AffectiveAir

Exploring pneumatic affective haptics on the shoulder

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Summary

The focus of this project was the research and development of an affective social touch wearable. AffectiveAir uses pneumatic actuation on the shoulder to convey a library of haptic sensations. The goal was to overcome physical limitations in potential digital communication contexts, by a non-verbal, tactile, and possibly intimate social touch using pneumatic actuation. This would offer a way for individuals to connect, much like in face-to-face interactions

The embodiment of the prototype is the result of an iterative design process based on literature research, benchmarks, and user tests. The wearable actuator, designed to be worn on the back of the shoulder, is secured using an elastic band that attaches to the wearer's pants. A custom-designed, thin polyurethane airbag with an integrated nozzle provides a soft, textile-integrated actuator solution. An external pneumatic control system controls the airflow, allowing for inflation under 1000- and deflation under 100 milliseconds. Effects of the actuator are monitored using an air pressure sensor and force sensitive resistor, offering controlled feedback and data logs for prototyping and user research.

Multiple user tests functioned as a means to explore and verify new designs throughout the project. Initial tests identified the shoulder as an effective and acceptable location for the feedback, and an airbag of 40x40mm was determined to provide the best balance between intensity and comfort for this specific location. Subsequent tests determined optimal pressure levels for pneumatic haptics on the shoulder and evaluated user responses to various pneumatic patterns.

Results revealed that it was challenging for participants to distinguish pressure levels from each other within the 0 to 500 mbar range. However, there were promising results in the general identification of increasing or decreasing pneumatic patterns using three pressure levels of 75, 200 and 500 mbar. 'TripleShort' received the highest identification rating at 85%, while 'short staircase down' received the lowest rating at 44%.

Patterns with a prolonged high pressure level at the end such as 'heartbeat forward' and 'long staircase up' received a slighly higher comfort and pleasantness rating compared to others, where the latter was rated the least exciting at lower speed. Overall ratings remained close to the median across tests with variable speed or pressure levels.

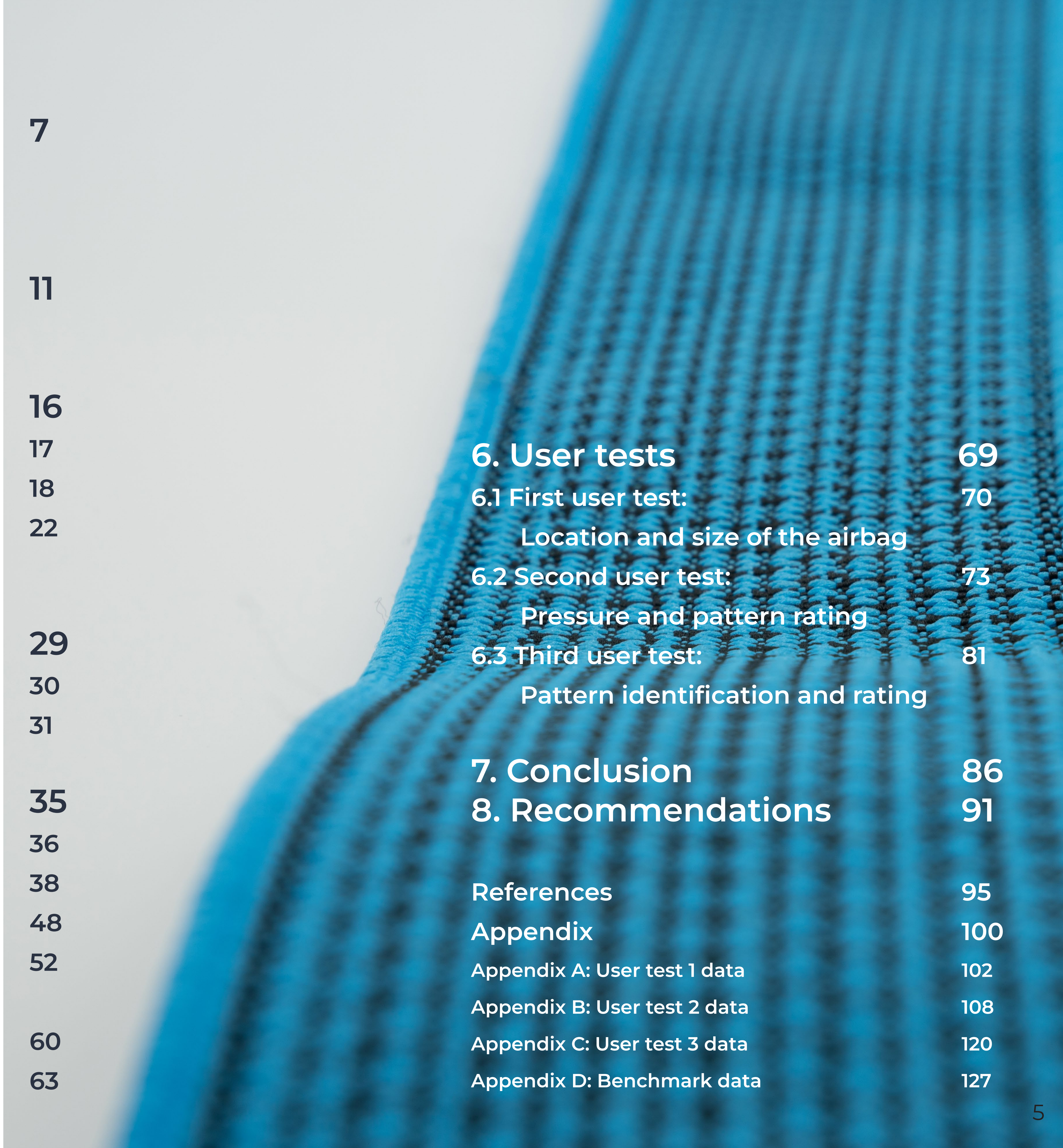
General user feedback on the prototype and haptic experience was positive, with participants noting the novelty and the sensation's occasional resemblance to intimate human touch. Feedback from the interview also notes how context and social relationship status closely relates to the acceptability of receiving such feedback. The ergonomics of the prototype were considered satisfactory, allowing for adjustment to fit any body size and position the feedback on the back of the participant's shoulder.

In conclusion, AffectiveAir demonstrated the potential for affective touch through a pneumatic shoulder wearable. It offers a library of identifiable and characterized pneumatic patterns and the ability to extend the possible actuations with adjustable parameters. The project's outcomes suggest promising potential for further research using affective pneumatic haptics, applicable not only in mediated communication but also in other possible areas such as gaming and navigation.


Photograph of final prototype


Close-up of tube and wiring

Contents



Introduction

1.

Project brief

People communicate through digital means in a variety of ways. Hybrid meetings have become the norm for businesses post-Covid, dating apps introduced video call features so people can connect quickly, and casual video calls with friends and family who are far from home is a common occurrence. While this mediated communication, often done through video calls, relies on the visual and auditory channel, other human senses are left behind. Social interaction and connectedness between people lacks in comparison to face-to-face interaction, by not having the ability to rely on subtle social cues like body posture, social touch, eye contact, and more. Prior research projects explored channels in addition to the auditory and visual spectrum, but so far none of them have had widespread adoption. Since there is room for opportunity and valuable research findings in the field of affective touch and social presence, this project will explore the possibilities.

Along with the rise of video calls and hybrid meetings, other technologies have advanced in fields that could be related. Smart fabrics and soft robotics are research fields that have steadily advanced through the years and could be implemented in this study. The project started off with a collaboration between Delft University of Technology and CWI Amsterdam, specifically the smart materials lab in Delft in combination with human-computer expertise from both parties. The goal of the project is to explore affective pneumatic haptics which could be applied in mediated interaction.

Context introduction

Project scope

The project covers the following:

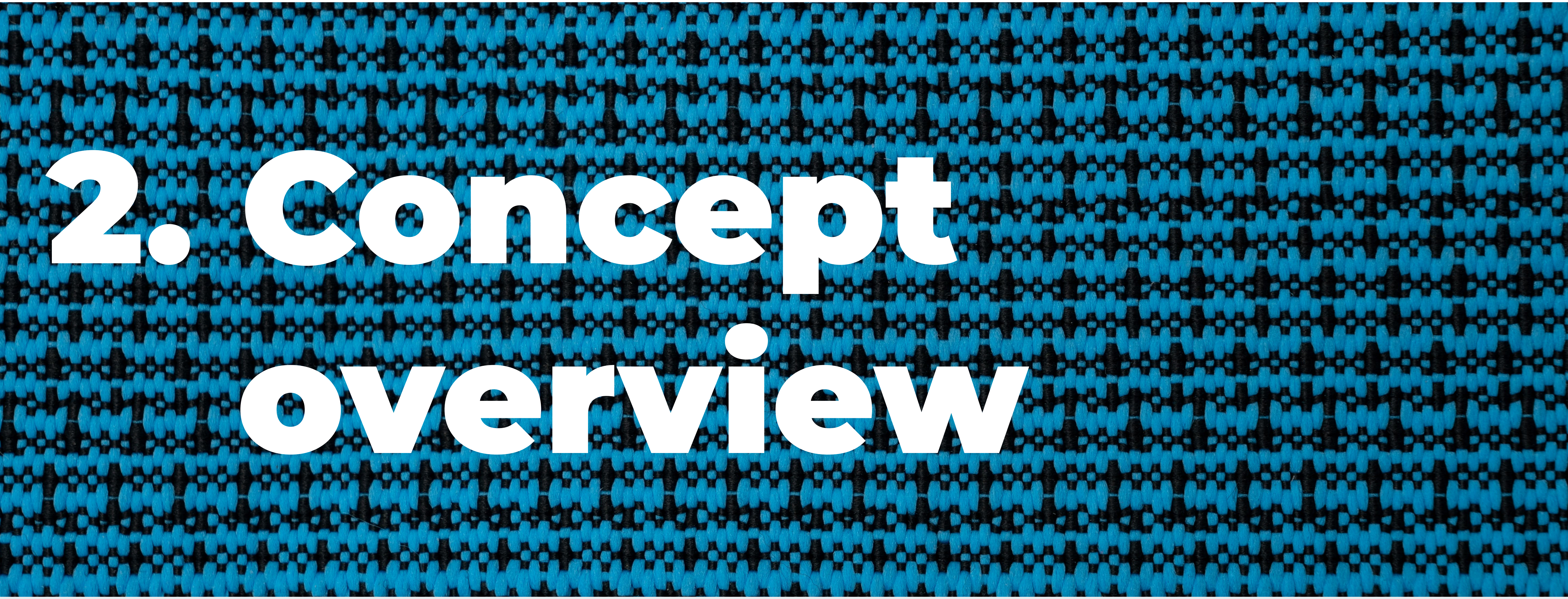
- Research on means of affective output in wearable actuators
- Research on ergonomics of the wearable
- Prototyping and user tests to validate research findings and proposals

The project starts with a literature research to define affective haptics, their relation to social presence, and possible contexts and explores possibilities for the wearable device. There are a variety of wearable actuators varying in ergonomics, perception to the user, aesthetics, and textiles which can be researched on further down the project. The study is followed by multiple prototype iterations that function to verify various ideas on interaction, ergonomics, and intricate details. A final prototype covering all research findings is developed to combine and validate the research. This report covers the process towards each research finding and design iteration. The prototype functions as a proof of concept embodying the final design results from the project.

The outbreak of a global pandemic in 2020 prompted increased use of virtual communication methods, including video calling services, which have remained popular to this day. Hybrid meetings, which involve some participants being physically present and others joining remotely via video call, have become increasingly common in many businesses. While hybrid meetings offer a variety of benefits, there are also some interactions that could be improved. Although video and audio channels are available, the lack of physical touch can be considered as a drawback compared to in-person interaction. To address this challenge, the research project will investigate the potential benefits of a wearable device that could facilitate physical touch during video calls, aiming to convey an affective state to the wearer. A potential future application for the wearable would be for mediated interaction where direct physical touch is often impossible.

Research on affective haptics wearables can be shaped in a variety of ways. Therefore a context is defined to work toward a solution with focus and coherence. The contexts share mediated social touch as an ultimate goal to convey an individual their affective state. Before the context can be applied in research, initial work on creating a wearable that can convey various types of touch is performed during this project.

The potential contexts cover video calls which can be performed through various means, settings, and devices. It ranges from casual FaceTime calls with close friends and family on the phone, to webinars with a broad audience of strangers. Alongside a purely digital meeting which was most apparent during the rise of the pandemic, hybrid meetings have become the norm in a variety of businesses. New challenges in an ‘unlevel playground’ become apparent when part of the meeting participants are remote, while others are physically present, such as expressing engagement during a meeting. Remote meeting participants have fewer means to show subtle social cues through a video feed, while participants who are physically present can show body posture, make eye contact, and use physical touch. This project explores a means of expressing physical touch through a wearable actuation. The goal is to design a wearable actuator that can express affective touch for potential mediated interactions. The wearable device should be usable within contexts such as business meetings and provide a means to express social cues through physical touch.



2. Concept overview

AffectiveAir: Concept overview

This chapter gives an overview of the final design developed during this project. It integrates research findings from literature, user tests, technical tests, and discussions with experts toward a final concept and prototype. For further information on each of these parts, please refer to their respective chapters.

AffectiveAir is a wearable device designed to deliver affective touch sensations on the shoulder using pneumatic actuation. It embodies a rich library of pneumatic actuations enabled by a combination of fitting hardware prototype and custom software. The software allows for adjustments in pressure covering multiple distinguishable levels for the wearer and tailored timing for either rapid or prolonged actuation depending on the requirement. Adjusting these variables in the prototype conveys different affective states, each with its own characteristics. For research and development purposes, the software also tracks sensor data and logs all information during either technical or user research.

The wearable component of AffectiveAir offers comfort and ease of use. An elastic band is worn over the shoulder and attached to the wearer their paints, offering a tailored solution and optimal mobility. The actuator itself is designed using thin flexible polyurethane plies and a single nozzle integrated into the airbag, offering a slim actuator solution integrated with textile.

The hardware controlling the pneumatics is connected externally during the research. The pumps offer inflation times under 1000- and deflation within 100 milliseconds. It also contains seven valves, providing control over the system's behavior and opportunity for future expandability. An air pressure sensor offers precise measurements and can be freely positioned at any location in the system. Additionally, a force sensitive resistor located on the airbag offers measurements of the translational force to the wearer. It also checks for ambient conditions such as standard fitting pressure. Valuable tube and wire connection points have a quick-release solution offering easy interchangeability of components in the prototype.

Figure 2.1: Photograph of final prototype

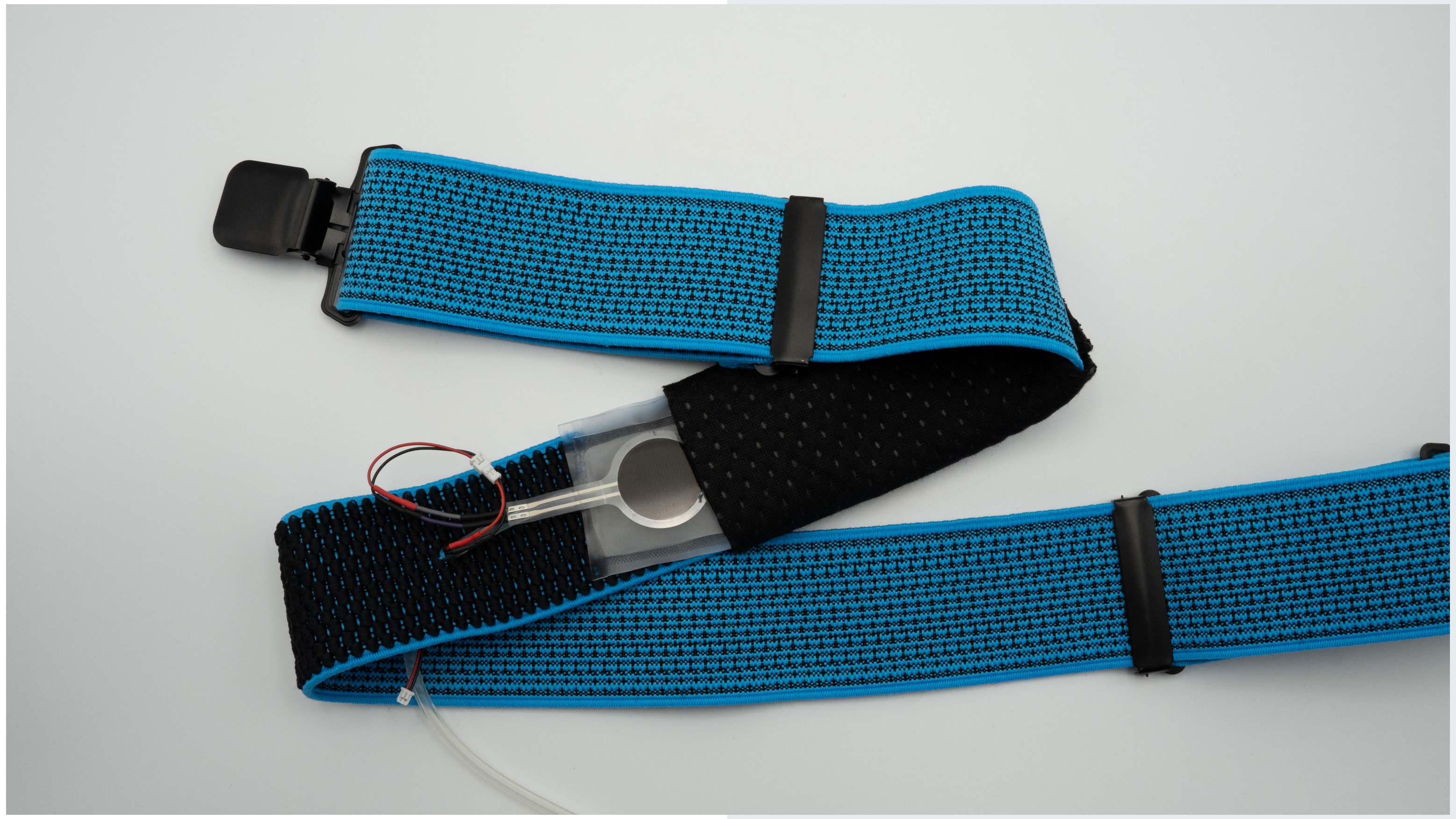


Figure 2.2: Overview of textile-integrated actuator and sensor

The iterations of AffectiveAir are influenced by the results of user tests during the project. The first test showed potential for locating pneumatic actuation on the shoulder in combination with an airbag of 40x40mm. Qualitative user feedback indicated that this was one of the optimal solutions between intensity and comfort, while it could also present a novel approach compared to prior studies in literature.

