasantness, excitedness, comfort and intensity per touch and modality

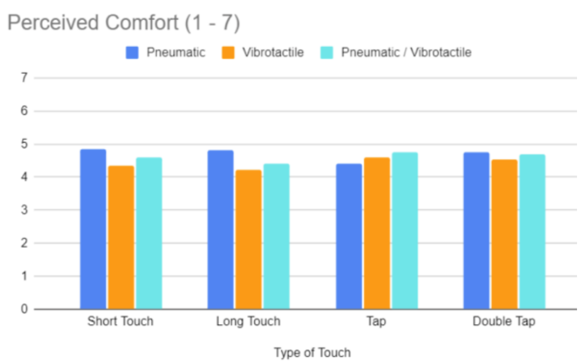
Results (ST = short touch, LT = long touch, TAP = tap, DTAP = double tap)



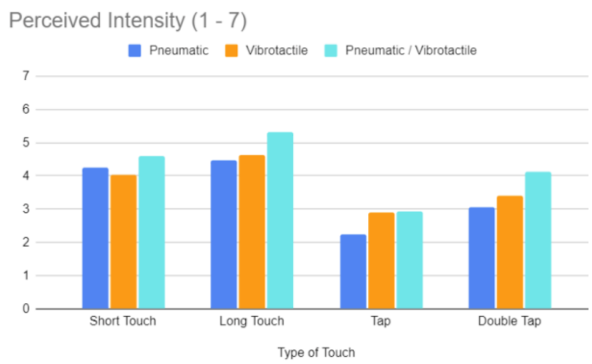
Significant difference for:
- ST (P/V) – ST (V)
- TAP (P) – TAP (V)
- TAP (P/V) – TAP (P)
- DTAP (P/V) – DTAP (V)



Significant difference for:
- ST (P/V) – ST(V)
- LT (P/V) – LT(P)
- LT (P/V) – LT(V)
- TAP (P) – TAP (V)
- TAP (P/V) – TAP (P)
- DTAP (P/V) – DTAP(P)
- DTAP (P/V) – DTAP(V)



Significant difference for:
- TAP (P) – TAP (V)
- TAP (P/V) – TAP (P)



Significant difference for:
- ST (P/V) – ST (V)
- LT (P/V) – LT (P)
- LT (P/V) – LT(V)
- TAP (P) – TAP (V)
- TAP (P/V) – TAP (P)
- DTAP (P/V) – DTAP (P)
- DTAP (P/V) – DTAP (V)

Figure 59: perceived pleasantness, excitedness, comfort and intensity per touch and modality. See Appendix D.3 for a more thorough statistical analysis.

Analysis

The ratings given by participants in terms of pleasantness lie close together with the pneumatic and pneumatic / vibrotactile modalities outperforming the vibrotactile modality for all four touches (see Figure 59). It should be noted that CT afferents exist in the lower wrist making it possible to sense an 'affective touch'. Regarding excitedness, the combined modality performed best for all touches except for the tap. In terms of comfort, the pneumatic modality performed best closely followed by the combined modality, except for the tap, where participants rated the vibrotactile and combined modality higher. Intensity shows expected results where the combined modality was found to be most intense, followed by the vibrotactile and pneumatic modality.

Unexpectedly, no difference was found in terms pleasantness and comfort for the long touch between the different modalities. This is in contrast with results found in Chapter 2.2.3 where was found that vibrotactile actuation sustained over a longer period of time can be perceived as more disruptive. According to the comfort ratings the pneumatic modality was more comfortable, although a significant difference was not detected.

7.2.4 Comfort-Rating Scale

Category	**Mdn (1 – 7)**	**SD**
Emotion: I am worried about how I look when I wear this device. I feel tense or on edge because I am wearing the device.	3	2.0
Attachment: I can feel the device on my body. I can feel the device moving.	5	1.6
Harm: The device is causing me some harm. The device is painful to wear.	1	1.7
Perceived change: Wearing the device makes me feel physically different. I feel strange wearing the device.	4	2.0
Movement: The device affects the way I move. The device inhibits or restricts my movement.	5	1.6
Anxiety: I do not feel secure wearing the device.	1	1.3

Figure 60: Comfort-Rating Scale of wrist-wearable device.

Regarding the comfortability of the device itself, most users could feel it well on their body and during movement (see Figure 60). In most cases it did not harm the user and they would not wear the device in public as it looks unusual. However, participants would be more inclined to wear the device around the house or if it could be hidden underneath clothing.

7.2.5 Qualitative Results

The feedback on the device shows a mix of excitement and helpful criticism, highlighting its potential and areas that need improvement.

Functionality and User Experience

The device's pneumatic actuation received generally positive feedback for its ability to simulate touch more realistically compared to vibrations, although this could vary from person to person. Participants mentioned issues with intensity and responsiveness, making it harder to feel the shorter touches. Pneumatic actuation was favoured frequently for its natural and comforting feeling, while vibrations were often described as mechanical and less pleasant. Participants suggested refining the responsiveness of the pneumatic actuation and to more closely match intensity with the vibrotactile actuation.

Realism of Touch

Despite the pneumatic actuation being well-received, the device's ability to replicate human touch remains incomplete. While short taps and certain patterns were described as relatively realistic, the overall touch experience lacked some key aspects of genuine human contact, such as temperature conductivity and texture.

Design and Comfort

A major area of concern is the device's size and design. Participants frequently noted that the device feels bulky and its exposed wiring felt fragile. To enhance user comfort and practicality, suggestions include making the device more compact and streamlined. Participants recommended a protective cover improving durability and appearance (see Figure 61). Some users compared the device to a blood pressure cuff due to a similar appearance and the pressure acting around the wrist and being less localised.

Future Directions

Despite the initial excitement and potential identified, work remains to refine the device's design and functionality. Key areas for improvement include enhancing the comfort and practicality of the device, and increasing the realism of the touch simulation. Participants were generally optimistic about the device's future, particularly in healthcare and communication, suggesting that with continued development, it could become a valuable tool in various applications.

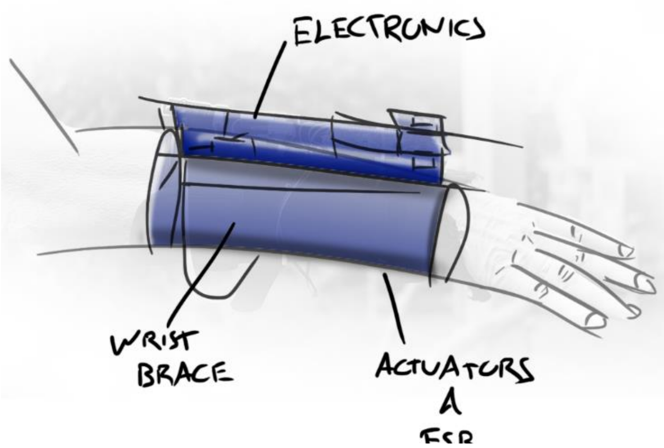


Figure 61: Drawing of the wearable device.

7.3 Discussion & Limitations

Discussion

The results of the study highlight the benefits of enhancing pneumatic actuation with vibrotactile actuation in representing human touch. Overall, the pneumatic/vibrotactile modality frequently and significantly outperformed or matched the individual modalities, suggesting its potential for a more realistic touch simulation in wearable systems.

The pneumatic/vibrotactile modality commonly received significantly higher ratings for its similarity to human touch, taking advantage of each individual modality's strengths. Specifically, for longer touches, it was more effective due to its ability to mimic the softness of human skin and the pressure of a touch, while for short taps, the vibrotactile component was clearer and enhanced the perceived realism.

These benefits were evident during touch pattern recognition, where users were most accurate when the vibrotactile/pneumatic or vibrotactile modalities were used due to their responsiveness. In addition, participants rated the pneumatic and combined modalities higher in terms of pleasantness than the vibrotactile modality across most touch types, although a similar difference for comfort was expected.

Limitations

In the study, participants found it challenging to compare different types of touch when rating valence, arousal, comfort, and intensity because filling out the answers was time-consuming. To improve future studies, the questions should be shortened to allow participants to more easily compare the various touches and modalities. Additionally, the device produced sounds and vibrations from the air pump and valve, which participants might have noticed, potentially affecting the results. Since these sounds can be undesirable in public settings, alternative pneumatics components could be further explored dependant on the use case. Furthermore, the airbag can be pre-inflated, or an additional pre-inflated bladder can be used to improve the response times of the pneumatic component. Similarly, having the actuators directly touch bare skin can increase the perceived intensity

In its current state, the device is limited in its capabilities and differs from a real human touch. Vibrations were often described as 'mechanical,' while pneumatic actuation felt more human-like, suggesting the need for further research to match both modalities more effectively. Furthermore, touch intensity and thermal conductivity are key aspects of human touch that can be implemented in future iterations. Lastly, this device would benefit from creating stroking sensations, stimulating CT-afferents, and exploring 'affective touch' applications in the field.

8. Conclusion and Recommendations

8.1 Conclusion

In this thesis, the development of a wearable system is described that simulate human touch through combined pneumatic and vibrotactile modalities. The final concept consists of two integrated devices: a wrist-worn wearable and an wireless controller. This design refines the prototypes introduced in Chapter 3 and 5, addressing previous limitations by incorporating smaller electronics and allowing it to be fully tetherless. The wearable device integrates sensors and actuators, ensuring effective simulation of touch, while the controller allows for programming and storing touch patterns, and is a useful asset for future experimentation.

An evaluation, as described in Chapter 7, assesses the system's ability to replicate human touch. The study confirms that a pneumatic/vibrotactile combination often matches or exceeds the performance of individual modalities across various touch patterns. This hybrid approach combines the pneumatic system's ability to simulate the softness and pressure of human skin with the responsiveness and noticeability of the vibrotactile component. The evaluation also reveals areas for improvement, particularly in device design, comfort, and the realism of the touch simulation.

In summary, this research offers the technologies allowing responsive wireless touch transmission for fully wireless wearable systems. This platform acts as a solid foundation to experiment from and test in real-world scenarios; allowing the creation of touch patterns and in-vivo testing with participants.

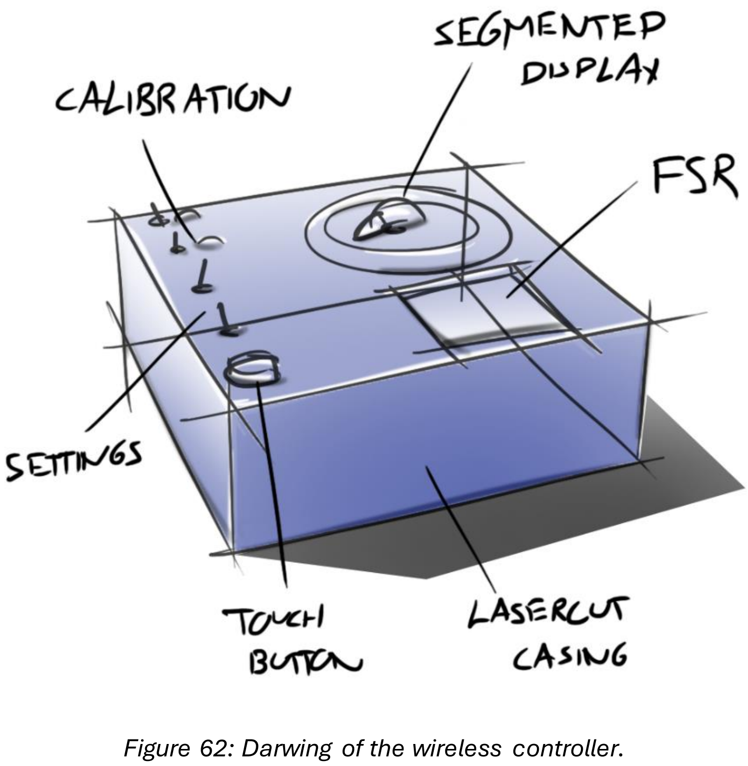


Figure 62: Darwing of the wireless controller.

8.2 Recommendations

The technology described and tested in this paper allows researchers and designers to experiment. Depending on the application, the technology can easily be adapted to suit different body locations and specific needs, such as implementing pressure sensitivity or developing a secondary wearable device that allows two-way communication of touch. For instance, the device could be modified to react more slowly to improve comfort and alter the perceived intensity.

However, the device, in its simplest form, can be improved in numerous ways. For instance, further investigation is needed to make the touch feel more human-like. Specific research into how pressure and vibrations could be more similar would benefit the experience of touch. Furthermore, more research is needed on personal preferences regarding pneumatic and vibrotactile modalities in portraying touch and the possibilities for combining them. For instance, this research mostly looked into combining them to create a sensation of touch, although they could also be used to give different indications of urgency, prevent satiety effects from occurring, and allow for more localised and uniform feedback.

As highlighted in the limitations section of Chapter 7, allowing thermal conductivity or multiple actuators could feel more human-like and enable more touch patterns to be created and experienced. "Affective touch" would benefit from these added technologies and allow the device to be tested in such applications, similar to those mentioned in Chapter 4.3. For example, it could assist with sensory impairments, provide comfort in patient care, and bring people in long-distance relationships together by simulating touch between people.

Through continued research and development, this technology has the potential to redefine how we connect and communicate, bringing people together with the warmth of human touch.