User test determined optimal pressure levels for haptic feedback in the system. 75, 200, and 500 mbar offered a wide and identifiable range of pressures. The final pneumatic pattern designs integrate these levels and show an identification rate of 44% to 85% on 8 patterns ranging from three short pulses on the same pressure level to a heartbeat-like waveform. Overall findings indicate that variable pressure could characterize a pneumatic pattern more effectively than variable timing. Feedback from interviews showed how this form of pneumatic actuation was experienced as rather novel and received positive responses overall. The feedback from the device was often viewed as somewhat intimate, leading to an interesting dynamic in user attitudes. Some participants showed a degree of openness towards using such tactile sensations in interactions with friends, yet there was a general reluctance towards the idea of employing these interactions with strangers.

AffectiveAir is the embodiment of months of research, iterative prototyping, and user tests, showing both effective and affective touch using air offering potential for application in a variety of contexts for mediated interaction and future research.

3. Literature research

This chapter describes literature on affective haptics, its relation to digital social interaction, socially acceptive touch, and existing work on social touch wearables. Research findings from literature are used to further frame the work within this project, develop prototype iterations and verify these iterations with user tests. The final part of this chapter defines focus of this project compared to existing literature, commonly known as the 'knowledge gap' this project will focus on.

The research questions in this literature research are:

- "How does mediated social touch related to social presence?"
- "What locations on the human body are suitable for (affective) social touch?"
- "What can we learn from 'affective touch wearables' in literature?"

Each research question is researched in their respective chapter, which follows after this brief introduction.

3.1 Social touch in a digital format

People can interact with a digital social environment in a variety of ways. To get an understanding of this mediated social context, this subchapter will focus on the purpose of mediated physical touch in social settings. The research question of this chapter is:

"How does mediated social touch relate to social presence?"

The chapter starts with an introduction of mediated social touch and it's value in a digital context. This is followed up by key terms and aspects of a digital social environment. The conclusion sums up the key values of mediated touch in digital contexts.

Mediated social touch in a digtal context

Current means of communication during video calls relies on the visual and auditory spectrum (Lowenthal et al., 2018). Since this interaction lacks on some senses in comparison to an offline interaction, powerful forces in communication, emotional regulation, attachment and more are reduced due to the lack of social touch (Cascio et al., 2019; Haans et al., 2006). The touch channel can compensate for the loss of nonverbal cues, enhance affective interaction between people, or could function in situations where other types of interpersonal interactions are impossible to use (Haans et al., 2006).

While haptic feedback technology is still in development to provide similar physical sensation to human touch, it is still possible to symbolize the touch of another person which offers room for exploration (Hadi et al. 2020). Haptics can also work as a modality to convey notifications in the form of haptic icons (MacLean et al., 2003). There also seems to be a realistic user-need to implement haptic icons from participants in past research (Rovers et al., 2004). Commonly used actuators to facilitate mediated touch is in the form of vibrotactile feedback (Borenji et al., 2017), but there are also other actuators available with their respective strengths and weaknesses. Chapter 3.3 will further discuss these various actuators and applications in relation to mediated social touch.

Social presence

What is social presence?

Social presence refers to the subjective experience of being present with a "real" person and having access to his or her thoughts and emotions (Biocca, 1997). Within human-computer interaction, social presence theory studies how the "sense of being with another" is shaped and affected by interfaces. The term 'Presence' consists of two interrelated phenomena (Heeter, 1992; Biocca, 1997): The first one is Telepresence, described as the phenomenal sense of "being there", including automatic responses to spatial cues and the mental models of mediated spaces that create the illusion of place. The second phenomenon is 'Social presence': the sense of "being together with another", including primitive responses to social cues, simulations of "other minds", and automatically generated models of the intentionality of others (people, agents, animals, gods, and so on) (Biocca et al, 2003). It is interesting to note that social presence does not solely rely on the physical presence of a person, but could also be influenced by the mere thought of someone, or the suggestion that someone is watching them (Dashiell, 1935; Wapner & Alper, 1952).

Value of increased social presence

Enhanced social presence can add value in variety of settings, such as teleconferencing, online learning, virtual reality, virtual therapy, and gaming (Borup et al, 2012; Tseng et al., 2015). Papers on online learning suggest that social presence can help to create a sense of immediacy, co-presence, connection, community, and bring nonverbal cues that convey affect and emotion (Steinweg et al., 2009).

How to increase social presence

In the study by Kim et al. (2011), four factor constructs for social presence were identified: mutual attention and support, affective connectedness, sense of community, and open communication. In this particular project, the focus lies on the affective connectedness aspect of social presence. By incorporating physical feedback in a wearable device, it may be possible to enhance the feeling of affective connectedness and ultimately increase social presence.

Other means to enhance social presence in an online learning environment are through the use of synchronous communication, personalization strategies, small-group work, and visual cues such as avatars and emoticons (Steinweg et al., 2009).

Co-presence, telepresence, self-presence

compared to social presence

There are a variety of terms closely related to social presence, which are co-presence, telepresence and self-presence.

Co-presence and social presence both cover the sense of being together with others in a shared physical or social context. Co-presence relies on an objective measurement of being in the same physical space, as opposed to social presence which can be a relatively more subjective experience.

Telepresence can be defined as "the extent to which one feels present in the mediated environment, rather than in the immediate physical environment (Oh et al., 2018), which seems to emphasize more on the subjective experience of an individual their location.

Self-presence is the extent to which the "virtual self is experienced as the actual self" (Aymerich-Franch et al., 2012). As opposed to telepresence, this term does not relate to how vividly one experiences his or her surroundings, but rather how connected one feels their virtual body, emotions, or identity (Ratan and Hasler, 2009).

Social presence differs from telepresence and self-presence, as it requires a co-present entity that appears to be sentient. without social presence, the other is only experienced as an artificial entity instead of a social being which can be related to more (Lee et al., 2006)

While this project focuses on mediated social touch to enhance social presence, aspects of the terms described above could be of relevance for future design implications. Social presence differs from telepresence and self-presence, as it requires a co-present entity that appears to be sentient. The interaction with social beings seems of more importance in this instance (Oh et al., 2018).

Social cues

Social cues are nonverbal behaviors or other forms of information that people use to communicate their intentions, emotions, and attitudes to others. They can include factors like facial expressions, tone of voice, posture, and gestures. In mediated communication contexts, such as online communication, social cues are often limited (Lea et al., 1992). However, the use of certain features in the form of avatars, emoticons, and nonverbal cues in text-based communication, are means used by people to convey social cues and enhance social presence (Oh., 2018). Social cues are one of the key elements in evaluating and measuring social presence in online communication contexts (Biocca et al., 2003). So by introducing mediated social touch, which is one of the social cues, it is possible to enhance social presence (Biocca et al., 1997).

Conclusion

The research question of this chapter is: “How does mediated social touch relate to social presence?”. While the scope of this question can be rather broad and introduces complexity from both a technical and sociorelational perspective, Various interpretations are discussed and combined. One of the key terms of this literature research is the definition of social presence, which has many definitions in literature. A short definition of the term can be ‘the sense of being with another’ (Biocca et al., 1997). A heightened sense of social presence brings various benefits like an increased sense of community (Steinweg et al., 2009), which can be manipulated by increasing affected connectedness (Kim et al., 2011). Mediated social touch brings enhances affective interaction between people, resulting in an increase in social presence.

3.2 Socially accepted touch

Touch, particularly of an affective nature, can function as a diverse means of transmitting social cues. Social relations and context factor in the consideration whether touch is considered acceptable. For example, receiving a hug from a close family member is often considered a form of expressing love, while receiving this physical sensation from a complete stranger can be considered awkward or inappropriate. There is also a desire for mediated forms of social touch in situations where alternatives would be mid-air gestures such as waving. Zhang et al., 2021 shows an example where participants reported a stronger preference for shaking the hand of a prototype instead of waving over a distance, highlighting the potential of mediated social touch in context. This chapter will research social contexts, regions on the body and nuances while trying to define what form of touch is socially accepted and ultimately befitting for a wearable solution. The research question of this chapter is:

“What forms of affective social touch are socially accepted?”

First, the chapter will identify acceptable touch regions on the body. This is followed by relevant situations where people are likely to initiate social touch. Lastly, a conclusion is given.

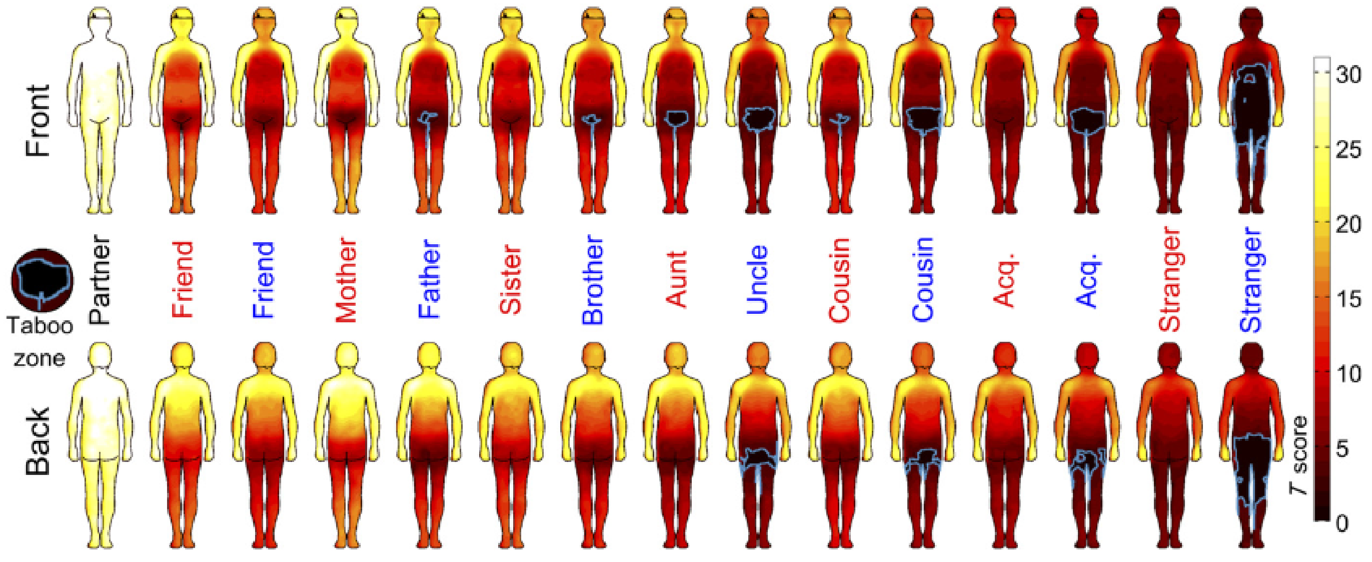


Fig. 1. Relationship-specific TAMs across all studied countries (N = 1,368 individuals). The blue-outlined black areas highlight the taboo zones, where a person with that relationship is not allowed to touch. The data are thresholded at $P < 0.05$, FDR-corrected. Color bar indicates the t statistic range. Blue and red labels signify male and female subjects, respectively.

Figure 3.1: heatmap of socially accepted touch areas (Suviletho et al., 2015)

Acceptable body regions for touch

Social touch can occur at various locations on the human body, with its acceptability primarily governed by interpersonal bonds. However, this project might also be applied in settings where interpersonal relationships may not be well-established, necessitating careful consideration of acceptable touch regions.

According to Suvilethto et al., 2015, the hands and arms are deemed to be the most socially acceptable areas for touch. Yet, there are scenarios where the hand is engaged, making it unsuitable for a tactile interface (Myles et al., 2007). So it might be beneficial to research other regions on the body within this project. The arm region, including the shoulder, upper arm, and forearm, exhibits a relatively high pressure sensitivity. Interestingly, these areas, especially for males, are found to be more sensitive than the hands (Myles et al., 2007). Furthermore, Delazio et al., 2018 suggests that the shoulder displays a relatively high perceived pressure sensitivity when exposed to pneumatic actuation, compared to other upper body locations.
These findings highlight the need for appropriate touch location selection in designing tactile interfaces, especially in low familiarity contexts. Since there are many factors contributing to the embodiment of the affective actuation, other elements such as the underlying message of touch should also be taken into consideration.

Relevant situations for social touch

There are several reasons that may warrant touch during social interactions. These include greeting or parting, indicating attention, or offering assistance (Suvilehto et al., 2015). Each instance represents a form of non-verbal communication that enhances the quality of interpersonal relationships. It is also interesting to note how adaptation to a physical stimulus occurs after presenting it for a lengthy amount of time, which results in a reduction of the perceived intensity of the stimulus. When embodying social touch in a wearable form it would be valuable to present the stimuli for relatively short lengths of time (Gemperle et al., 2003).

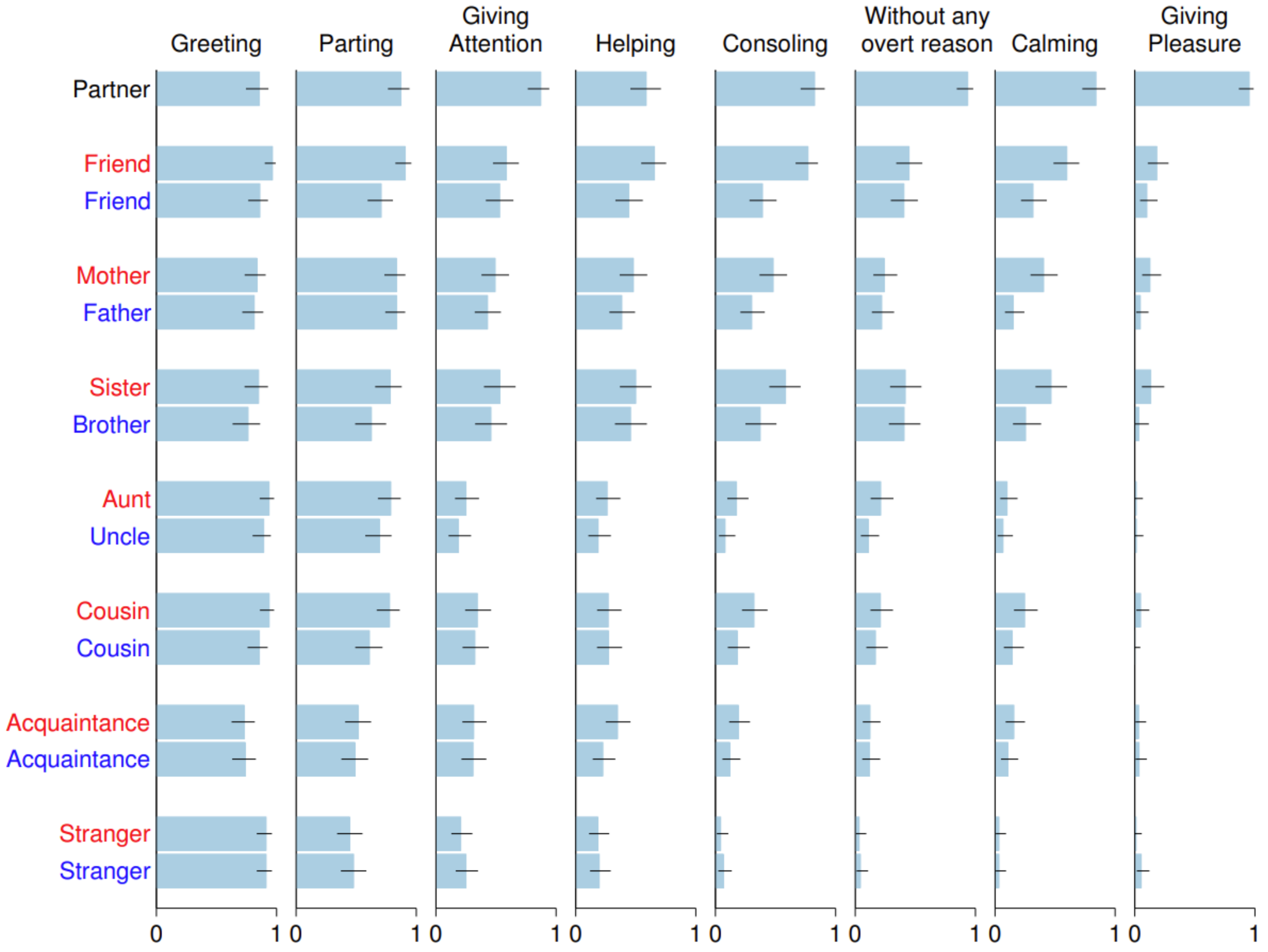


Figure 3.2: Likelyhood of touching different social-network members for different reasons (Suviletho et al., 2015)

Demographic influence: culture, age, and sex on affective touch

The cultural background plays a crucial role in the acceptability of affective touch, as demonstrated by a broad study conducted across several European cultures, including Finland, France, Italy, Russia, and the United Kingdom (Suvilehto et al., 2015). However, cultural demographics extend beyond continental boundaries and significantly impact the context of affective touch.

As an example, Mexican Americans reportedly demonstrate a higher cultural acceptability of affective touch with acquaintances, rather than close relations, and in public settings, as opposed to private environments, when compared to European Americans. It's worth noting that ethnocultural norms among Mexican Americans seem to encourage affective touch in non-intimate contexts, particularly among men, to a greater degree than European American norms (Burleson et al., 2019).

Sex also poses a significant influence on the acceptability of affective touch. Females, in general, were found to be permissible to touch a wider range of body areas than their male counterparts. Interestingly, the acceptability of social touch appears to be independent of an individual's age (Suvilehto et al., 2015).

Lastly, personal comfort with affective touch also plays a role in its acceptability, indicating a significant subjective element to the norms around touch (Burleson et al., 2019). Overall it is important to consider how every individual has their personal comfort levels determining the extent of socially accepted touch.

Conclusion

This chapter uncovered several key elements regarding socially accepted forms of affective touch, which can be applied in the design of the wearable solution in this project. Social touch acceptability varies depending on the body region, where the hands and arms are commonly considered most acceptable. Since the hand is often occupied for other functionalities it might be more valuable to research a wearable on the arm area. Context around social touch matters. Situations like greeting, parting, drawing attention, or providing help often warrant touch, especially for strangers and acquaintances. Demographic elements such as culture also contribute to the acceptability of affective touch. For example, Mexican American individuals seem more accepting of touch in comparison to European people. While age does not significantly contribute to the acceptance of affective touch, sex does. Individuals seem more permissible of the touch of female individuals. Apart from demographics, it is important to consider that the acceptance of social touch also differs per individual.

Taking these findings into account, the next steps in this project explore existing wearable prototypes in literature and tests with participants to explore responses to an affective touch wearable. Designs iterations incorporate these insights to develop a sensitive and socially acceptable affective touch wearable.