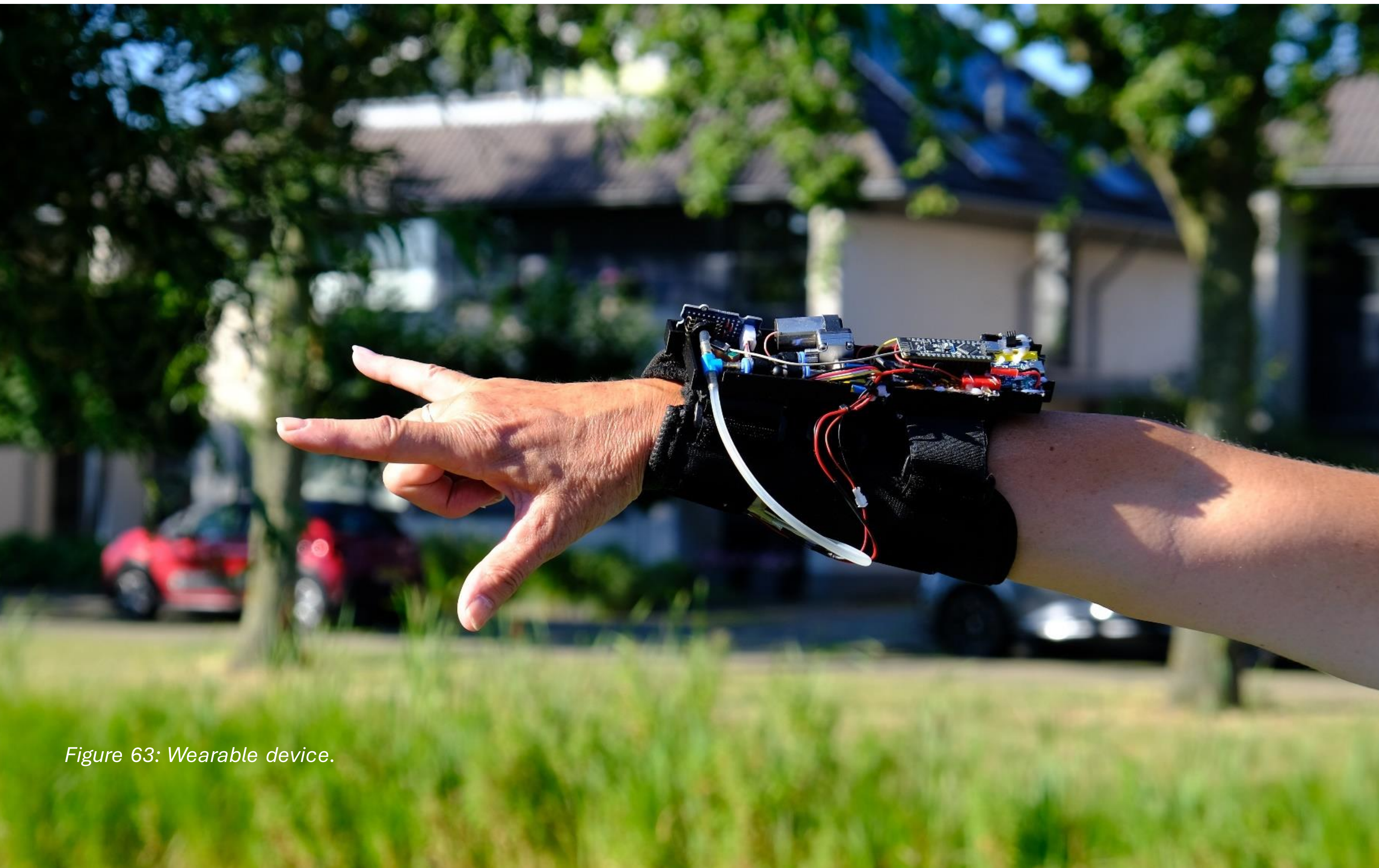


Figure 63: Wearable device.

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10. Appendices

Appendix A: Additional Experimentation

Other small experiments were conducted mostly to obtain a better understanding of the technology and its' limitations. These are described in this subchapter.

A.1 Test with Vibrotactile and Pneumatic Actuators on different Locations

Goal

Testing whether the illusion of compensating for the lack of response time from the pneumatic system still works when the locations of the actuators is differently.

Method

Using the prototype described in Chapter 3.1, the ERM motor on top of the air bag was tested and moved to the side of the wrist so they were side-by-side.

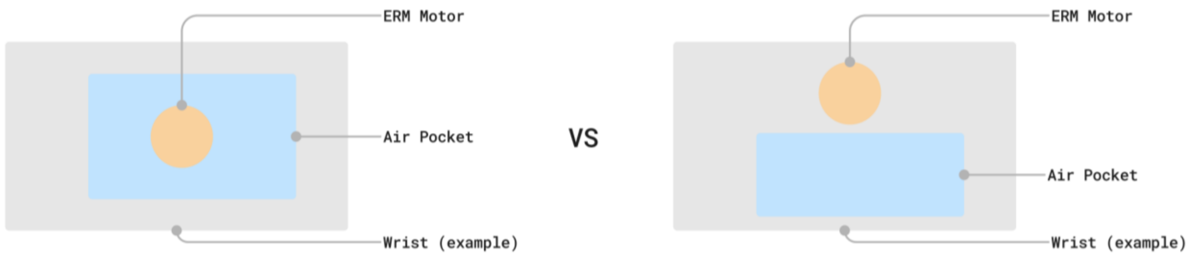


Figure A1: Test setups in which the ERM motor is directly placed on top of the air bag and one in which both actuator types are spread apart.

Results

When placing the vibrational motor in a different location than directly on top of the air bag, the illusion doesn't work as well. They do feel like a different system and less connected. The feeling of the vibrational motor is stronger when placed directly on the wrist.

Reflection

Direct contact between the vibrational motor and the skin makes it feel more direct and stronger. This is something which needs to be further researched, preferably with a vibrational actuator which can be directly placed underneath the air bag. The location of both actuators matters. If one is too far from the other the illusion of a single system is destroyed.

A.2 Test with Different-Sized Airbags

Goal
Comparison between actuation feel of different sized air bags.

Method
Two prototypes of Clint's work were used (Van Leeuwen, 2023), a 40 x 40 mm and a 10 x 10 mm air bag. These were placed inside the sleeve of the same prototype used in Chapter 3.1. A schematic of the test setup has been drawn in Figure A2.

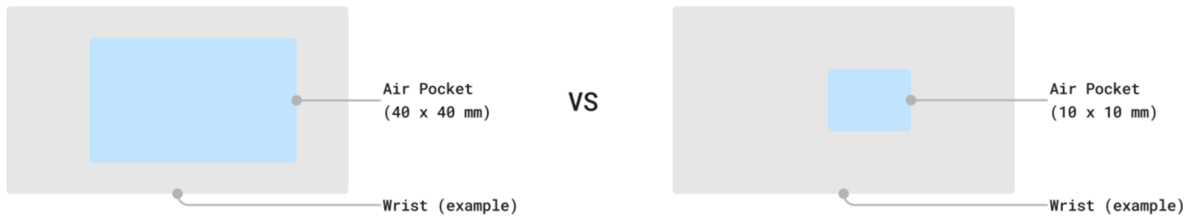


Figure A2: Test setups in which a large air bag (40 x 40 mm) is compared to a smaller air bag (10 x 10 mm) produced by Van Leeuwen (2023).

Results
The localised air bag was almost unnoticeable, possibly caused by the stretchy fabric which doesn't give much support to press against and apply pressure on the skin. Normal movement of the smaller pouch is way less than the 40 x 40 mm version (estimated 1 cm compared to 3 cm of travel), although it was way quicker to inflate. It did feel more like "poking" instead of applying uniform pressure. The larger cushion felt more comfortable over time.

Reflection
The feeling between different-sized air bags can differ drastically. Larger cushions take longer to inflate, are more comfortable due to distributed pressure and are less rigid allowing better user interaction. Both types have their purpose, although with larger pneumatic air bags response times are more of an issue.

A.3 Test with Vibrational Motor on different Surface Areas

Goal
To see what effect the surface area of a vibrational motor (ERM) has on the feel on the wrist.

Method
Three snap-fit ERM holders were 3D printed with each a different surface area (15 x 15 mm, 25 x 25 mm, 40 x 40 mm) (see Figure A3). The smallest size is slightly larger than the ERM motor, while the largest size can just fit on the wrist. A simple vibrational pattern was created in Arduino that switches between 5 V and 0 V in a 1 s interval. These holders were tested on the skin of the wrist underneath a textile sleeve (see Chapter 3.2).

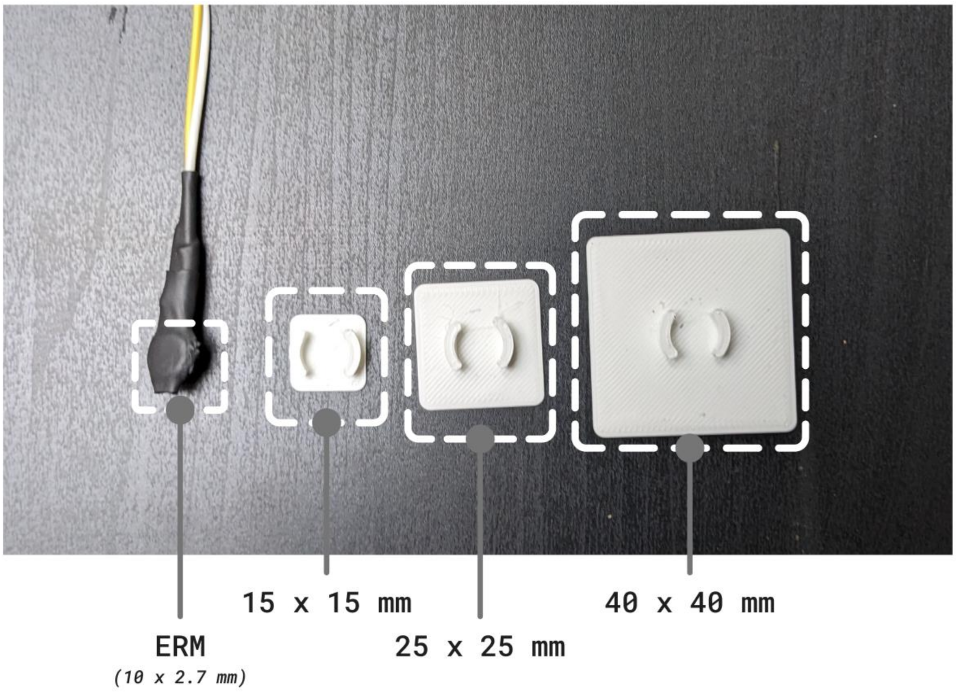


Figure A3: ERM motor with different holders with multiple areas.

Results
The ERM as it stands felt most intense on the wrist, while the larger surface area dampened the vibrations and increased comfort. What was noticed however was that the reaction time is slower for larger surfaces, likely caused by the energy loss due to the transfer of vibrations to a larger mass. Furthermore, the ERM motor needs to be glued in place to properly hold it as the snap-fit causes it to vibrate between the connection.

Reflection
Depending on the purpose of the vibrational motor, a more intense or more distributed, comfortable actuation could be achieved by changing the surface area.

A.4 Test with a LMR in different Orientations

Goal
As LMRs work through moving a mass along its axis, a difference in feel could be expected depending on the orientation of the actuator (see Figure A4). As was found in Chapter 3.2, the directionality of a continuing vibrational pattern wasn't sensed, however, this might be different when simulating an impact force.

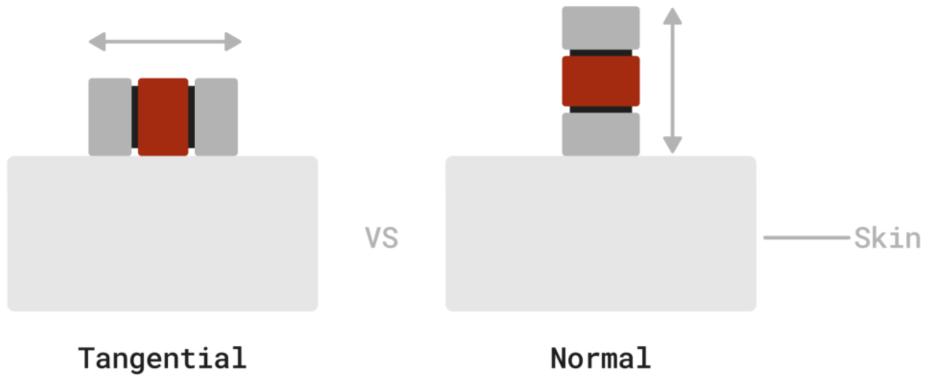


Figure A4: LMR actuator in different orientations: tangential and normal to the skin.

Method
This was tested on the wrist underneath the sleeve used in the same Chapter. An impact sensation could be created using the 'buzz' and 'tick' effects of DRV 2605 example library code (Adafruit, n.d.).

Results
The normal orientation felt slightly stronger as opposed to the tangential direction, however, the change in orientation couldn't be sensed. An ERM was also used to see if it was possible to create as direct of an impact, however, this was not possible due to the ramp-up time needed.

Reflection
The increased intensity of putting an LMR normal to the skin is negligible with an impact force. However, if the research direction requires a very rapid actuation, LMRs can be a suitable option.

Appendix B: Informed Consent Form

Mobile Touch

You are being invited to participate in a research study titled "Responsive Wireless Tactile Communication for Portable Pneumatic Wearables". This study is being done by Mark Kruijthoff from the TU Delft in a team supervised by Kaspar Jansen (Chair), Himanshu Verma (Mentor) and Abdallah El Ali (Mentor).

The purpose of this research study is to investigate the benefits of combining pneumatic and vibrotactile actuation in representing touch patterns in wearable devices. This study will take you approximately 25 minutes to complete. The data will be used for publishing a Master's thesis and a research paper. We will be asking you to provide feedback certain touch patterns and modalities regarding a new type of haptic device. Hereby it is important to give feedback which is unbiased, ensuring validity of the findings.

To the best of our ability, your answers in this study will remain confidential. We will minimise any risks by anonymising any pictures/videos taken during the research and anonymising the results so they cannot be linked towards specific individuals.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions.

By signing this form you consent to the collection and handling of data as described in the form.

____________________ ____________________ ________

Name of participant Signature Date

____________________ ____________________ ________

Researcher name Signature Date

Appendix C: Pilot Study

A pilot test was conducted with 3 participants (see Figure C1). During this test, the testing protocol presented in Chapter 7.1 were followed, which took around 15 – 20 minutes. The results can be found below. Any revisions for the final study are further described at the end of this subchapter.

Figure C1: Research setup for pilot test.