3.3 Affective touch wearables in literature

Literature shows various wearables that enable social touch in various shapes and forms. This chapter will highlight and discuss various 'social touch wearables' and relevant findings which could add value to this research project. The research question of this chapter is:

"What can we learn from 'affective touch wearables' in literature?"

First an overview of various actuators will be discussed, followed by the actuator choice of this project. Elements from related wearables with various actuators are analyzed and used as inspiration for design decisions and the embodiment during the project. Lastly, various actuation signals and patterns created by their respective actuator are described to investigate the relation to human interpretation of such a signal.

Facilitating mediated social touch can be accomplished with a variety of actuators in wearable form. Vibrotactile actuators are commonly used due to their low power consumption, small size, and ability to produce a range of haptic sensations. They can be effectively configured to convey rich actuations, but can result in negative responses after experiencing high-frequency movements for a prolonged time. (Het et al., 2015). It also exhibits a strong attention capture, limiting its use to short and prominent notifications (Poh et al., 2017). While vibrotactile feedback is suitable for protracted touches, such as pressing and squeezing, other touches were more difficult to imitate. Especially dynamic touches that move or dynamical change in pressure could be improved (Huisman et al., 2013).

Shape memory alloys are less commonly used in wearables, but offer a silent, soft and lightweight wearable integration. Expansion of a shape memory alloy is relatively slow however (3-4 seconds , which is not the optimal fit for the context of this project (Chernyshov et al., 2018).

Pneumatic pressure feedback offers similar characteristics to the aforementioned actuators in both footprint and flexibility, making it suitable for wearable applications. The entire system can become relatively larger due to the need for a pump and valve system, which also introduces noise. However, pneumatic feedback can have a low response time (below 1 second) as opposed to shape memory alloys. It also offers a wide range of attention capture, and can provide constant background feedback in a more pleasant way compared to vibrotactile feedback. Pressure feedback can support less attention-demanding situations or intimate feedback resulting in an actuation that can feel more human-like (Pohl et al., 2015; Pohl et al., 2017). Other than having a pressure scale ranging from very subtle to very strong, individual airbags can be distinguished from each other and used for a variety of usecases. Literature highlights the possibility of using pneumatic feedback for directional commands, rich alterts, and remote inter-person communications (He at al., 2015).

Vibration and compression feedback also differ from each other in the way the force reaches the user, where compression results in an inwards force, while vibration provides tangential forces (Pohl et al., 2017). The combination of these two actuations could bring opportunity in further research.

Conclusion: pneumatic actuator choice for this project
This project will research the possibilities of providing mediated social touch with a pneumatic actuator. It is a form of actuation that has been explored less in literature and real-world applications, offers interesting strengths compared to other actuators, and suits the context due to the possible richness of a pneumatic actuation. This combination of factors brings the opportunity of creating novel research findings.

Pneumatic hardware designs in literature

Literature shows various pneumatic wearables in explorative development stages. They are often embodied in a cuff around the wrist, sleeve around the arm, or vest covering the entire upper body. Knowledge and research findings on airbag design, hardware control systems, and haptic icons are implemented during the development of the pneumatic wearable in this project.

Airbag designs

Material
Materials used to create the air container of the pneumatic wearable are often silicone, polymer sheets, neoprene, and polyurethane. Silicone air containers can be formed in complex shapes by using a sophisticated mold, but a combination of high density and thick walls result in an air container that is rather difficult to integrate in fabric (He et al., 2015). Polymer sheets offer less complex internal geometry compared to silicone. However, it is a low profile solution due to its thin walls and profile in idle configuration making it a suitable option for textile integration (Raitor et al., 2017). Neoprene covered with fabric is commonly used in blood pressure cuffs, and offers a rigid and strong seal with similar characteristics to polymer sheets (Pohl et al., 2017).

This project uses polyurethane sheets which have similar characteristics to the polymer sheets discussed before. It offers a low profile that can be integrated into fabric designs, offers enough flexibility in internal chamber design, and suits rapid prototyping due to its heat sealing characteristics.

Inlet, outlet, internal geometry
Airbag designs can feature either a singular inlet and outlet (Delazio et al., 2018) or distinct ones for inlet and outlet flows (Raitor et al., 2017). Employing a single channel design not only simplifies the configuration but also limits the potential leakage points. The footprint of the airbag is also reduced which suits it's wearable application. Separate channel for the inlet- and outlet flow offers more control on the behavior of the airbag .This project has opted for a singular channel airbag design to streamline complexity and reduce potential failure points in the initial functional prototypes. Prior results from literature suggest that single channel designs can enable advanced pneumatic actuations. Geometry options range from a simple airbag with a single central force (Wu et al., 2019) to a channel pattern for an evenly distributed pressing force (Raitor et al., 2017).

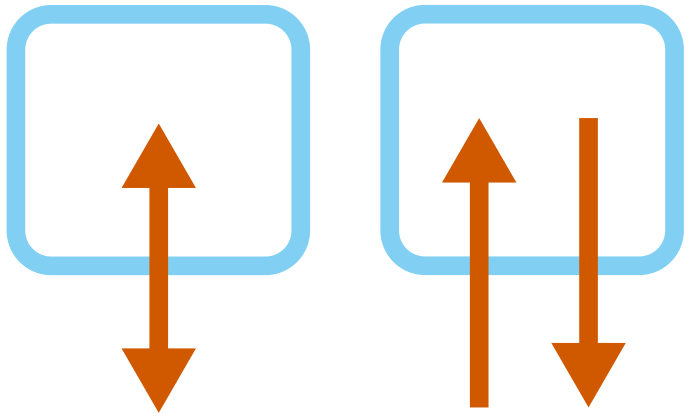


Figure 3.3: Schematic of single and double nozzle airbag design airflow

Pump considerations

The size of the electronic control and pump system can vary significantly. Thus, it is not unusual for this part to be placed outside of the wearable embodiment, limiting the user's mobility. Stronger pumps offer a higher peak pressure and higher flow rate, typically at the expense of increased energy consumption and size. For example, Delazio et al., 2018 incorporates two compressors generating pressures up to 3300 mbar. Wu et al., 2019 uses one compressor for pressures up to 800 mbar. Smaller pumps that can be worn around the arm can create pressures up to 200 mbar (He et al., 2015). It is interesting to note that a pressure of 25 mbar could suffice to notice pressure change on the wrist which could be applicable similar locations on the body (Pohl et al., 2017). A smaller pump could suffice in this project, but the flow rate should not be neglected which is lower on smaller pumps as well. A low flow rate in combination with a relatively large airbag would result in a long duration to peak pressure, which would be experienced as rather slow feedback. When simulating human touch or affective types of touch it would be beneficial to have the ability to create quick pulses. For example, Delazio et al., 2018 noted that replicating a punch was rather difficult to replicate despite the usage of two large compressors, which suggests a higher flow rate or smaller airbag size might have been more suitable for this specific actuation. Overall a balance should be found on the optimal pressure range, flow rate, size of the electronics, and airbag size. This project has opted to use the Programmable air development kit due to its suitability for rapid prototyping while offering a decent pressure range up to 500mbar and low rate of 2L/min. The custom PCB with dimensions of roughly 150x150x200 mm make it somewhat difficult to integrate it in the wearable design at an early stage, but could be developed on after verifying the hardware configuration for the context.

Takeaways from literature on pneumatic hardware

Literature research show various embodiments of pneumatic prototypes. Some design decisions are inspired from this research. The material of the airbag will consist of polyurethane sheets for their low profile, flexibility, and suitability for rapid prototyping which makes them a suitable choice for textile integration. A singular channel airbag design streamlines complexity while prototyping, while still enabling advanced pneumatic actuation as demonstrated in the literature. Deciding on the optimal pump for the project depends on factors such as pressure range, flow rate, volume of the electronics, and airbag size. The programmable air kit offers a balance between these factors and enables rapid prototyping due to its accessibility in both hardware and software. Future iterations could work on integrating all electronics in one wearable solution to increase mobility and integration of the prototype. The focus of this project is to explore and define variables characterizing the pneumatic actuation before integrating the optimal components.

Pneumatic patterns in literature

Past literature show various methods to implement and modify pneumatic actuation. Prototypes range from modified electronic control algorithms to advanced wearable air containers designed and tested in-house. One form of more commonly used pneumatic feedback is in the form of a blood pressure cuff. (Pohl et al, 2015) shows three possible types of actuation patterns in the form of sustained pressure, full sawtooth, and an oscillating sawtooth. By adjusting the power level of the pump, characteristics of each pattern could be modified influencing the experience for the user.

(Raitor et al., 2017) takes pneumatic feedback located around the wrist one step further by segmenting the cuff in four sections, enabling 4-directional pressure feedback for haptic (directional) guidance. Results show how translation and rotational cues were identified with 99.4% accuracy , suggesting the added value to directing the wearer (Raitor et al., 2017).

An example of an exploration of richer sensations can be seen in (Delazio et al, 2018), demonstrating fourteen pneumatic patterns which are distinguished of a combination of seven parameters. Examples of these variables are inflation pressure (psi), target force (N), time per cycle (ms), duration (ms), target frequency (Hz), etc. While the goodness rating score for some patterns score relatively low (such as a punch), suggesting whether the optimized effect parameters correspond well to the descriptive language phrase, actuations like a calm or racing heartbeat, hug, rain, or mechanical vibration can inspire actuation designs further in the project due to their relative success within this research.

Other wearables were able to create a convincing tracing sensation by actuating an array of airbags sequentially (He et al., 2015, Raitor et al., 2017, Delazio et al., 2018). A gentle stroke on the arm, snake moving over the body or other actuations could be actuated using this technique. The combination of both large airbag and pump sizes does make it more difficult to fully integrate into one wearable solution without limited mobility (Wu et al., 2019). The aforementioned types of pneumatic touch could be applied in an affective touch wearable that could try to convey touch in potential social contexts. Think of simulating or symbolizing social cues such as a greeting, parting, giving attention, and helping, which were discussed in the previous chapter.

Other literature on repeated actuation of a single airbag is described in Pohl et al., 2017. The research shows how three short or long pulses are considered the most calm patterns. Arythmic patterns were considered unpleasant and should be avoided when trying to receive positive responses during this project. A heartbeat and 'shortLongPause' pattern were also considered as relatively pleasant, rhythmic and calm patterns.

Actuation speed is also an important element when working with pneumatic haptics. For example, when trying to recreate the sensation of lateral motion, an inflation time of 120 milliseconds (with a 50% overlap for each airbag) is one of the key aspects to create a convincing sensation.

Inspiration from expressive visual actuation

Other than looking at the characteristics of pneumatic actuation, other actuation methods with similar characteristics could help to gain more of an understanding in the possible expressiveness of actuators. LED lights show similarities to pneumatics in their rapid actuation and waveform-like ability to express (in light intensity instead of force). Research reveals how the vocabulary of lighting expression in popular use today is “small, fairly unimaginative, and generally ambiguous in meaning” (Harrison, 2012). The research uses Iterative design sessions considering the location and goal of point lights, working towards 24 expressive light behaviors (Harrison, 2012) displayed in Figure 3.4.

The expressivity of LED lights could be categorized in five factors: notifications, active, unable, low-energy state, and turning on. Since these categories show variation in expressivity, they could be used as inspiration for the pneumatic designs in this project. Social cues such as a greeting or giving attention could work with a ‘notification’ or ‘turning on’ waveform, while a more calming or consoling waveform could be a ‘slow pulse’. It can be valuable to keep these expressive LED designs in consideration during the design process.

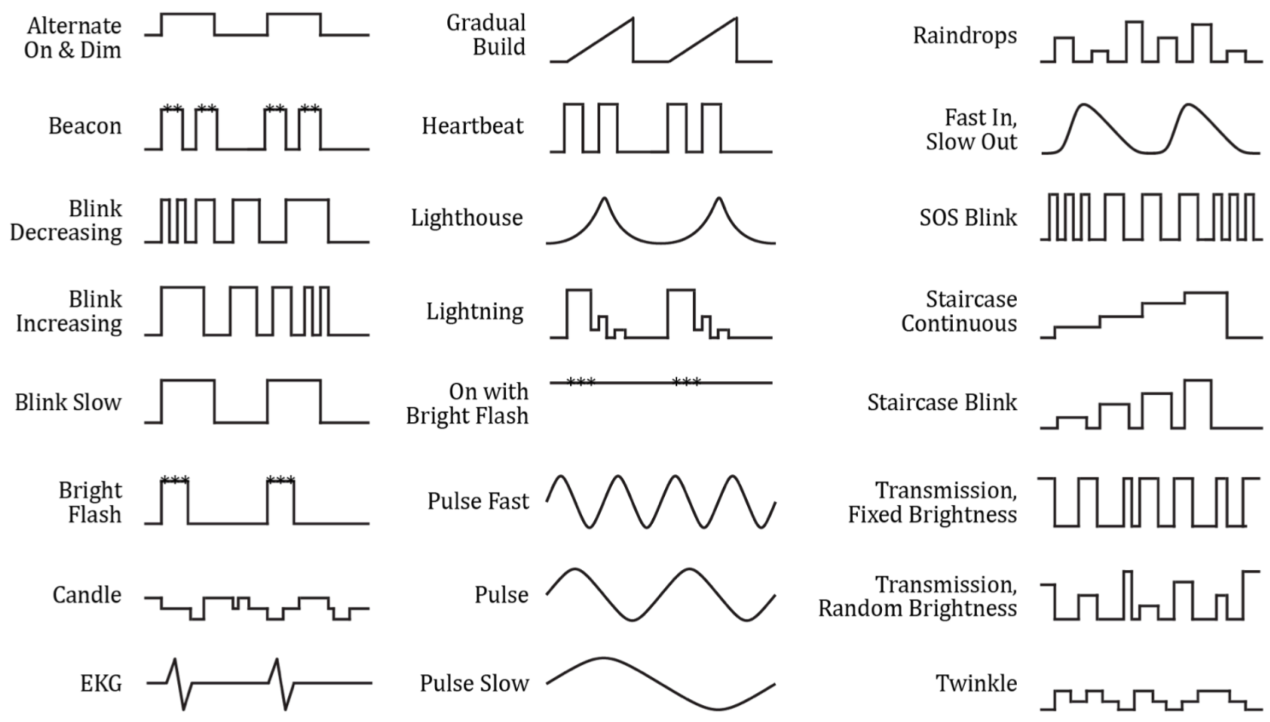


Figure 3.4: Sparklines representing the illumination intensity over time for our 24 proof-of-concept light behaviors (Harrison et al., 2012)

Conclusion

The literature exploration of various actuator mechanisms led to the choice of pneumatic actuation for the designs in this project. The less-explored yet intriguing properties of pneumatic actuators presented a valuable research opportunity, given their capability to provide rich haptic sensations.

Findings from the literature also highlighted various prototype designs on materials, the inlet and outlet design, and specifications of the pump in relation to the context. Polyurethane sheets are considered most suitable due to their low profile, flexibility, and suitability for rapid prototyping. The use of a singular channel airbag design is deemed beneficial, reducing complexity while still enabling advanced pneumatic actuations. Considerations on the pump impact the performance of the prototype, where an increased pressure output range and flow rate often comes at the cost of a larger pump impacting wearable integration. The programmable air kit was chosen for it’s flexibility in prototyping while also containing pumps with decent performance.

Literature on pneumatic patterns offered valuable insights into the potential for creating diverse haptic sensations. Human touch such as a tracing sensation can be replicated, directional cues are clearly understood, and a variety of rich actuations beyond conventional human touch can be created. Inspiration for expressive actuators can also be found in other fields such as in LED lights. 24 light behaviors can inspire the design of pneumatic patterns within this project.

The exploration and understanding of affective and expressive actuators provide a foundation for future designs during the project. Design iterations on both the hardware and software end in relation to contextual factors discussed in previous chapters work towards a potentially affective pneumatic wearable solution with a rich library of actuations.

4. Context definition

4. Context definition

4.1 Problem definition

In our modern, digital age, human social interaction is often mediated through screens and devices. While video calls and instant messaging have made remote communication easier, they do not fully replicate the experience of face-to-face interactions. One major aspect missing in mediated communication is touch, which contributes significantly to the intense affective experience of co-located communication.

This lack of physical contact has led to a growing interest in touch-enabled agents in various fields, such as healthcare, therapy, teaching, and virtual reality to enhance positive interactions (Cascio et al., 2019). Affective touch, which can be mediated reliably, has been found to modulate physiological responses, increase trust and affection, help establish bonds between humans and avatars or robots, and initiate pro-social behavior (Van Erp, 2015). Since hybrid meetings have become normalized in our society, applications of affective touch over a distance could bring appeal and value on a daily basis. This project explores the possible value of affective social touch with a novel embodied prototype to acquire new research findings.

Design goal

One of the main goals in this project was to create a social touch wearable that can fit a variety of social contexts. There is a variety of literature on affective touch for more intimate relationships, but the design in this project should be applicable to other social relationship statuses as well. The project started with a focus on potential video call contexts, but during the development and testing the focus shifted to the affective expression of the wearable and how individuals perceive the rich pneumatic actuation. Therefore the design goal of the project is to design a wearable actuator that can express affective touch for potential mediated interactions.

After analyzing the literature on social touch, acceptability of touch depending on sociorelational factors, and prior work with affective touch wearables, the framework for the project was set. The project scope worked towards having a wearable on the shoulder with a relatively small airbag in combination with the pump system. This combination of design decisions offers a unique pneumatic wearable solution that has a relatively low amount of research in literature, offering the opportunity for valuable and novel research findings (Pohl et al., 2017).

4.2 Target group and scenarios

One of the main goals in this project is to develop an affective social touch wearble that can be applied in mediated communication contexts. An example of this would be a hybrid meeting, where remote participants lack the means of physical touch to express themselves using a handshake or tap on the back. The optimal type of mediated social touch can depend on the spefic video calling context, which is why this chapter will describe some of the contexts that are kept in consideration during the design process. The four scenarios are a hybrid meeting, virtual conference, remote lecture, and smartphone video call. An example of differences in context is how a remote lecture offers a many-to-one scenario (a multitude of students is paying attention to one professor), while a smartphone video call is more commonly used for one-to-one interactions. The latter situation also offers the opportunity for a more intimate connection between individuals, which could suggest the value of having a slightly different type of feedback for couples for example. Literature on mediated social touch often leans toward a more intimate type of touch targeted toward close relationships and medical settings (Vyas et al., 2023), but this project will focus on touch that is also viable between strangers and acquaintances. Factors such as the acceptability of social touch per scenario, actuation speed of the pneumatic system, and other elements are taken into consideration during the design process.

Potential contexts

This chapter will discuss the potential value and aspects per scenario when integrating affective mediated social touch in the interaction. The four scenarios are a hybrid meeting, virtual conference, remote lecture, and smartphone video call.