Results

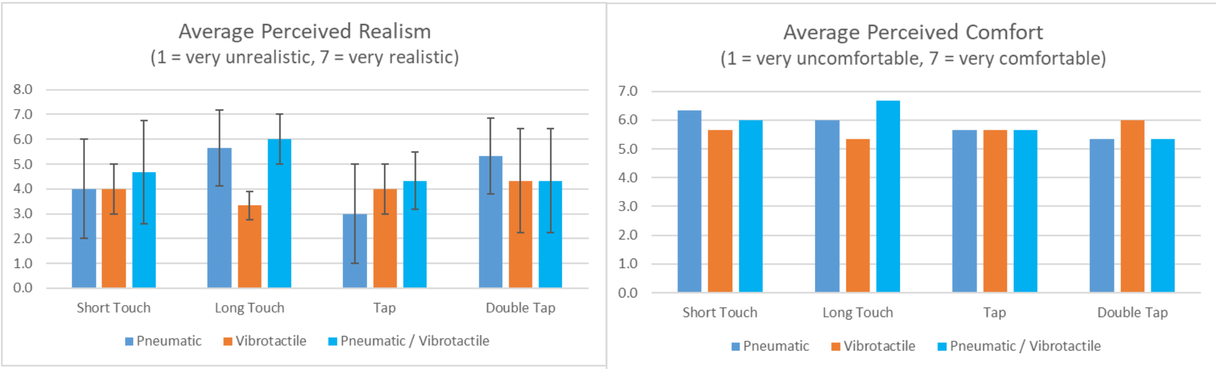


Figure C2: Average perceived realism with error-bars showing the standard deviation (left); average perceived comfort per touch type and modality (right).

Perceived (pneumatic) \ Actual (pneumatic)	ST	LT	TAP	DTAP
ST	2	1	0	0
LT	1	2	0	0
TAP	0	0	3	1
DTAP	0	0	0	2

Perceived (vibrotactile) \ Actual (vibrotactile)	ST	LT	TAP	DTAP
ST	2	0	0	0
LT	1	3	0	0
TAP	0	0	3	0
DTAP	0	0	0	3

Perceived (vibrotactile / pneumatic) \ Actual (pneumatic / vibrotactile)	ST	LT	TAP	DTAP
ST	2	0	0	0
LT	1	3	0	0
TAP	0	0	3	0
DTAP	0	0	0	3

Figure C3: Confusion matrix showing the guesses participants made when presented with each type of touch per modality.

Avg vibrotactile intensity (0 - 1023)	Avg std. dev
490	291

Figure C4: chosen vibrotactile intensities by participants

Findings from pilot test

1. Sounds from the device were still hearable even with the ear protection on.
2. Participants had difficulty rating comfort for the shorter pulses. When one does not feel the device actuating it is difficult to rate its comfort.
3. Some participants wanted to repeat a touch, which could not be done with the current prototype.
4. The participants had difficulty at the start rating the realism as the prototype and how it feels was new to them.
5. Results regarding perceived realism and comfort are very close to one another.

Improvements for final test

1. Utilise headphones playing white noise
2. Add arousal, valence and intensity to comfort metric. Add n/a option to comfort if one doesn't feel the actuation
3. Allow for repeating touch patterns if the participant requests it.
4. 4.1 Do a small practice round showing to participants how the device feels

   4.2 Conduct half of the experiments in reverse order to further prevent order effects
5. Conduct the experiment twice, to gain more detailed data while still remaining under testing time under half an hour.

   Others:
   - Note down body weight, body length, experience with smartwatches (y/n) -> if y: which model of smartwatch? (in case this data is needed in future research / evaluation)
   - Vibrotactile adjustment: first let them experience both modalities individually, afterwards ask them to adjust the vibrations so they feel both
   - Change realism to accuracy.
     - Not closely aligned – closely aligned on a 1-7 Likert scale.
   - Added CRS (comfort-rating scale)
   - Added qualitative questions at the end

Appendix D: Analysis of User Study

D.1 Similarity to human touch

Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles 25th	Percentiles 50th (Median)	Percentiles 75th
ST (P)	35	4.857	.9669	3.0	7.0	4.000	5.000	5.500
LT (P)	35	5.129	.9803	3.0	7.0	4.500	5.000	5.500
TAP (P)	35	2.214	1.7459	1.0	7.0	1.000	1.000	3.000
DTAP (P)	35	3.357	1.8213	1.0	7.0	2.000	3.500	5.000
ST (V)	35	3.500	1.4349	1.5	7.0	2.500	3.000	4.500
LT (V)	35	3.557	1.6617	1.0	7.0	2.500	3.500	5.000
TAP (V)	35	3.229	1.6906	1.0	7.0	2.000	3.000	4.500
DTAP (V)	35	3.843	1.5566	1.0	7.0	3.000	3.500	5.000
ST (P/V)	35	5.200	1.1128	3.0	7.0	4.500	5.000	6.000
LT (P/V)	35	5.357	1.1086	3.0	7.0	4.500	5.500	6.000
TAP (P/V)	35	3.286	1.6009	1.0	7.0	2.000	3.000	4.500
DTAP (P/V)	35	4.100	1.3655	1.5	7.0	3.000	4.000	5.000

Tests of Normality

	Kolmogorov-Smirnov[a] Statistic	Kolmogorov-Smirnov[a] df	Kolmogorov-Smirnov[a] Sig.	Shapiro-Wilk Statistic	Shapiro-Wilk df	Shapiro-Wilk Sig.
ST (P)	.118	35	.200*	.964	35	.291
LT (P)	.124	35	.193	.964	35	.299
TAP (P)	.271	35	<.001	.737	35	<.001
DTAP (P)	.172	35	.010	.928	35	.024
ST (V)	.179	35	.006	.936	35	.042
LT (V)	.171	35	.011	.931	35	.031
TAP (V)	.211	35	<.001	.905	35	.005
DTAP (V)	.146	35	.058	.966	35	.346
ST (P/V)	.172	35	.011	.931	35	.030
LT (P/V)	.151	35	.041	.945	35	.081
TAP (P/V)	.132	35	.125	.944	35	.075
DTAP (P/V)	.099	35	.200*	.974	35	.567

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Normality was not found for several modalities and touch patterns. This is why a non-parametric test was chosen (Friedman's ANOVA).

Test Statistics[a]

N	35
Chi-Square	149.101
df	11
Asymp. Sig.	<.001

a. Friedman Test

There was a statistically significant difference in perceived resemblance to video depending on which modality was played, $\chi2(2, n=35) = 149.101$, $p < 0.01$.

Test Statistics[a]

	TAP (V) - TAP (P)	TAP (P/V) - TAP (P)	TAP (P/V) - TAP (V)
Z	-3.253[b]	-3.605[b]	-.572[b]
Asymp. Sig. (2-tailed)	.001	<.001	.567

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

Test Statistics[a]

	DTAP (V) - DTAP (P)	DTAP (P/V) - DTAP (P)	DTAP (P/V) - DTAP (V)
Z	-1.377[b]	-2.621[b]	-1.364[b]
Asymp. Sig. (2-tailed)	.168	.009	.173

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

Test Statistics[a]

	ST (V) - ST (P)	ST (P/V) - ST (P)	ST (P/V) - ST (V)
Z	-4.215[b]	-2.205[c]	-4.791[c]
Asymp. Sig. (2-tailed)	<.001	.027	<.001

a. Wilcoxon Signed Ranks Test

b. Based on positive ranks.

c. Based on negative ranks.