Hybrid meeting
A hybrid meeting can be divided in four key moments. First it starts with a walk-in moment where the participants who are physically present walk into the room, while the remote participants join the meeting, and pop up on the screen of the presenter with either their name or a live video feed of their webcam. The meeting starts off with a presentation lead by one participant. During the presentation questions may pop up from the participants, which can be expressed in a variety of ways. People can hold up their hand, politely interrupt the speaker, make eye contact or use other methods to get the attention of the speaker. For remote participants it could be more difficult to express these social cues, because their full body and subtle cues are harder to see when they are a small part of a display or not visible at all during the presentation. After finishing the presentation there is some time left for discussion, where the focus shifts to the crowd. In order to ask a question of the speaker, participants can use similar social cues as during the meeting, by raising their hand, speaking up, or making eye contact. While remote participants don’t have the ability to make eye contact, there is a bigger chance that they do get noticed at this point by either the speaker or the public who is physically present. An example of being noticed is by having a notification when one of the remote participants types out a question.

Interesting aspects of this scenario where mediated social touch might bring potential value are:

- Subtle interruptions from the crowd during a presentation, for facilitate collaborative turn-taking (Garcia 1999)
- Gesturing to the content of a presentation (Bragdon, 2011)
- A form of non-verbal communication which could make up for the lack of eye-contact (Bohannon, 2013)

Virtual conference
Virtual conferences are online events that allow attendees to participate remotely from anywhere in the world through video, audio, and chat tools. New technologies such as Virtual Reality (VR) offer means to simulate physical face-to-face interactions. When an individualinteractss with an agent in a VR environment, haptic technology can add to the affective state of the participant. Especially pneumatic and servo actuators could suit these types of scenarios (Ahmed, 2016). Simulating physical touch similar to a handshake, hug, or tap on the shoulder could be beneficial for such contexts.

Online education
A worldwide shift to online education started during the covid-19 pandemic (Dhawan, 2020). Mediated interaction relied on text, audio and visual means, which resulted in some observational components being difficult to replicate in this virtual context (Ensher, 2003). Subtle non-verbal cues like a nodding crowd and facial expressions are more challenging to convey in these contexts. Low social presence can be a particular issue in asynchronous text-based situations, leading to the feeling of impersonality and disengagement from online learning (Kear, 2014). This can result in a means of online communication that can be impersonal to some students, leading to poor online relationships, or lack of participation. The literature review discussed how mediated social touch can increase social presence, which should help in negating these challenges in the online environment, contributing to valuable positive interactions akin to face-to-face situations. Some literature also notes how social presence can be considered as 'a dynamic sense of others and relationships with them in mediated environments' (Kehrwald, 2010), suggesting value of dynamic sensing in the form of mediated touch for example, as opposed to a static personal profile (Kear, 2014).

Smartphone video call
Mediated communication through the means of a smartphone could bring slightly different values from the contexts described above. Smartphone video calls can involve a one-one-one conversations, providing a more intimate and focused setting for personal communication. When communicators spend adequate time through mediated communication with each other, strong relational links can be formed (Chidambaram, 1996). Mediated social touch can contribute to this strong affective bond by offering touch on a variety of locations depending on social acceptability and interpersonal relationships.

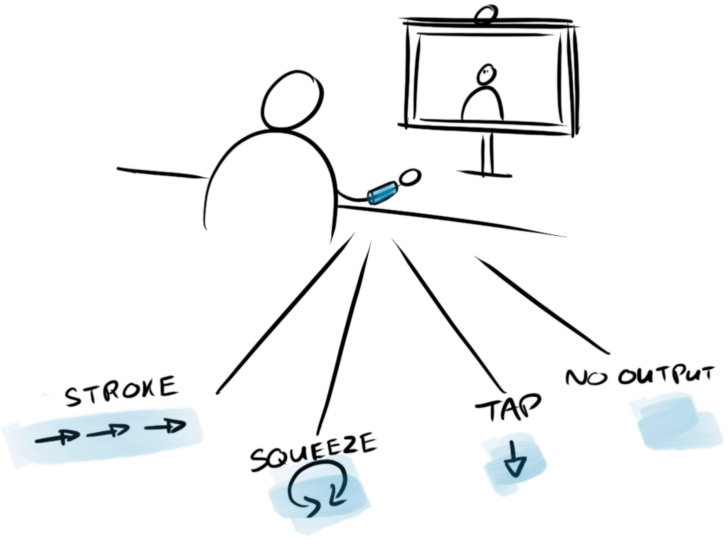


Figure 4.1: Sketch of mediated social touch

Conclusion

This chapter discusses the potential target group and potential usecases for an affective social touch wearable. By defining and analyzing four contexts, a concept can be designed and developed which can cover specifics for these situations. Different social settings and interpersonal relationships define what type of touch is applicable in face-to-face scenarios, and are valuable to keep into consideration while designing affective touch suitable for mediated contexts. These points are:

- A hybrid meeting could benefit from a means of offering subtle hints while someone is presenting

- Some form of directional feedback could help relate to the content of the presentation

- Subtle non-verbal cues such as eye contact, facial expressions, and a hand pointing up to ask a question could be expressed in a form of mediated social touch

- Simulating physical sensations akin to a handshake, hug, or tap on the shoulder with the social touch wearable could be valuable in all of the four example contexts

- Mediated interactions on a more personal level could ask for a more affective form of mediated touch. This depends on factors such as touch location on the body and feedback intensity.

5. Prototype

Iterative design approach

Various iterations of the pneumatic prototype were developed and tested throughout the project. Early versions provided a means to familiarize with the performance and characteristics of pneumatic actuators, by validating performance with measurements or user tests. Further developments in both the wearable design and the pneumatic actuation were based on findings from those tests and literature research conducted in parallel within the project's timeline.

5.1 Iteration overview

The prototype comprises three main elements. The first is the pneumatic control system containing the hardware and software to operate the wearable. These components are housed in a soundproofing box and are connected to the system's other two elements. The second element is the wearable part of the prototype, consisting of an airbag, a textile band worn over the shoulder, and a force sensor located near the airbag. Lastly, a computer is used to issue commands to the control system and record input from participants during user tests. This chapter will describe the prototype's development of the prototype during the design process on each of these three elements.

First iteration

The first iteration served to get accustomed to the possible sensations with pneumatics. Technical challenges such as wiring, limiting potential leakage, and programming were resolved. During the test, the experience of the actuator was tested at four locations on the arm (by manually adjusting the tube channeling). Using a relatively simple time-based open programming loop, various pneumatic patterns, inspired by literature, were designed and used during the first tests. Insights gained from these tests and future challenges on the hardware- and wearable end are integrated and resolved in subsequent iterations.

Second iteration

The second iteration introduced more sophisticated pulse designs that employed a pressure target in the software (replacing a simple timer) and reads the air pressure to create a feedback control loop. Four base pulse designs based on literature were tested, and three of those pulse designs were implemented in various forms during the second user test. The computer provides an interface used during the user test to track feedback from the participants and control the specific actuation from the wearable. The wearable design was updated to an ergonomic solution positioned on top of the shoulder.

Third iteration

The third and final iteration continues on the work from the previous iteration, incorporating optimal pressure levels and greater customizability to create optimal pulses for the wearer. While a wide variety of pneumatic patterns are feasible with the software, the user tests employed eight patterns iterating on pattern designs from the previous iteration. This approach allowed for the verification of important aspects such as pattern identification and ratings. The final version of the prototype includes features such as optimal pressure levels, optimized pressure patterns, an adjustable pulse control GUI, and aesthetic finishes. These advancements render the prototype a comprehensive solution that meets user needs while providing an aesthetic and comfortable wearable experience.

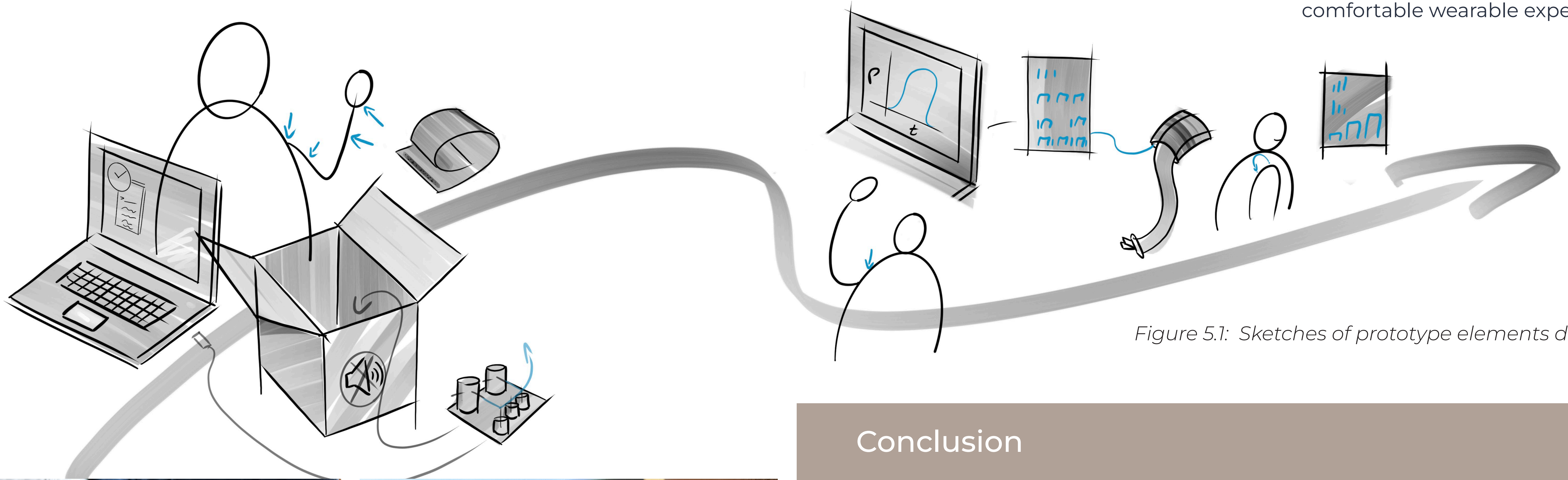


Figure 5.1: Sketches of prototype elements during iterations

Figure 5.2: Early iteration of the prototype

Figure 5.3: Late iteration of the prototype

Conclusion

In conclusion, the development of the prototype can be divided in three elments: the pneumatic control system, wearable component, and a computer for command input and data recording. An iterative design approach allowed for testing and refinement throughout the entire design process.
The first iteration focused on familiarizing with pneumatic actuation with the first functional prototype and explorative user test within this project. The second iteration implemented feedback control loops, introduced more sophisticated pulse designs, and worked towards a more quantitative assessment of characteristics such as optimal pressure levels. The third iteration integrates these findings and refined the software to generate optimal pulses for the wearer. Overall, the prototype evolved into a fine-tuned package with accompanying hardware, software, and fabric design.

5.2 Airbag Design

General introduction to airbags

Airbags, essentially air-filled containers, can be used in a variety of ways. In this project they serve as the part of the actuator which is directly felt by the user. Common materials for constructing airbags are polyurethane, silicone, neoprene and latex. This project opted for polyurethane due to its low density, durability, and suitability for rapid prototyping. An airbag requires a nozzle to control the flow of air in- and out of the container, allowing for precise inflation and deflation according to the desired functionality. This chapter explores various airbag designs approaches, methods of integrating a nozzle in the airbag, and discusses various challenges, such as creating a proper airtight seal.

The airbags used for prototyping during this project consisted of two polyurethane (PU) plies with a single nozzle made from similar material which acts as both the inlet- and outlet airflow channel. Compared to other pneumatic airbags in literature, this design offers a relatively low-profile design that can be integrated by sowing it in various textile designs.

⬜ = Airbag iteration

🟦 = Prototyping method

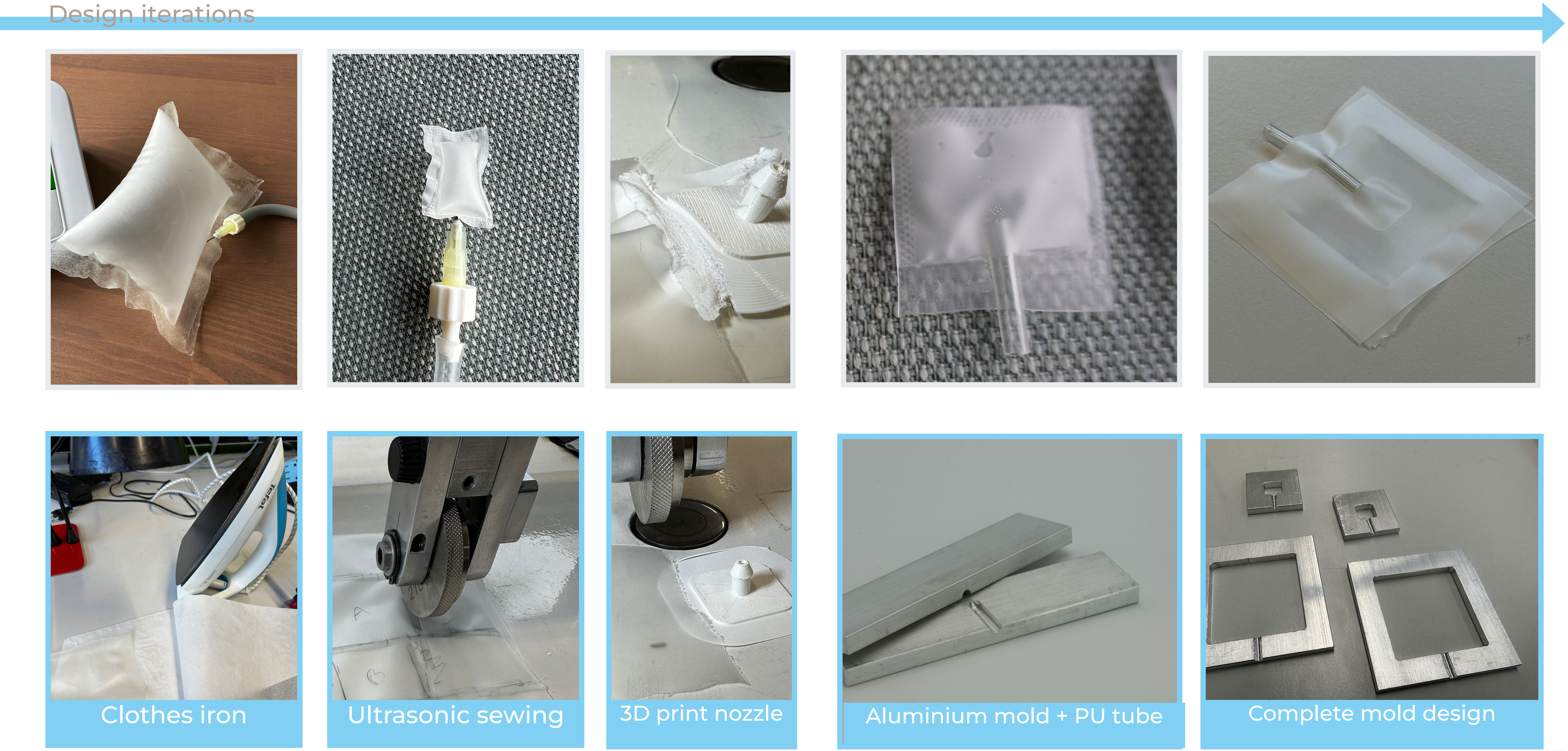


Figure 5.5: Airbag design iteration overview

Heat sealing method

The principle of sealing the edged of the polyurethane sheets works with heat sealing. By heating the material to roughly 140 degrees Celsius, the sheets soften and bond to each other creating an airtight seal, similar to the fabrication method of inflatable boats. A variety methods to heat the sheets were tested while prototyping, ranging from a household iron, ultrasonic sewing, and lastly a custom-made aluminium mould with a heat press.

Figure 5.6: Early prototype using a clothes iron

Clothes iron
The first airbag prototypes were sealed using an iron and baking paper for an even heat distribution. After applying heat for 30 seconds on the maximum heat level of the iron (1200W), a bond was created that could withstand the pressure levels created by the pump (rated up to 500 mbar). While this is a straightforward method of sealing the edges, there is a desire to create a more controlled seal with a smaller footprint. Therefore other methods of sealing the edges of the airbag were explored.

Ultrasonic sewing
Ultrasonic sewing generates heat through friction, thus allowing us to create a bond between two plies by rolling a metal wheel over them. Long lines and thin edges can be created in a smooth way, enabling the creation of more sophisticated shapes compared to the previous method. While the machine requires some calibration before each use and experience to create the desired (more advanced) seals, various prototypes have been created using this method (Figure 5.7).

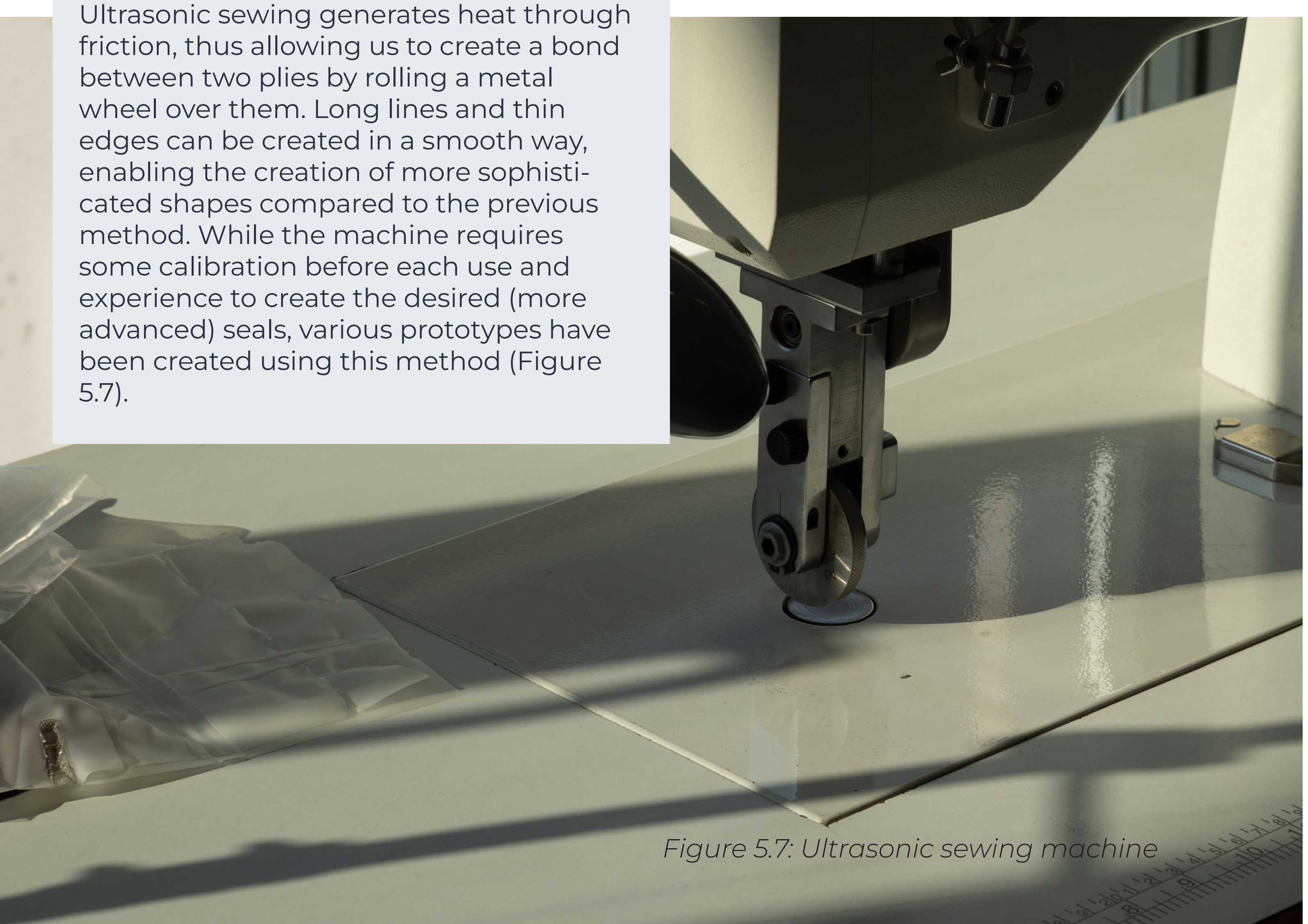


Figure 5.7: Ultrasonic sewing machine

Aluminium mold

The final iterations of the airbag prototype use aluminum molds to create a controlled and airtight seal. This was especially helpful to create a proper seal around the nozzle, which is a 20x3mm piece of polyurethane tube in final iterations. Initially, all edges were sown with the ultrasonic sewing machine, one edge was cut open to be resealed including a nozzle with the aluminum mold. The design of the mold was expanded to increase the consistency of the airbag prototypes, while also reducing the manual labor needed to create an airbag. Figure 5.8 shows how the nozzle is bonded to the ultrasonic sewn airbag, while Figure 5.9 shows the final mold design which is the result of a optimized prototyping method.

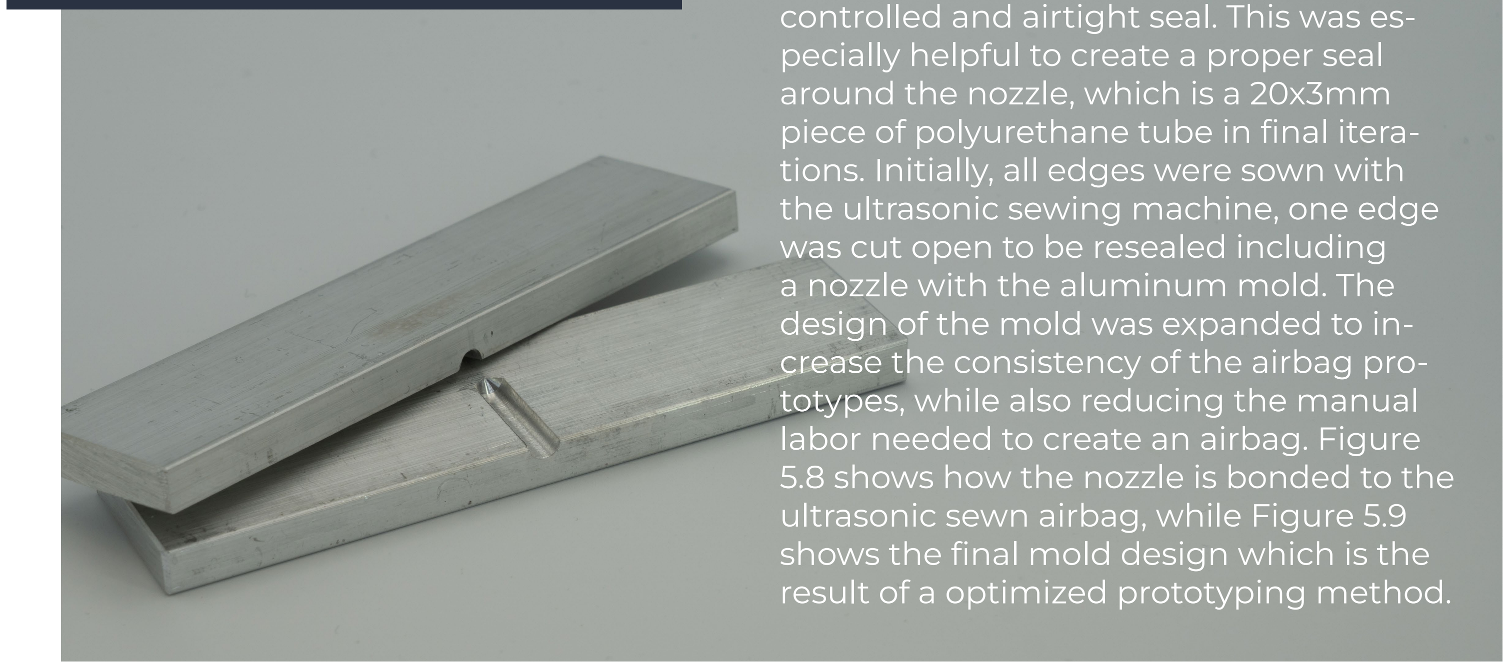


Figure 5.8: First mold to heat seal PU nozzle

Between two plies of polyurethane, a hard tube of the same material is carefully placed and aligned with the mold, creating a small ´sandwich´. The sandwich is placed in a hot press at 145 degrees Celsius for one to three minutes depending on the mold size, and thereafter cooled off in a bath of water for a minute. After carefully removing the airbag from the mold and cutting excess material along the edges with scissors, it is ready to be integrated into the textiles of the prototype. The airbag can either be permanently sown to the fabric using the thick edges, or have a more interchangeable bond using Velcro or form fitting.

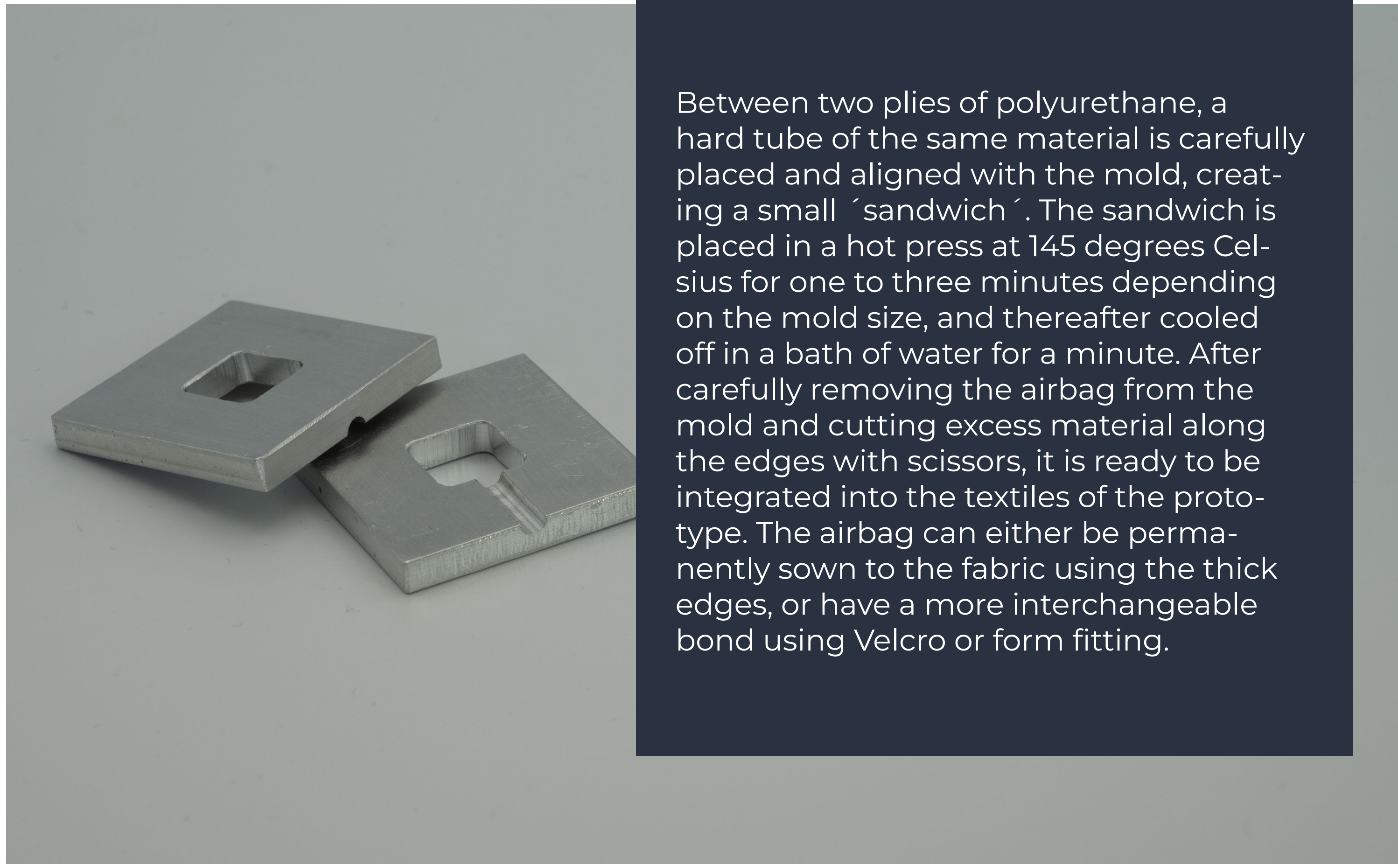


Figure 5.9: Final mold design integrating all seals in one part

Nozzle connections

To control the airflow in and out of the airbag, a nozzle connected to a tube, leading to a pump system is needed. Creating an airtight seal of the nozzle to the airbag itself can be challenging due to bonding methods and complex geometries. A relatively straightforward way to inject air into the bag is by inserting a needle. Initially, this method was used to quickly test various airbag shapes and sizes in the early stages of the project. While this is a convenient method to create an inlet, leakage was an issue. Due to small gaps around the outer perimeter of the needle, air slowly leaked out of the system. The needle was also relatively bulky and stiff compared to the thin polyurethane airbag it is attached to. An alternative to the needle, which seemed promising at first, was a 3D-printed nozzle made from a similar material to the polyurethane plies. Difficulties in printing a compact nozzle in the right orientation and challenges in bonding the 3D-printed part to the plies led to the conclusion that it would be too complex and time-consuming to create an airtight seal around the nozzle using this method. The third and final solution to creating a satisfactory nozzle connection was by switching to a small piece of PU tubing, which was heat bonded around the polyurethane plies using an aluminum mold. By stacking two mold pieces of 20x50x5mm and drilling a hole of 3mm at the edges, a mold was created that contacted the outer curvature of the PU tube. This resulted in a proper contact area for even pressure and heat distribution between the plies and tube, creating an airtight seal.

In the design process, both single and double nozzle configurations were considered. While a separate inlet and outlet design offers benefits in precise pressure control and a smoother deflation control, as can be seen in Delazio et al., 2018, a single-nozzle design is expected to offer sufficient pneumatic control with the programmable air kit (discussed in the next chapter) while offering a design that can be more integrated into textiles due to a relatively lower number of tubes.

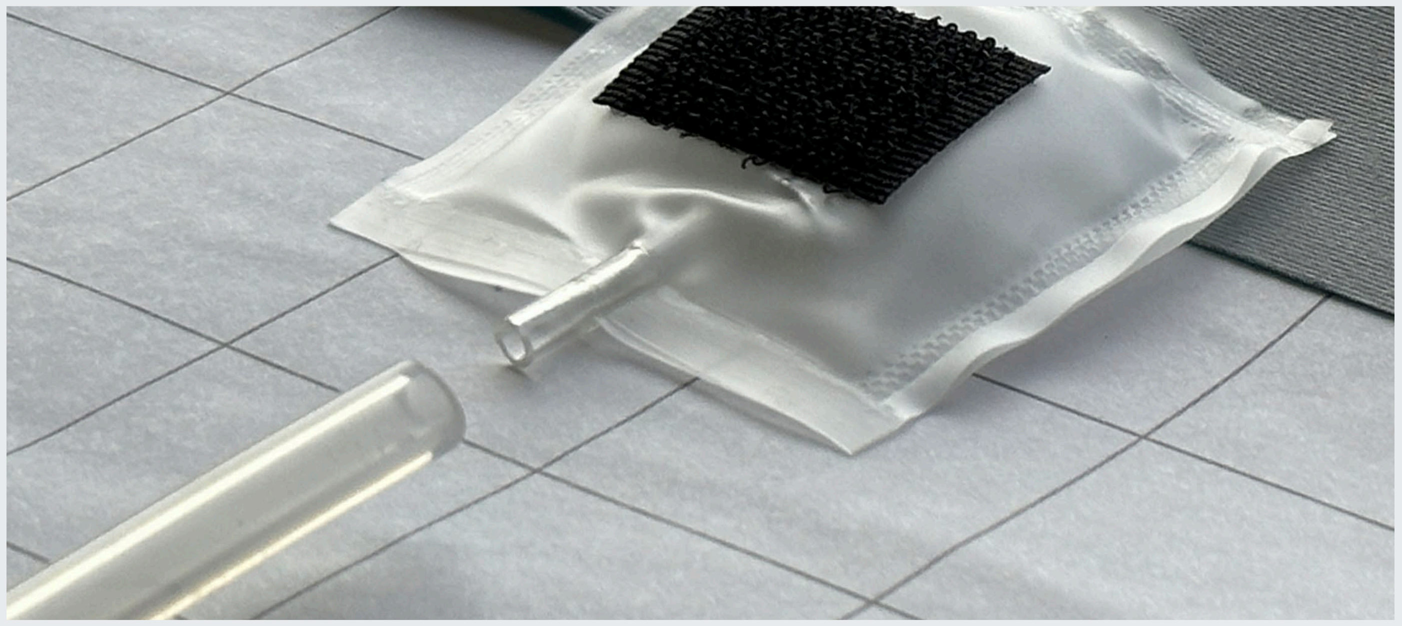


Figure 5.10

Figure 5.11: Closeup of first nozzle design

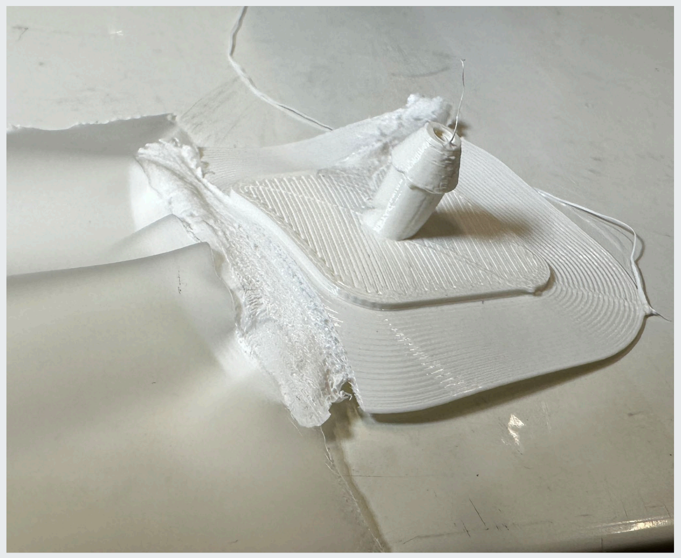


Figure 5.12: Failed 3D-printed TPU nozzle

Figure 5.13: Heating aluminum mold to create an airtight seal around the nozzle

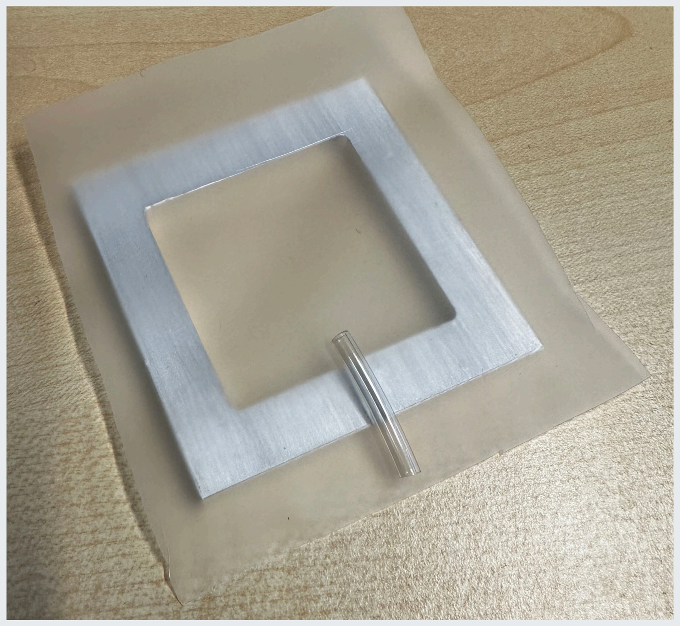


Figure 5.14: PU tube placed on top of PU ply

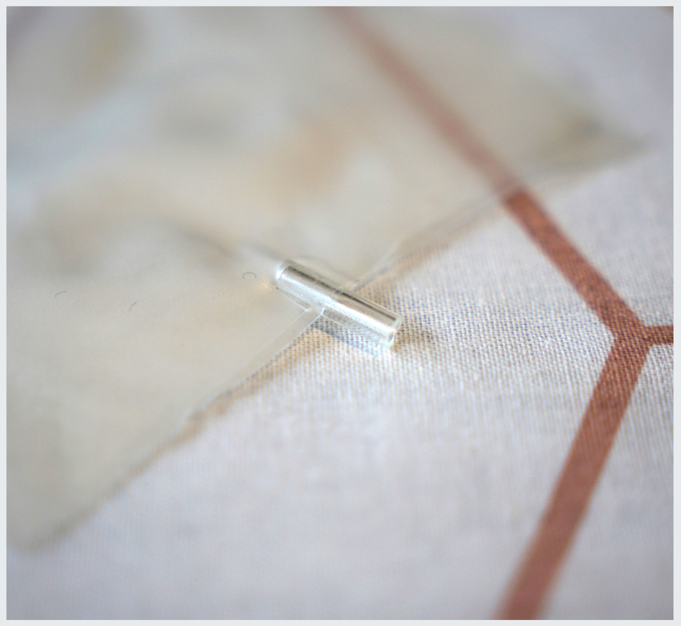


Figure 5.15: PU nozzle integrated

Geometry of the airbag

Varying the geometry of the airbag can have affect the haptic experience on the user end, which can result in various types of pneumatic actuation experiences when looking at the prototypes in the literature review. Early iterations of the airbag designs attempted to integrate types of touch in the geometry shapes and channels of the airbag itself, which was supposed to result in various haptic experiences. After testing however, this method did not achieve the envisioned actuation. So it was left aside in the later stages of the project.