Test Statistics[a]

	LT (V) - LT (P)	LT (P/V) - LT (P)	LT (P/V) - LT (V)
Z	-3.773[b]	-1.490[c]	-4.184[c]
Asymp. Sig. (2-tailed)	<.001	.136	<.001

a. Wilcoxon Signed Ranks Test

b. Based on positive ranks.

c. Based on negative ranks.

Bonferroni adjustment: Divide original significant value by the number of tests (3).
0.05/3 = 0.017 (new significant value)

D.2 *Touch pattern recognition*

Pneumatic

	ST	LT	TAP	DTAP
TP	42	57	44	40
FP	28	13	26	30
FN	22	25	17	2
TN	188	185	193	208
Precision	0.60	0.81	0.63	0.57
Recall	0.66	0.70	0.72	0.95
F1 Score	0.63	0.75	0.67	0.71

Vibrotactile

	ST	LT	TAP	DTAP
TP	47	66	58	65
FP	23	4	12	5
FN	13	22	3	0
TN	197	188	207	210
Precision	0.67	0.94	0.83	0.93
Recall	0.78	0.75	0.95	1.00
F1 Score	0.72	0.84	0.89	0.96

Pneumatic / Vibrotactile

	ST	LT	TAP	DTAP
TP	40	64	58	64
FP	30	6	12	6
FN	19	27	1	5
TN	191	183	209	205
Precision	0.57	0.91	0.83	0.91
Recall	0.68	0.70	0.98	0.93
F1 Score	0.62	0.80	0.90	0.92

D.3 Pleasantness, Excitedness, Comfortability and Intensity

D.3.1 Pleasantness

Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles 25th	50th (Median)	75th
ST (P)	35	4.671	1.0637	2.5	6.5	4.000	4.500	5.500
LT (P)	35	4.714	1.0592	3.0	7.0	4.000	5.000	5.500
TAP (P)	35	3.071	2.2300	.0	7.0	.000	3.500	4.500
DTAP (P)	35	4.357	1.7131	.0	7.0	3.000	5.000	5.500
ST (V)	35	4.157	1.2234	2.0	7.0	3.500	4.000	5.000
LT (V)	35	4.014	1.8450	.0	7.0	2.500	4.000	6.000
TAP (V)	35	4.171	1.4700	1.5	7.0	3.000	4.000	5.500
DTAP (V)	35	4.300	1.5010	.0	7.0	3.000	4.000	5.500
ST (P/V)	35	4.686	.8836	2.5	7.0	4.000	5.000	5.000
LT (P/V)	35	4.329	1.3281	2.0	7.0	3.500	4.500	5.500
TAP (P/V)	35	4.514	1.6516	.0	7.0	4.000	4.500	6.000
DTAP (P/V)	35	4.757	1.1655	3.0	7.0	3.500	4.500	5.500

Test Statistics[a]

N	35
Chi-Square	32.635
df	11
Asymp. Sig.	<.001

a. Friedman Test

Significance for $p < 0.017$

Test Statistics[a]

	ST (V) - ST (P)	ST (P/V) - ST (P)	ST (P/V) - ST (V)	LT (V) - LT (P)	LT (P/V) - LT (P)	LT (P/V) - LT (V)	TAP (V) - TAP (P)	TAP (P/V) - TAP (P)	TAP (P/V) - TAP (V)	DTAP (V) - DTAP (P)	DTAP (P/V) - DTAP (P)	DTAP (P/V) - DTAP (V)
Z	-2.254[b]	-.058[c]	-2.397[c]	-1.911[b]	-1.882[b]	-1.154[c]	-2.830[c]	-3.681[c]	-1.357[c]	-.546[b]	-1.707[c]	-3.056[c]
Asymp. Sig. (2-tailed)	.024	.954	.017	.056	.060	.248	.005	<.001	.175	.585	.088	.002

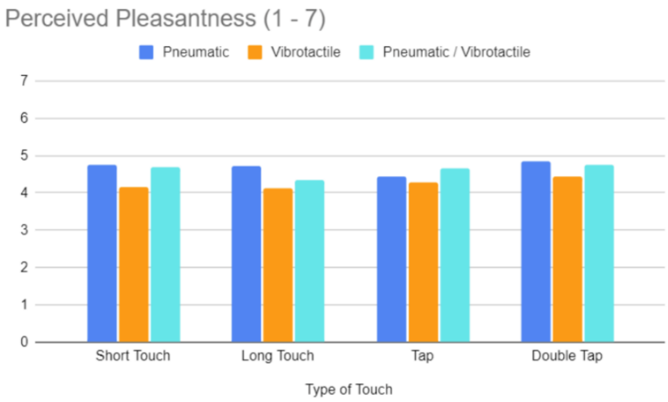
a. Wilcoxon Signed Ranks Test

b. Based on positive ranks.

c. Based on negative ranks.

Significance for:

- ST (P/V) – ST (V)
- TAP (V) – TAP (P)
- TAP (P/V) – TAP (P)
- DTAP (P/V) – DTAP (V)



D.3.2 Excitedness

Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles 25th	50th (Median)	75th
ST (P)	35	3.886	1.1949	1.0	6.0	3.500	4.000	4.500
LT (P)	35	4.114	1.0920	1.0	6.0	3.500	4.000	5.000
TAP (P)	35	2.100	1.8740	.0	7.0	.000	1.500	3.500
DTAP (P)	35	2.957	1.6377	.0	6.5	1.500	3.000	4.000
ST (V)	35	3.829	.9773	1.0	5.5	3.500	3.500	4.500
LT (V)	35	3.929	1.4045	.0	6.0	3.000	4.000	5.000
TAP (V)	35	2.900	1.3162	1.0	7.0	1.500	3.000	3.500
DTAP (V)	35	3.400	1.3869	.0	6.5	2.500	3.500	4.000
ST (P/V)	35	4.343	1.0966	1.0	6.5	3.500	4.500	5.000
LT (P/V)	35	4.700	1.2845	1.0	6.5	3.500	5.000	5.500
TAP (P/V)	35	3.157	1.4439	.0	6.5	2.000	3.000	4.000
DTAP (P/V)	35	4.071	1.0856	2.0	6.5	3.000	4.000	5.000

Test Statistics[a]

N	35
Chi-Square	116.524
df	11
Asymp. Sig.	<.001

a. Friedman Test

Significance for p < 0.017

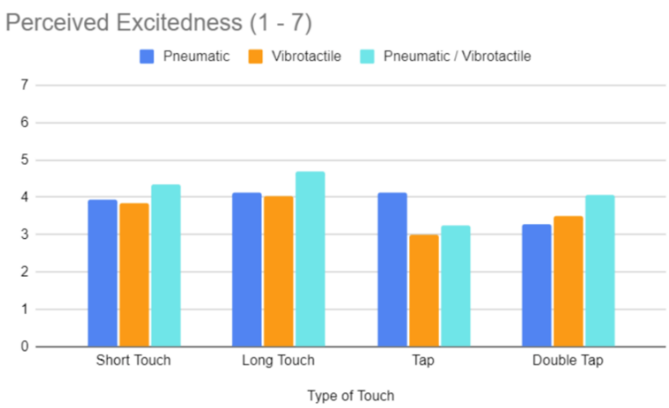
Test Statistics[a]

	ST (V) - ST (P)	ST (P/V) - ST (P)	ST (P/V) - ST (V)	LT (V) - LT (P)	LT (P/V) - LT (P)	LT (P/V) - LT (V)	TAP (V) - TAP (P)	TAP (P/V) - TAP (P)	TAP (P/V) - TAP (V)	DTAP (V) - DTAP (P)	DTAP (P/V) - DTAP (P)	DTAP (P/V) - DTAP (V)
Z	-.385[b]	-2.217[c]	-2.769[c]	-.626[b]	-2.864[c]	-2.864[c]	-2.564[c]	-3.171[c]	-1.294[c]	-1.435[c]	-4.122[c]	-3.427[c]
Asymp. Sig. (2-tailed)	.700	.027	.006	.531	.004	.004	.010	.002	.196	.151	<.001	<.001

a. Wilcoxon Signed Ranks Test
b. Based on positive ranks.
c. Based on negative ranks.