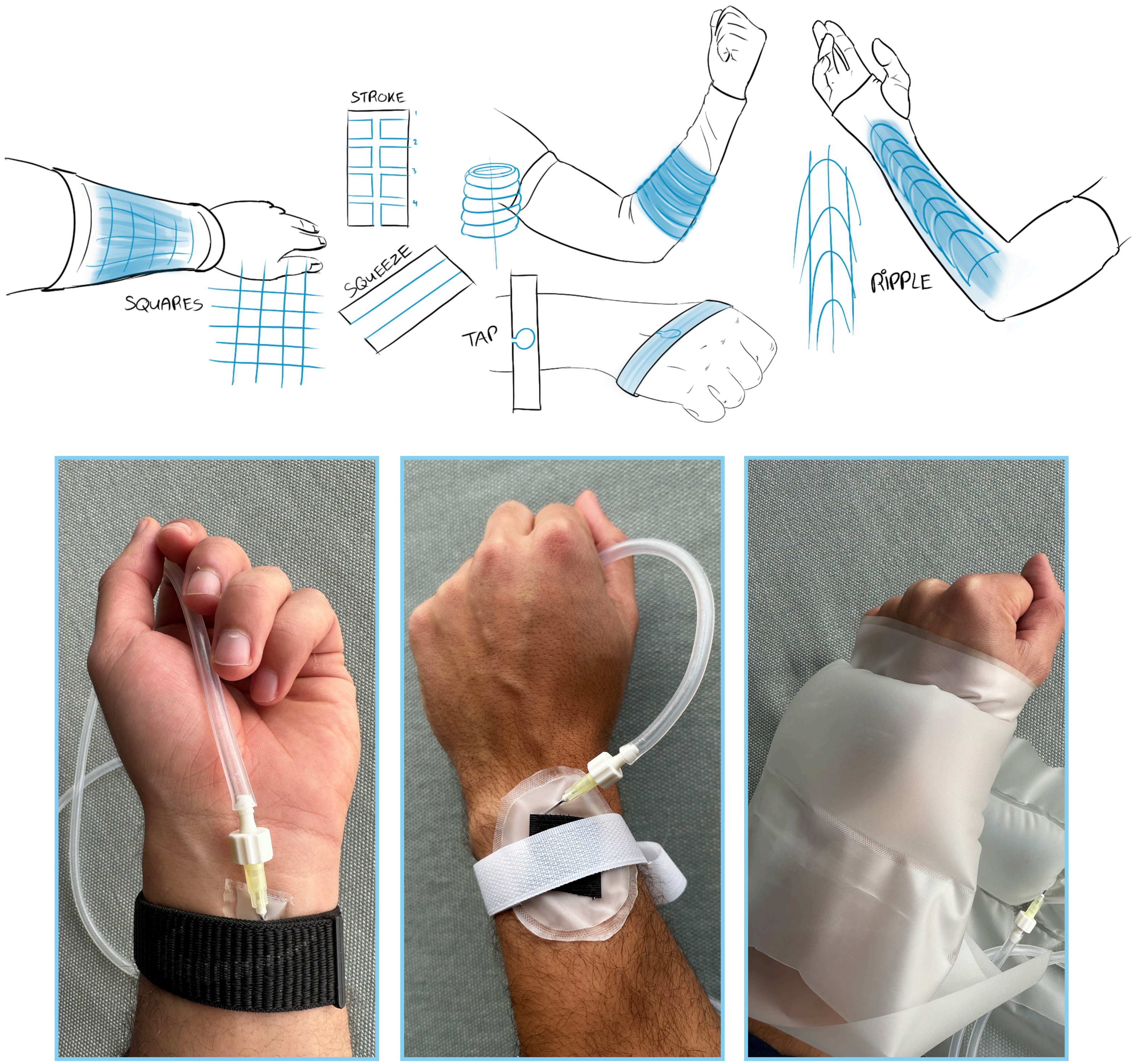


Figure 5.16: Sketches and prototypes of acuation embedded in airbag design

Internal channels and small airbags
The prototypes discussed before did not only conclude how different actuations are difficult to embody in the design of the airbag itself, but also indicated how size and shapes influence the actuation of a more simple square or round airbag shape. Relatively small airbags of 10x10 cm in combination with an airflow of 2 liters per minute from the pump system offered quick actuation that could reach maximum deformation within a second. The small dimensions not only affected the time to peak deformation, but also the surface area contacting the skin. Raitor et al., 2017 integrated channels in their airbag design to offer a larger and more uniform surface area contacting the skin, while the single chamber design in this project offers a relatively small contact area at the apex of the deformation. The goal of this design is to work towards a force that is more concentrated similar to the fingertip of a person, which could be related to a 'poke'. While initial prototypes showed the potential value of relatively small airbags and their poke-like actuation, practical difficulties in having the airbag force reach the user became more prevalent. Sub-optimal mounting of the airbag to the user, resulting in relatively large air gaps (10mm) or thick layers of clothing could completely negate the translation of the airbag feedback to the user. There are also other types of mediated social touch possible with a pneumatic wearable befitting to the context, which can be a squeeze of lateral motion actuation for example. Therefore larger airbag volumes are also explored in the project.

Figure 5.17: Failed prototype trying to embed a 'stroke' actuation within the airbag design

Larger airbag benefit: finding a balance
Alongside relatively small airbags of 10x10 mm, other sizes of 20x20, 30x30, and 40x40mm were explored during the project. The main benefits of having a rather small airbag are the relative feedback responsiveness and poke-like actuation similar to the size of a fingertip. Increasing the size of the airbag results in the following: Inflation time is expected to increase from under one second to two to three seconds due to the larger potential volume. The apex of the deformation, touching the user, will also have a larger surface area resulting in a more distributed force. This could result in less of an association with a fingertip and might be associated with the palm of the hand instead for example. More interestingly, prototypes with larger airbags show how the large deformation also influences the mounting mechanism. The fabric around the airbag, keeping it in place on the user their body, elongates and outputs pressure on the wearer their body. When this happens under a watch strap the entire wrist seems to become uniformly compressed. Around the arm, the inflation of a strapped airbag shows similar characteristics to a blood pressure cuff (which contains an airbag covering the entire circumference of the arm). Lastly, larger airbags can cover more distance due to their height increase while inflating. This deformation is needed to some degree to cover the distance in instances where the airbag is sub-optimally mounted to the wearer due to either air gaps or thick layers of clothes.

Conclusion on size
The prototypes suggest that a smaller airbag might feel more as a poke-like actuation due to the concentrated force, while larger airbags result might feel more like a squeeze due to the deformation of the entire strap. Response time also factors in the decision on the optimal airbag size (smaller = faster), while larger airbags can overcome sub-optimal mounting on the user end due to air gaps and thick clothing. These assumptions are further investigated in the first user test described in this report. Another test focused on the technical aspects of the pneumatic system maps characteristics such as responsiveness of various airbag sizes.

Figure 5.18: Photo of 10x10, 20x20, 30x30 mm airbags from prototype

Conclusion: how to prototype the optimal airbag

In conclusion, this chapter discusses various prototyping methods and accompanying insights resulting in the optimal airbag for the requirements of this project. Based on the experimental findings and previous research, the following manufacturing process is recommended:

Begin with two plies of polyurethane and a 20mm long segment of 3mm outer diameter PU tubing. Carefully stack these components in the aluminum mold to achieve a precise and uniform airbag shape with an airtight seal. Heat the assembled mold at 145 degrees Celsius for 1 to 3 minutes depending on the size of the airbag (10 to 40mm squared). After cooling the mold in a body of water, cautiously remove the airbag from the mold and inspect for potential leaks using the water (in case the submerged airbag shows bubbles during inflation, it might be an indication of a leak).

By following these prototyping steps, the airbags used in the final iterations of this project can be replicated and used for various types of affective social touch interactions. The next chapter will discuss electronic controls and various actions that can be achieved by precisely controlling the pressure and pulses over time.

5.3 Hardware control system

General hardware overview
The hardware that controls the airbag's pneumatic actuation is based on the Programmable-Air development kit from Crow Supply. Further hardware expansions are added to enhance possible actuations and measurement methods. Utilizing a development kit for pneumatic prototyping not only offers a relatively straightforward starting point, but also provides flexibility and the ability to rapidly experiment with different variations during the prototyping process. The development kit consists of two pumps and three solenoid valves. By opening each valve the system can either inflate, deflate, or release air. Software on the Arduino Nano controls the behavior of the system and can be programmed to expand its useability.

Four additional solenoid valves, an air pressure sensor, and a force-sensitive resistor were added to the system to expand the capabilities of the prototype. Multiple airbags can be added to the system and individually controlled, and precise measurements can be performed near the airbag with both the force sensor and air pressure sensor when positioned correctly.

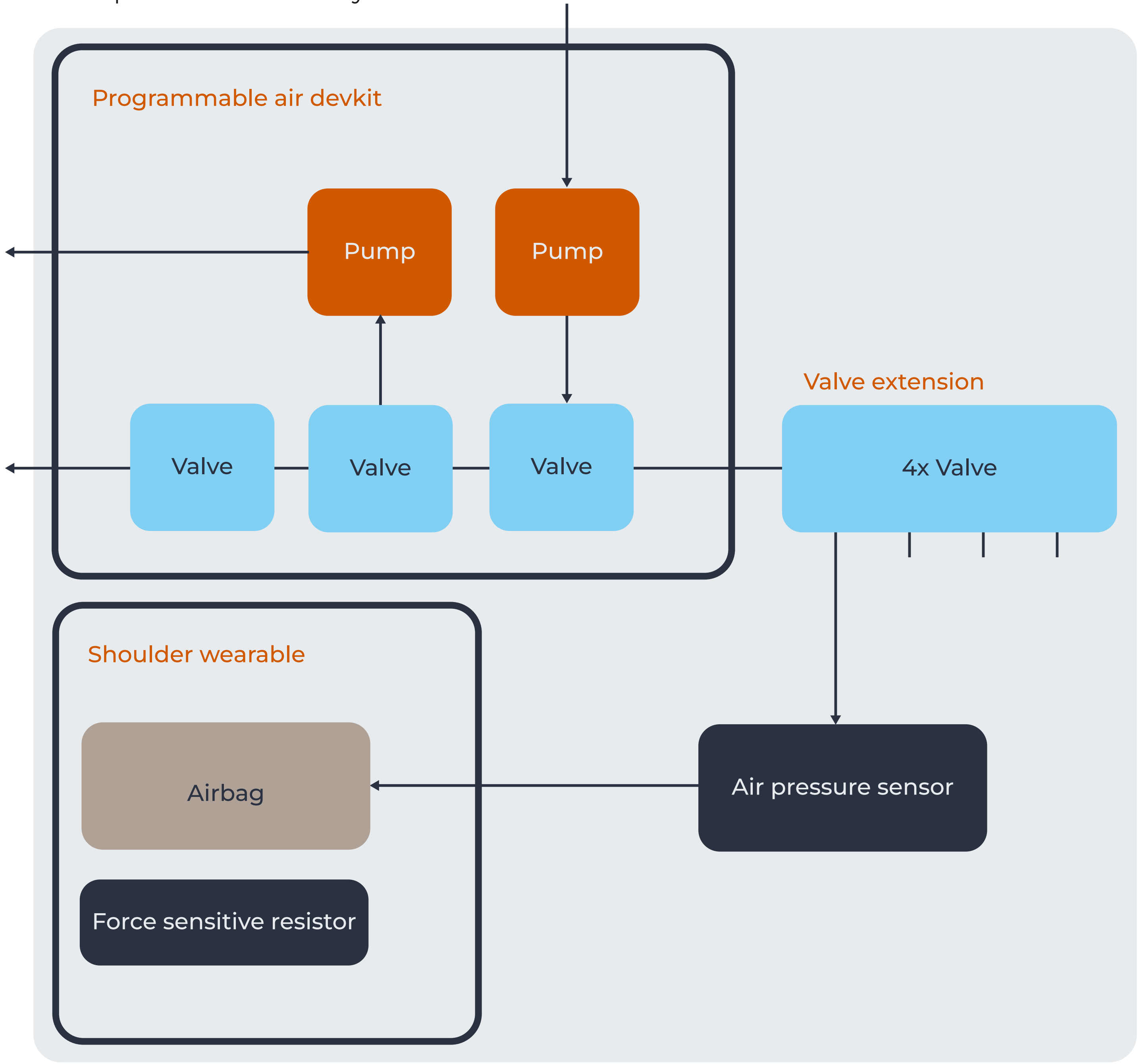


Figure 5.19: System overview of pneumatics

Pumps, valves, tubes, connectors

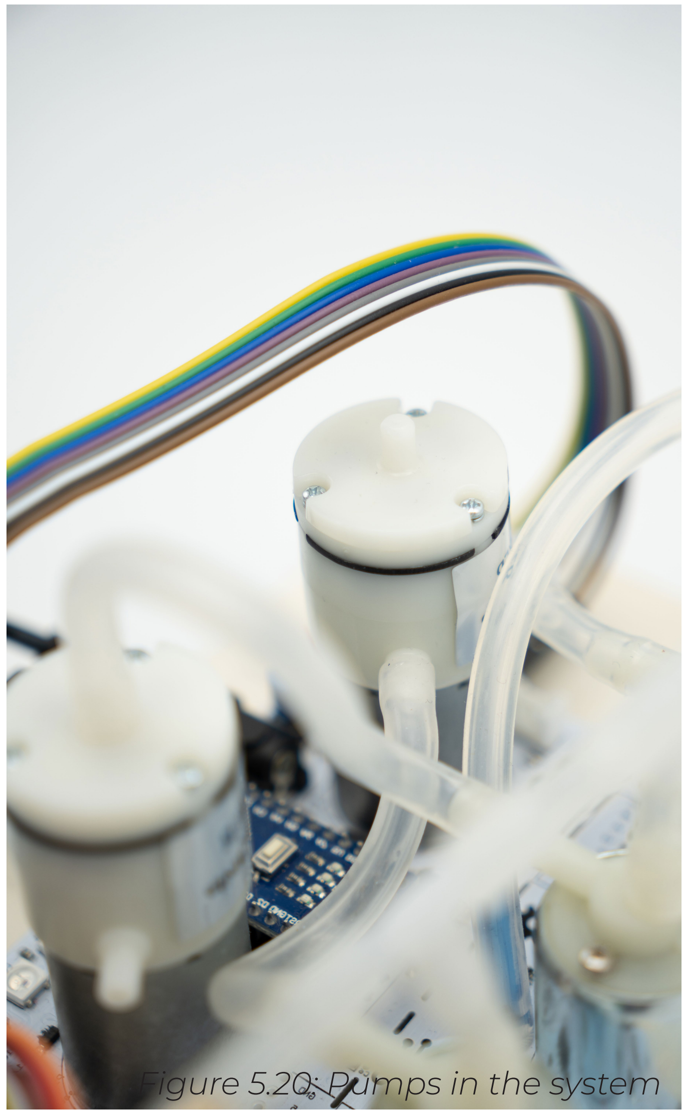


Figure 5.20: Pumps in the system

Pumps
The prototype incorporates two pumps, which are designed to move air in and out of the device. The pumps are specified for generating a maximum pressure of 500 millibars each (relative to the local atmospheric pressure, 500 mbar equals 0.5 atmosphere / 7.5 PSI / 50 kPa) and a minimum pressure of -500 millibars (-0.5 atmosphere / -7.5 PSI / -50 kPa), with a flow rate of 2 liters per minute, per motor.

Valves
Solenoid valves control the behavior of the pneumatic system used in the prototype. The Keurig cjv23-c12a1 solenoid valves complement the other components in the system due to their specified pressure range, flow rate, and nozzle dimensions. Four additional 12V solenoid valves with similar characteristics were added to the system to offer expansion and individual control of multiple airbags. Four IRF540 transistors manage the power for these additional valves. In addition to the expansion capabilities, the valves were also added to explore further control over the pneumatic behavior of the system.

Figure 5.21: Main valves in the system

Tubes and connectors

To transfer air between the components, silicone and polyurethane tubes are used. The flexibility of the silicone tubes allows them to connect to the rigid nozzles of the airbag and components of the Programmable-air kit. Polyurethane tubes are more rigid compared to silicone, and used for push-fit connections to facilitate easy (dis)connects of expansions to the system. A small piece of polyurethane tube is also integrated in the design of the airbag offering similar benefits to the push-fit system. By fitting a silicone tube over the outer diameter of the polyurethane nozzle, the airbag prototype can maintain a low-profile design when integrated into textiles.

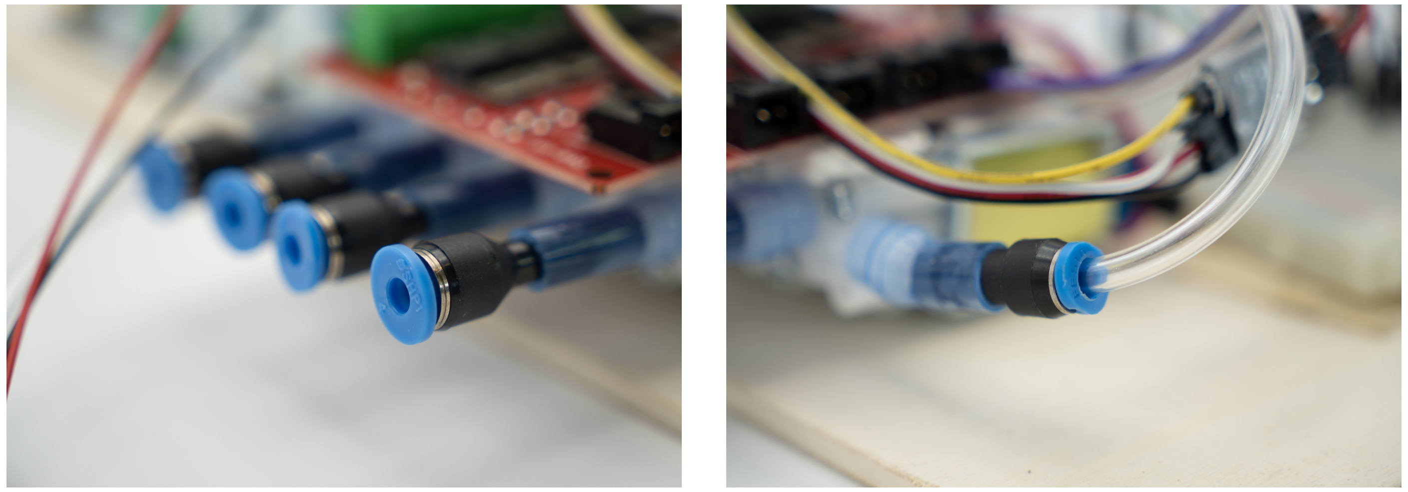


Figure 5.22: Expansion valves with quick release connector

Measuring air pressure in the system

An air pressure sensors keeps track of the air pressure while actuating, and brings the opportunity for a feedback loop in the software. While the programmable air kit has a built in pressure sensor (2SMPP03), requirements such as flexible positioning and higher accuracy resulted in the addition of the MPX5050GP air pressure sensor. With a measuring range of 0 tot 50kPa and maximum error of 2.5% accurate readings can be performed near to the airbag. While the pressure readouts should cover the factory specifications of the pump, later tests show how the pump can overshoot beyond its specified range. While this research continues with this sensor setup, a sensor with more range such as the MPX200GP in combination with a PID control system would introduce a greater measuring range and more control over the pressure curve in possible future work.