Significance for:

- ST (P/V) – ST(V)
- LT (P/V) – LT(P)
- LT (P/V) – LT(V)
- TAP (V) – TAP (P)
- TAP (P/V) – TAP (P)
- DTAP (P/V) – DTAP(P)
- DTAP (P/V) – DTAP(V)



D.3.3 Comfortability

Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles 25th	50th (Median)	75th
ST (P)	35	4.771	1.0734	2.0	6.5	4.000	5.000	5.500
LT (P)	35	4.829	1.1437	1.5	7.0	4.000	5.000	5.500
TAP (P)	35	3.071	2.2562	.0	7.0	.000	3.500	5.000
DTAP (P)	35	4.271	1.6420	.0	7.0	3.500	4.500	5.500
ST (V)	35	4.329	1.2304	2.0	7.0	3.500	4.000	5.500
LT (V)	35	4.086	1.7510	.0	7.0	3.000	4.000	5.500
TAP (V)	35	4.457	1.5116	1.5	7.0	3.500	4.500	5.500
DTAP (V)	35	4.400	1.4441	.0	7.0	3.500	4.500	5.500
ST (P/V)	35	4.600	.9762	2.0	6.5	4.000	4.500	5.000
LT (P/V)	35	4.400	1.2532	2.0	7.0	3.500	4.500	5.500
TAP (P/V)	35	4.600	1.6125	.0	7.0	4.000	5.000	6.000
DTAP (P/V)	35	4.686	1.1763	2.0	7.0	3.500	5.000	5.500

Test Statistics[a]

N	35
Chi-Square	25.280
df	11
Asymp. Sig.	.008

a. Friedman Test

Significance for $p < 0.017$

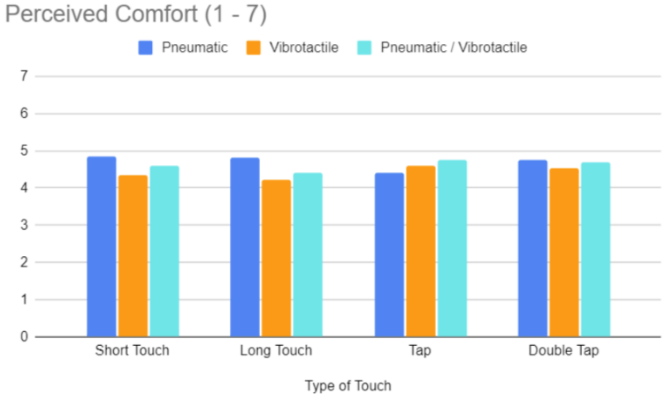
Test Statistics[a]

	ST (V) - ST (P)	ST (P/V) - ST (P)	ST (P/V) - ST (V)	LT (V) - LT (P)	LT (P/V) - LT (P)	LT (P/V) - LT (V)	TAP (V) - TAP (P)	TAP (P/V) - TAP (P)	TAP (P/V) - TAP (V)	DTAP (V) - DTAP (P)	DTAP (P/V) - DTAP (P)	DTAP (P/V) - DTAP (V)
Z	-2.340[b]	-1.226[b]	-1.388[c]	-2.319[b]	-2.221[b]	-.919[c]	-3.414[c]	-3.712[c]	-.747[c]	-.255[c]	-1.696[c]	-1.789[c]
Asymp. Sig. (2-tailed)	.019	.220	.165	.020	.026	.358	<.001	<.001	.455	.799	.090	.074

a. Wilcoxon Signed Ranks Test
b. Based on positive ranks.
c. Based on negative ranks.

Significance for:

- TAP (V) – TAP (P)
- TAP (P/V) – TAP (P)



D.3.4.Intensity

Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles 25th	50th (Median)	75th
ST (P)	35	4.114	1.0716	2.0	6.0	3.500	4.000	5.000
LT (P)	35	4.471	1.2482	2.0	7.0	4.000	4.500	5.000
TAP (P)	35	1.500	1.3173	.0	5.5	.000	1.500	2.500
DTAP (P)	35	2.743	1.4109	.0	4.5	1.500	3.000	4.000
ST (V)	35	4.043	1.0316	2.0	6.0	3.500	4.000	4.500
LT (V)	35	4.500	1.6225	.0	7.0	3.500	4.500	6.000
TAP (V)	35	2.800	1.2902	.5	5.5	2.000	2.500	4.000
DTAP (V)	35	3.300	1.2730	.0	5.0	2.500	3.500	4.500
ST (P/V)	35	4.586	1.0181	2.5	6.0	4.000	4.500	5.500
LT (P/V)	35	5.300	1.0724	2.5	7.0	4.500	5.500	6.000
TAP (P/V)	35	2.857	1.3857	.0	5.0	2.000	2.500	4.000
DTAP (P/V)	35	3.886	1.0716	2.0	5.5	3.000	4.000	4.500

Test Statistics[a]

N	35
Chi-Square	189.621
df	11
Asymp. Sig.	<.001

a. Friedman Test

Significance for $p < 0.017$

Test Statistics[a]

	ST (V) - ST (P)	ST (P/V) - ST (P)	ST (P/V) - ST (V)	LT (V) - LT (P)	LT (P/V) - LT (P)	LT (P/V) - LT (V)	TAP (V) - TAP (P)	TAP (P/V) - TAP (P)	TAP (P/V) - TAP (V)	DTAP (V) - DTAP (P)	DTAP (P/V) - DTAP (P)	DTAP (P/V) - DTAP (V)
Z	-.161[b]	-1.834[c]	-2.781[c]	-.333[c]	-3.857[c]	-2.713[c]	-3.381[c]	-3.943[c]	-.281[c]	-1.601[c]	-4.024[c]	-2.492[c]
Asymp. Sig. (2-tailed)	.872	.067	.005	.739	<.001	.007	<.001	<.001	.779	.109	<.001	.013

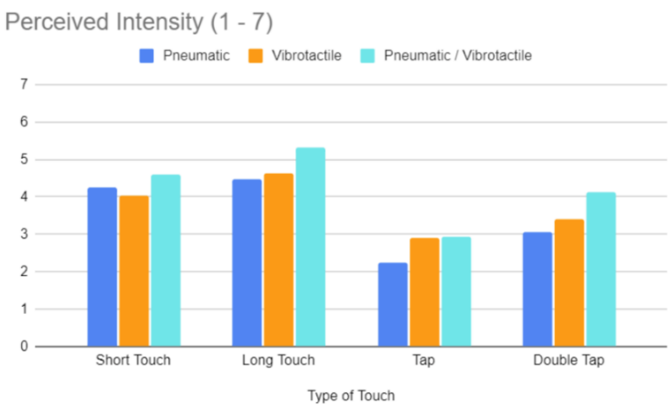
a. Wilcoxon Signed Ranks Test

b. Based on positive ranks.

c. Based on negative ranks.

Significance for:

- ST (P/V) – ST (V)
- LT (P/V) – LT (P)
- LT (P/V) – LT(V)
- TAP (V) – TAP (P)
- TAP (P/V) – TAP (P)
- DTAP (P/V) – DTAP (P)
- DTAP (P/V) – DTAP (V)



Appendix E: Project Brief

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student Mark Kruijthoff **Student number** 4,824,679

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Enriching pneumatic feedback with vibrotactile actuation

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

The field of Human Computer Interaction (HCI) is evolving rapidly, particularly in wearable design due to the technological advancements made in recent years. This can range from virtual communication towards emotional regulation reflecting the diverse ways technology can augment or simulate human interaction.

Touch hereby plays a significant role, serving as a fundamental means through which humans convey and perceive information, especially emotions. Understanding and incorporating tactile actuators and sensors into wearable interfaces poses a considerable challenge for designers and researchers alike. Namely, the process before user-testing such as selecting the right type of interface to use for the right purpose and the prototyping process itself.

This implies a need for a user-friendly prototyping toolkit that can bridge the gap between conceptualization and implementation. An accessible toolkit tailored to wearable HCI can serve as a valuable resource, enabling designers to generate and experiment with haptic feedback signals.

As this is a common issue, many toolkits such as Compressables, TECHTILE toolkit and HapticTouch toolkit have been established. However, a toolkit combining both pneumatic and vibrotactile haptics has not been developed as of yet, while the combination of these two types of haptic actuation is interesting to research (see assignment). Through utilizing the insights gained from a previous IDE Master's thesis of Clint van Leeuwen's Affective Air (see Figure 1) on pneumatic technology, this thesis will build on top of previous work by implementing vibrotactile technology, developing a user-friendly interface for designing haptic patterns and by making the device easily wearable.

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introduction (continued): space for images

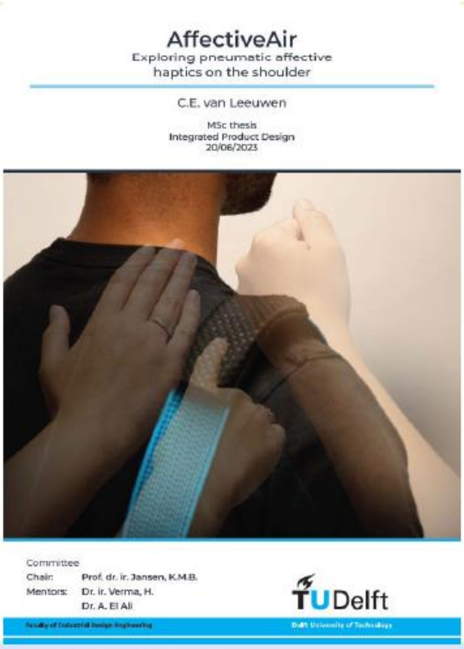

image / figure 1 Clint van Leeuwen's Msc thesis - Affective Air

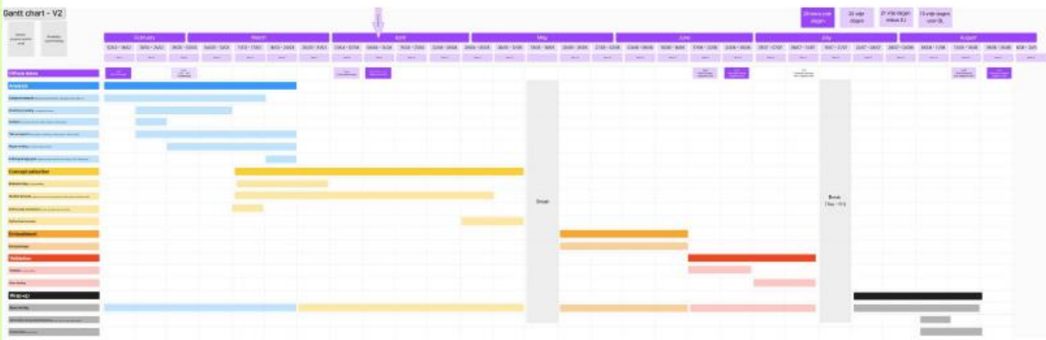

image / figure 2 Gantt planning (draft)

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

A significant issue HCI researchers and designers alike face is understanding and incorporating tactile sensors and actuators into wearable interfaces. There are many types of actuation such as vibrotactile, pneumatic and thermal, with each presenting its advantages and disadvantages. For instance, pneumatic actuation often takes time and applies gradual pressure while vibrotactile actuation can be localized and instant. Combining these two types of actuation therefore forms a unique set of technologies which yields a potent landscape for researchers and designers to experiment from.

Furthermore, being able to design customized haptic patterns and having the possibility to quickly test them on a wearable can substantially aid HCI researchers as the prototyping stage can be shortened. Using a user-friendly interface for designing these patterns, designers can overcome the difficulties often associated with programming.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Exploring expressivity through enriching pneumatic feedback with vibrotactile actuation in wearables.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

To best approach the goal of the project, it would have four main phases: analysis, conceptualization, embodiment and validation. The analysis phase will explore the context of this project. This means analysing stakeholders, literature research and above all, gaining insights into the requirements of the exact solution.

After the analysis phase, certain design opportunities are likely to arise and based on effectiveness, the given timeframe and personal ambition, a direction will be chosen for the designing phase. In this phase, the product will be developed in an iterative manner where small ideas can be quickly prototyped and tested. The following phase (validation) concludes in a higher fidelity prototype which is easily wearable. Furthermore, Clint van Leeuwen's Affective Air will be used as a starting point for the wearable prototype that will be easily wearable and usable for user testing.

Finally, in the validation phase the product is tested on its effectiveness through user testing. After graduation, I continue to publish the results of the work.
A Gantt planning of this project can be found in Figure 2.

Project planning and key moments

*To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting**, **mid-term evaluation meeting**, **green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	15 Feb 2024
Mid-term evaluation	9 Apr 2024
Green light meeting	27 Jun 2024
Graduation ceremony	19 Aug 2024

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	28
Number of project days per week	4,0

Comments:
Break from 13/05 - 19/05

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

This project entails what I am most passionate about; true innovation and prototyping. Having a graduation project reflecting my interests is important to me, especially since I would like to follow my interests as part of my future career. Better getting acquainted with technologies such as wearable interfaces, electronics and pneumatics is therefore an important learning goal to me.

Furthermore, what interests me is the research approach this project takes. As much of the true innovation lies within the field of research, I would like to explore what its like and if it would be something I would like to pursue in my career.

Personal learning ambitions:
- Getting more familiar with wearable, electronics and pneumatic technologies
- Individually structuring, organising and committing to a project for a full semester
- Experiencing the research approach of this project
- Exploring career opportunities within the field of HCI (both for product design as well for research opportunities)