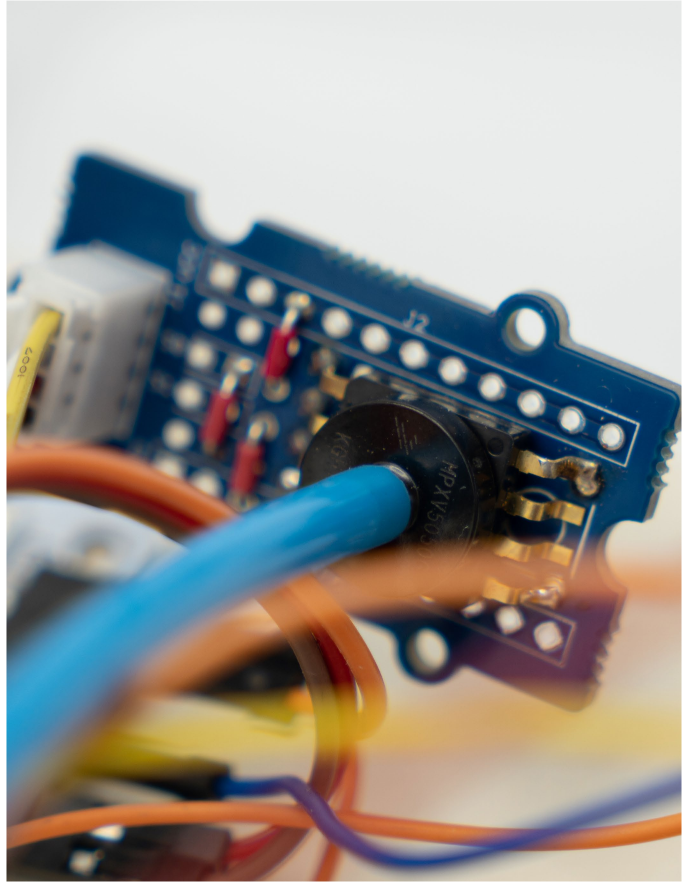


Figure 5.23: Air pressure sensor

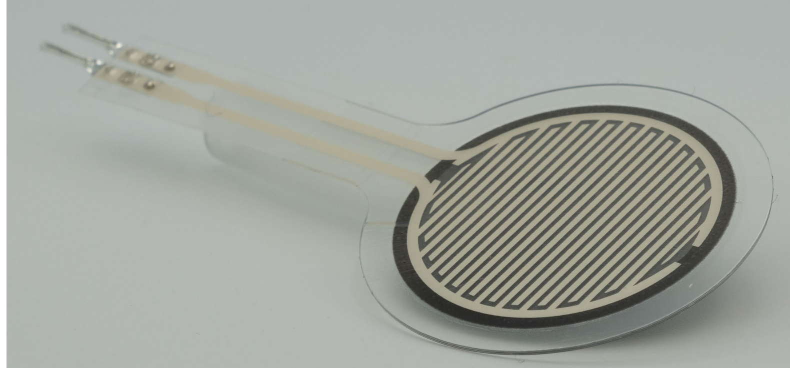


Figure 5.24: Force Sensitive Resistor

Measuring force on the wearer

A Force Sensitive Resistor (FSR) is integrated in the prototype to directly measure the amount of force translated to the skin of the wearer. While the air pressure sensor cannot account for gaps between the airbag and the skin, the FSR measurements can indicate how much force is translated to the wearer. While there are other sensors on the market that can measure force with a higher accuracy, the thin form factor which has little interference with the fabric integration is a strong point of this sensor setup. The FSR is used to benchmark the pneumatic prototype and track the performance of the system during the second and third user test.

The FSR used in this prototype is the MD30-60. A diameter of 30mm offers a small footprint offering flexibility in mounting, while still measuring the exerted force of the airbags due to its similar size. The sensor can read forces from 0 to 30 kg. This translates to a maximum pressure of 4200mbar which can be measured on the surface area of the sensor, which well over the 500mbar the pump can suffice.

Conclusion of the hardware overview

In summary, the programmable air kit provides a flexible starting point for pneumatic prototyping and experimentation. The kit includes two pumps and three solenoid valves, which is expanded on with four additional valves for possible future work (where multiple airbags could be actuated simultaneously). Software on an Arduino Nano controls all components, offering various actuations that can be programmed. Silicone and polyurethane tubing were used for air transfer, respectively offering push-fit compatibility and flexible low-profile connections. The MPX5050GP measures air pressure in the system and can be flexibly placed while the MD30-60 Force Sensitive Resistor measures force on location, further representing the actuation on the user.

5.4 Software controls and pneumatic patterns

General introduction to the software
By closely regulating the airflow in and out of the airbag, various pneumatic actuations can be created. After researching relevant literature and assembling the hardware, some software can be developed to achieve this. An Arduino microcontroller controls the pumps and valves in the system, and measures the effects of these actuators with an air pressure sensor and a force sensitive resistor. Custom pulses programmed in Arduino offer sine, square, oscillating, or static pulse types and variations thereof. Other parameters alongside the pulse type bring variation in pump power level, pressure target, and frequency targets, peak hold times, and more. The sensors enable a feedback loop controlling the behavior of the pneumatic system. Set parameters and measuried data from the sensors can be controlled and logged via Serial, which can communicate with Python. Python offers a graphical user interface for the second and third user test, providing a means to control the pneumatic prototype during the trials, measure user input, and also measure the real-world performance of the pneumatic system.

Arduino controls for actuators
The custom-programmed pulses can be called as a function in the Arduino code. The state of the system is kept track of in a variable ('systemState'), which is set to idle by default. Literature discusses various pneumatic patterns (also known as haptic icons), and the pulse designs of the prototype are iterated based on prior work, benchmarks, and findings from user tests. Three iterations of pneumatic pulse patterns were used during the project. A brief overview of the pneumatic pulses per iteration is:

1. First iteration: Sine pulse, square pulse, hold pulse, oscillating pulse
2. Second iteration: triple short, triple long, short long, heartbeat
3. Third iteration: triple short, short staircase up, short staircase down, triple long, long staircase up, long staircase down, heartbeat forward, heartbeat backward.

First iteration - Exploring technical limitations

The first iteration uses four base pulses which can be expanded on to create a wide library of haptic actuations (Figure 5.19).

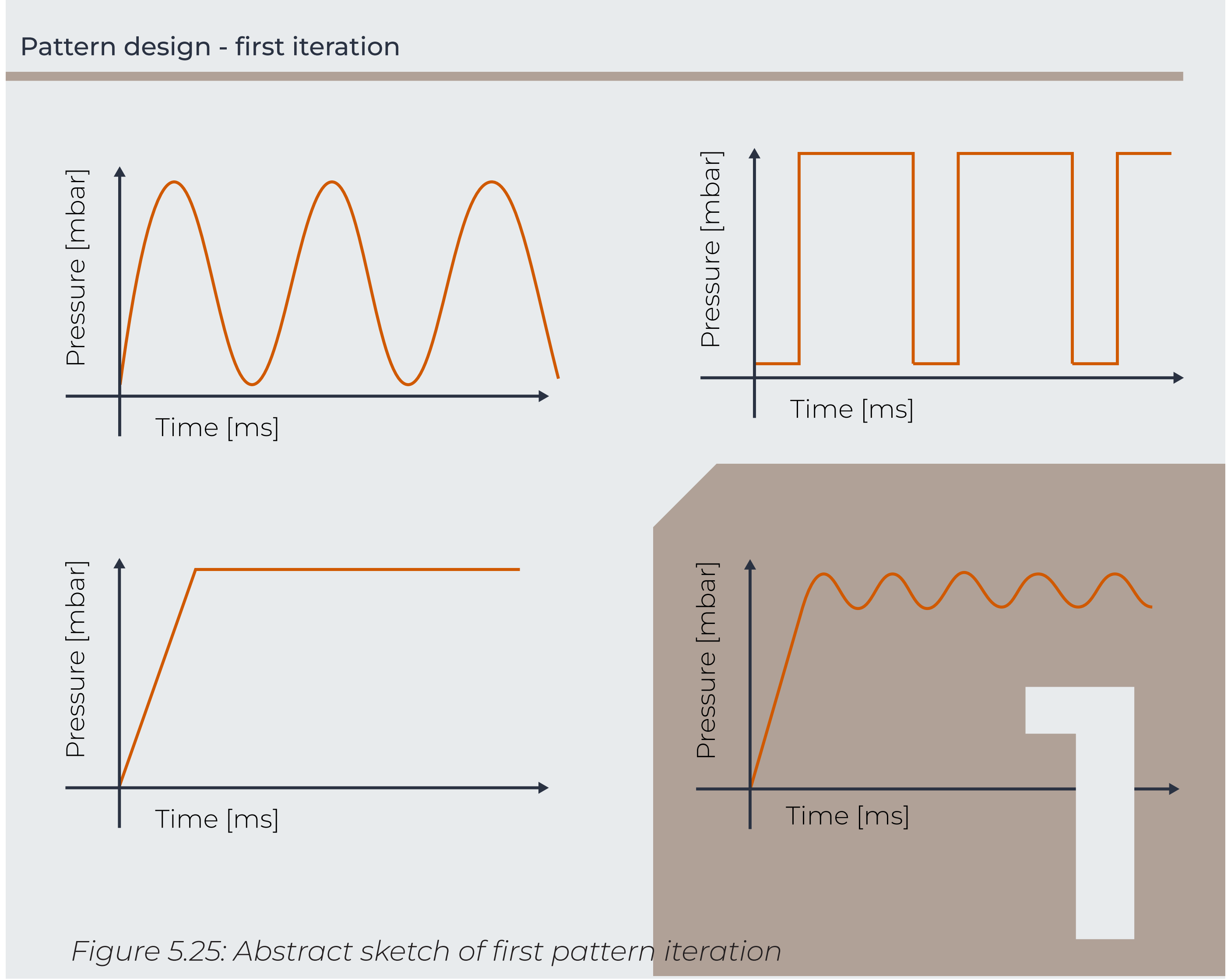


Figure 5.25: Abstract sketch of first pattern iteration

1. Sine pulse: A pneumatic pulse that creates a smooth and continuous waveform that rises and falls smoothly over time. Haptic sensations produced from this type of pulse can feel like a smooth increase or decrease of pressure over time.

2. Square pulse: By abruptly increasing the pressure, holding the peak pressure for some time, and ending the pulse abruptly by sharply decreasing the pressure, a square waveform can be created. On the user end this sensation can feel like a sudden impact or jolt.

3. Hold pulse: After quickly reaching the target pressure, the system will shut all valves and maintains the target pressure. In the case of leakage, pressure will deviate from the target pressure level. The system will recognize these occurances and add a small amount of air to stay close to the target pressure level. The sensation of having static pressure could feel like continuous pressure or squeezing, depending on how the airbag is attached to the user.

4. Oscillating pulse: When the system reaches the target pressure, the pressure waveform will alternate between two values slightly above- and under the target pressure (with a fixed frequency and amplitude). An oscillating pulse can produce sensations that could be experienced as a rapid pulsation.

Second iteration: From hardware to a user focus

The four base pulses were benchmarked to compare the envisioned pulses to the real-world performance of the prototype. The next chapter will discuss the limitations of each pulse type. After verifying the performance of each pulse, three pulses were continued with due to their satisfactory performance. Variations on the successful base pulses were made to create more advanced pulses inspired by well-received feedback from previous research work. These four pulses are ‘TripleShort’, ‘TripleLong’, ‘Short-Long’, and ‘HeartBeat’ (Figure 5.26).
Alongside the preprogrammed behavior, parameters such as pump power level, pressure target, and frequency target can change the experience of each respective pulse. The four base pulses are used in the second user test with varying parameters to research what the optimal pneumatic actuation would be based on a variety of characteristics and scores.

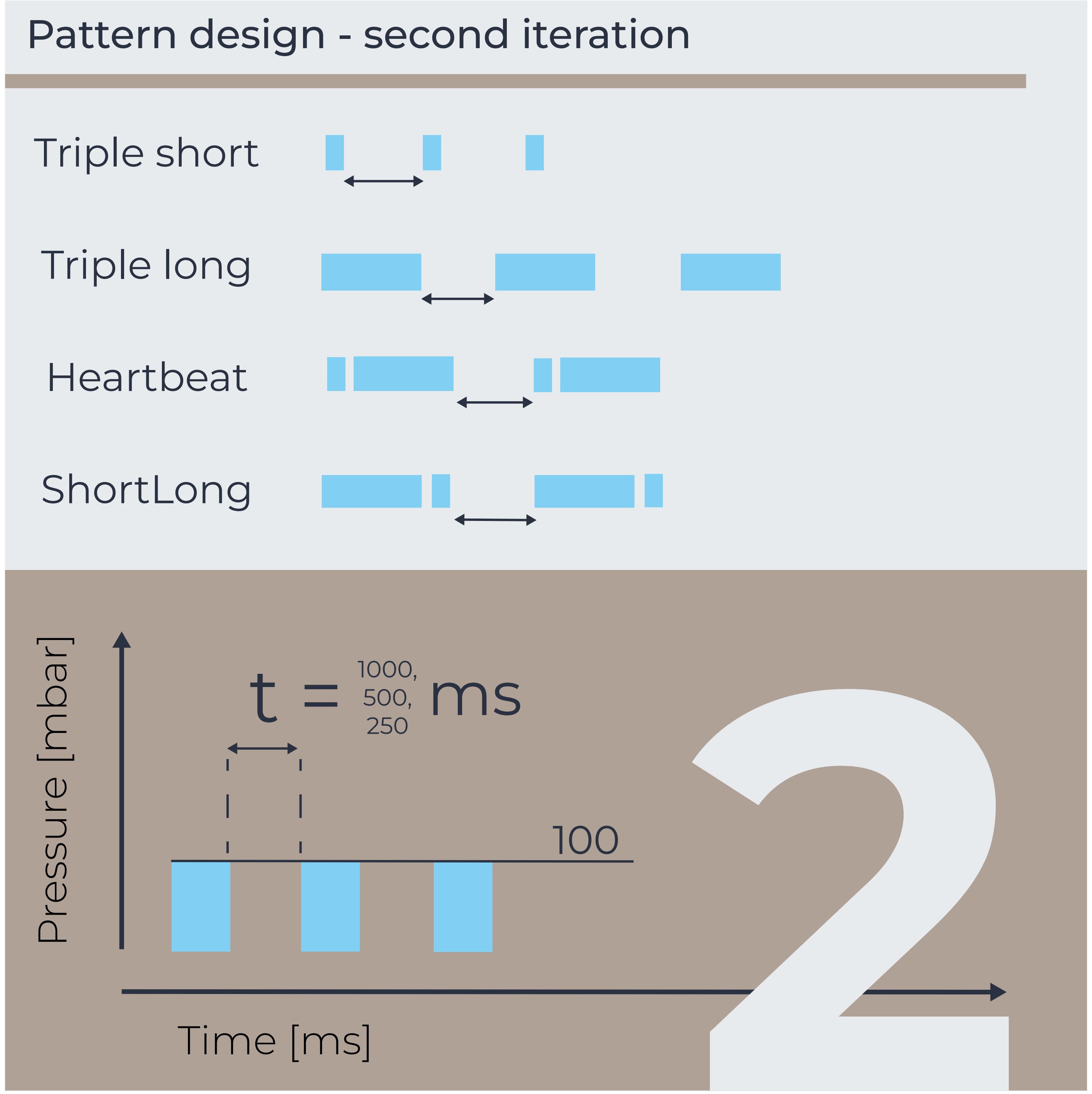


Figure 5.26: Abstract sketch of second pattern iteration

Third iteration: User patterns further defined

The third and final iteration of the pneumatic patterns is built on the previous patterns, with a focus on creating more distinguishable patterns and more varied ratings on four characteristics (intensity, comfort, pleasant, exciting).

The previous iteration of pneumatic patterns received rather similar ratings on all four characteristics, which raised several questions. One of these questions was whether the pulses were distinguishable in the first place, which is why this iteration focuses on variables other than frequency. Instead of variable timing for each of the four preset pulses, variable pressure levels and hold times are introduced in the third iteration. A pattern contains three pulses, and each pulse has a variable pressure level and peak hold time. Patterns from previous iterations can be replicated and contain more detail due to this adjustability.

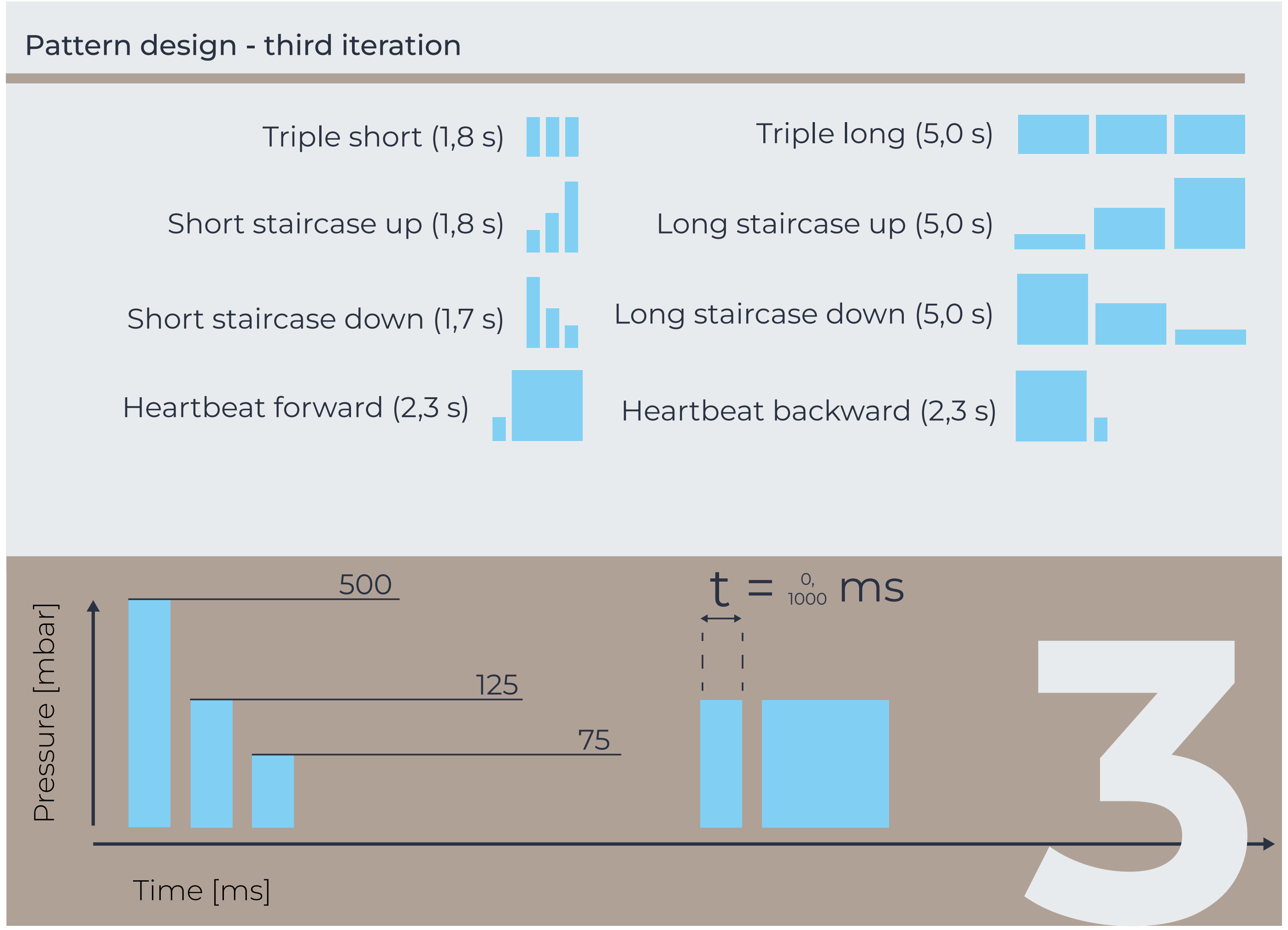


Figure 5.27: Abstract sketch of third pattern iteration

Specific points for the pressure level and hold time parameters were set based on user test results from the second iteration. Three pressure levels of 75, 200, 500 millibar represent low, medium and high pressure. Two hold time values of 0 and 1000ms offer a short ‘sine’ pulse and longer ‘square’ pulse. By adjusting these two parameters, eight pattern types were designed and used during the third user test. The focus of the test was to verify distinguishability and have more varied ratings per pattern compared to the previous test results. Further chapterss will elaborate on the results of the tests.

Analog sensor readings

Air pressure values
The MPX5050GP gauge air pressure sensor is placed in the system to monitor and control the behavior of the airbag, creating a closed feedback loop in the software. Analog values output from the sensor are converted to values ranging from 0 to 500 millibar, similar to the specified output range of the pumps in the system. In practice however, the pumps are able to deliver pressure slightly beyond their ratings and the reading range of the air pressure sensor. Beyond 533 millibar the sensor stops giving usable readings, which the pumps reach at times when overshooting beyond a pressure target of 500 millibar for example. Due to prioritization in the project all measurements are done with this pump and sensor setup, but future iterations could benefit from a sensor with a larger measuring range or a PID control system managing overshoot.

Force sensitive resistor values
The force sensitive resistor (FSR) measures the amount of force translated to the wearer, which help in analyzing the practical actuation of the system. While air pressure can suffice to control the pneumatics, more measurements could show details on the mounting of the system, static pressure or force, and the resulting translated force to the wearer.

Measurements of an FSR are not as precise as those from a more conventional load cell (commonly used in scales), but the small and thin form factor suit the wearable setup where other sensors would simply not fit. The measured values from the FSR are still meaningful for possibly further analyzing the data from the user tests. Force readings could theoretically be up to 80 Newtons, depending on contact area and pressure level (500mbar on a 40x40mm airbag with full contact would result in: Force = Pressure * Area = 50,000 Pa * 0.0016 m^2 = 80 N).

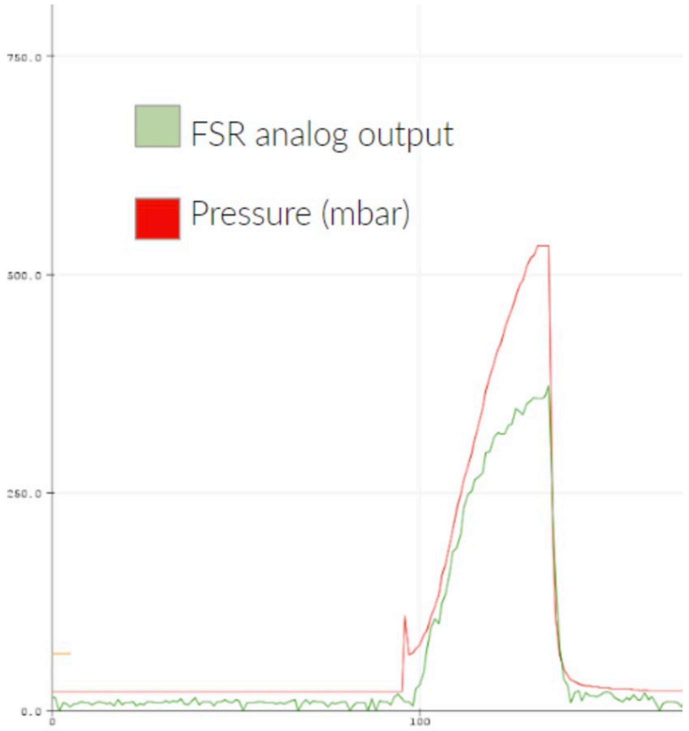


Figure 5.28: Plot of Air pressure and FSR value

Measuring system performance

Arduino

During user tests the performance of the pneumatic system is logged in a .csv file. The Arduino code contains a function called readSensors() which reads the sensors, outputs a list of variables in Serial, and saves these values in a log file on a computer using Python. Other variables keep track of factors such as time while benchmarking the prototype, or participant ID's during user tests for later data analysis. An example of variables saved and printed by Arduino in Serial are described in the Table below.

Variable	**Example value**	**Description**
participant_id	20230425142332	Unique identifier for each participant used during user test (formatted in Year:Month:Day:Hours:Minutes:Seconds (YYYYMMHHmmss))
systemState	“idle”, “tripleshort”	The current state of the system, indicating whether it is idle or the type of pulse currently actuating
timestamp	142416	Timestamp passed by Python to the Arduino for logging purposes, formatted in Hours:Minutes:Seconds (HHmmss)
newTime	42987	Internal Arduino timer counting in milliseconds
trialNumber	1	Participant trial number passed by python to the Arduino for logging purposes. Each trial usually varies in either pressure, systemstate, or frequencyTarget
pressureTarget	200	Target pressure for pulse actuations
pressure	99	Pressure log in millibar, printed every 25ms while the system is actuating
fsrAnalogValue	38	Force Sensitive Resistor (FSR) log in analog value, for logging purposes
power	50	PWM power of the pump. 35 is the lowest level where the internal motors spin in practice. 100 is maximum power level.
frequencyTarget	60	Target frequency in Hz, used in ‘tripleShort, tripleLong, shortLong and heartBeat’

Table 5.1: Arduino Parameters

Python

The second and third user test setup work with an interface and code written in Python. The code controls the behavior of the system by sending commands via Serial to the Arduino. The interface offers a means of giving feedback during the user test while various pneumatic behaviours are displayed in a randomized order. An example of the user feedback that is logged during user test is described in Table 5.1.

Variable	**Example value**	**Description**
participant_id	20230425142332	Unique identifier for each participant used during user test (formatted in Year:Month:Day:Hours:Minutes:Seconds (YYYYMMHHmmss))
trialNumber	3	The current trial number for the participant, to keep track of their progress.
try_count	2	A counter for each trialNumber, that keeps track of the curren try count. The value is increased by one when the participant retries their current trial, and reset to 1 when they continue to the next trial during the user tests.
feedback	1	Used to track whether the participant felt the feedback or not in test 2.1
pattern_description	heartBeat	Description of the current pattern
pattern_guess	heartBeat	Participant their guess on the pattern they felt
feedback_correct	TRUE	Descriptor to keep track of whether the participant answered right or wrong. If pattern_description and pattern_guess are equal, the value will be true.
intensity, comfort, pleasant, exciting	7	Using a Likert scale from 1 to 7 the participants can rate the pneumatic actuation they felt during a trial on multiple categories.

Table 5.1: Python Parameters

Conclusion on software controls and pneumatic patterns

The software and designs of the pneumatic patterns play a crucial role in the functionality and performance of the prototype. Using Arduino and Python, precise control over the desired airflow and measurement of real-world performance allows for the creation and validation of various pneumatic actuations. The Arduino software handles the base configuration of a variety of pulses for each iteration, while the Python code sends commands and variables such as the desired pressure level for a specific pulse type. Sensor and user data is collected using the same code in Python for further analysis during the project.

The iterative pulse design started with four base waveforms, where three were successfully prototype while one, the oscilating waveform, did not seem possible due to hardware restrictions. The second iteration built upon these three pulses and literature to introduce pulse designs such as ‘TripleShort’, ‘TripleLong’, ‘ShortLong’, and ‘HeartBeat’. The third iteration focused on creating more distinguishable patterns by adjusting pressure levels and peak hold times, resulting in eight final pattern designs.

Each pneumatic pattern iteration was validated with a benchmark or user test, by analyzing the log files and implementing the insights. A description of the log values is listed at the end of this chapter to give an overview of the functionality and capabilities of the prototype, which could be used in future work within a multitude of contexts.

5.5 Benchmarks and limitations

To test and verify the performance of the prototype, a benchmark with the first iteration of pneumatic patterns was performed. Assessing the technical performance of the system defines the boundaries of the possible actuations influencing the haptic experience, while also giving insights into the design space for the wearable prototype.

Background and goal

Four base pulse designs were listed in the first iteration, which is further described in a prior chapter. The goal of this test was to verify whether the prototype could create the four desired actuations from the initial designs (sine wave, square wave, oscillating wave, hold pressure).

Method

Each of the four desired pulses are programmed in Arduino. The pulses are actuated with three varying power levels ('lowest', 'medium', and 'highest' power) with three airbag sizes (10x10, 18x25, 35x35 mm), resulting in 36 total measurements. By measuring with varying power levels and airbag sizes, valuable insights on the overall pneumatic system and the impact of slight adjustments were gained.

The setup worked by mounting the airbag and FSR around the upper arm of a mannequin. Consistency in the test setup while swapping the airbag was achieved by having the same gap between the arm and the strap using a marker with a diameter of 10mm. The desired pulse type and power level were adjusted in the software. Variables such as pulse type, timestamp, air pressure, FSR value and power level were logged in a .csv file for analyzation purposes.

Benchmark of medium airbag (18x25mm)

	Inflation time to 400 mbar [ms]	Overshoot [mbar]	Deflation time [ms]
High power (100% pwm)	820	>130	100
Medium power (65% pwm)	270	125	60
Low power (30% pwm)	144	20	50

Table 5.3: Medium airbag benchmark results

Results and conclusion

Results and conclusion

While analyzing the log files it became clear that the performance of three out of four envisioned base pulses was satisfactory for the envisioned use case (sine wave, square wave, hold pressure), while the oscillating pulse did not perform as envisioned. The lack of a designated outlet channel in the airbag itself resulted in too little control of the outlet flow, so the oscillating pulse was left out in the design of further iterations.

Overall performance characteristics of the prototype are as follows: When varying the power level, the system could reach the target pressure (400 millibars) after 820, 270, or 144 milliseconds on a medium-sized airbag (18x25mm). However, since the software does not make use of a PID system, overshoot quickly increases with each power level. The overshoot was 20, 125, or over 130 millibars (up to where the sensor could read) on the respective low to high power levels. Deflation times were up to 50, 60, and 100 milliseconds positively related to the amount of overshoot.

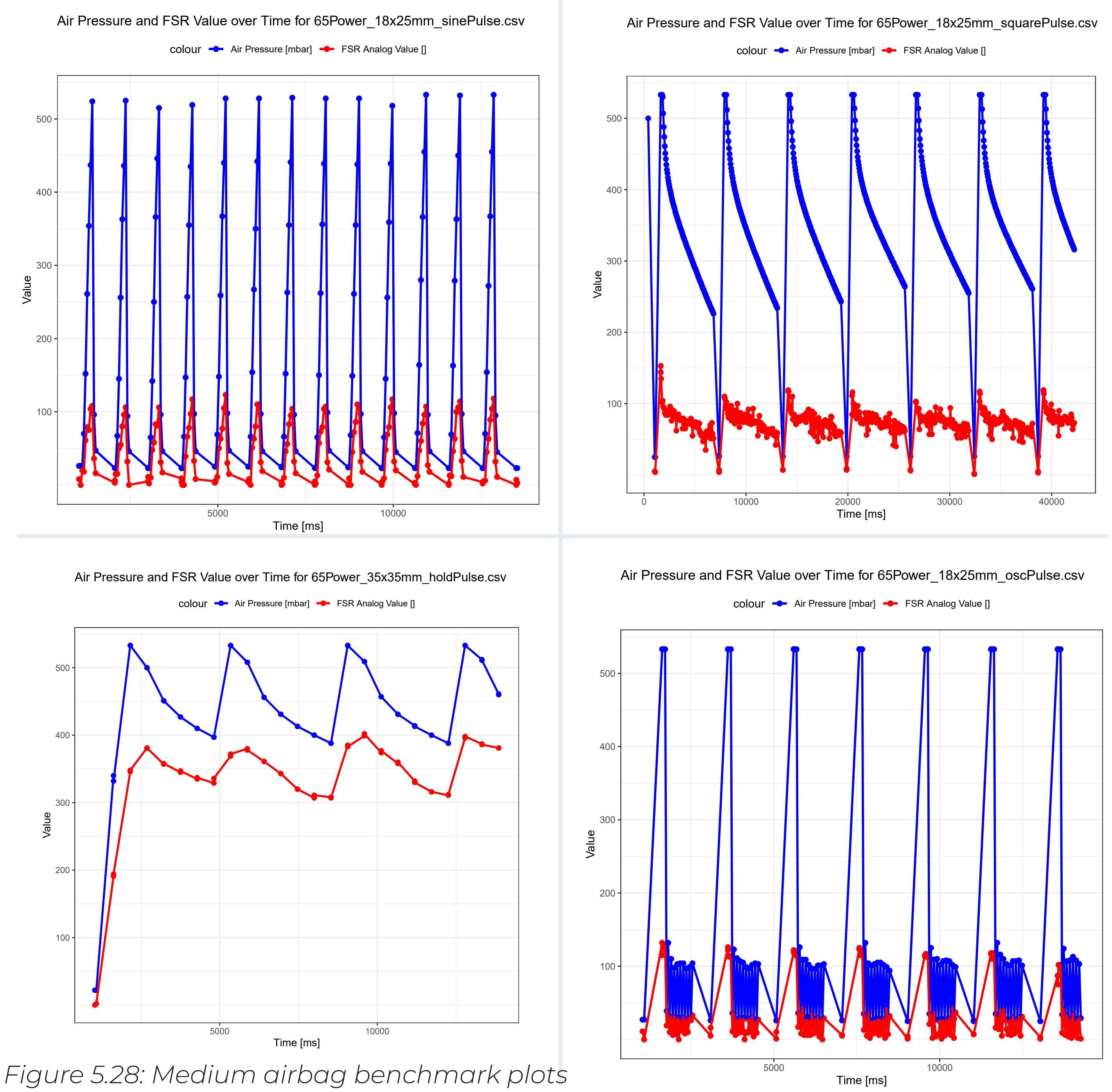


Figure 5.28: Medium airbag benchmark plots

Discussion and limitations

The overall performance of the pneumatic prototype is satisfactory for this project. The feedback can be responsive and varied using three types of pulses which can actuate within a second. The feedback loop works and visually seems to be able to create and measure various pressure levels. There are some limitations to the system however which should be taken note of. The oscillating waveform was not successfully prototyped due to a lack of outlet flow control. The results show how the airbags relieve pressure relatively quick (even after physically reducing the outlet size) when opening the vent valve. Alternative methods such as very slowly spinning the 'sucking' valve did not solve this challenge either. While Delazio et al., 2017 showcased a prototype where one single channel could function as both the inlet and outlet, specifications of the airbag and pneumatics in this prototype ask for an alternative means to control outlet flow. A future design could implement a separate inlet and outlet channel to control these two factors independently. A longer breathing (waveform) like actuation could be achieved with such an airbag design. Nonetheless, the current version of the prototype can create enough variety in actuations to continue iterating on the existing design.

Some limitations with a limited impact on the system, are the lack of a PID system and hardware limitations of the air pressure sensor. Overshooting beyond the target air pressure happens especially at higher power levels, since there is no anticipation and compensation for high 'acceleration' when nearing the target. While more control of the system could be desired for test setups in research, real-world applications of this pneumatic system could work without a PID system due to the limited pressure range. By logging both the desired and real-time air pressure, the impact of no PID system is kept track of in test setups.

The air pressure sensor is a slight limitation in combination with the pumps used in the prototype. While both components are rather for a pressure up to 500 millibars, the pumps are able to overshoot to air pressure values which the sensor is not able to keep track of. This could be resolved by switching the sensor for one with a wider range, but by manually avoiding high target pressures in combination with high power levels the overshoot can be limited as well. Due to time prioritization, the latter solution has been opted for, but further work could benefit from a different air pressure sensor choice such as the NXP MPX200GP. One last limitation related to the air pressure sensor is its physical location in the pneumatic system. Due to a desire for a low-profile wearable design the air pressure sensor is positioned 1 meter from the airbag. Distance between the sensor and airbag might have introduced delays in the feedback loop.

Lastly, ambient conditions such as atmospheric pressure could have an impact on the measurements and results (Pohl et al., 2017). While future test setups and iterations do not track the ambient air pressure, small adjustments on the bottom target air pressure have been integrated as a result of varying air pressure throughout the timespan of the project.

With the aforementioned opportunities and limitations of the pneumatic prototype in mind, further iterations on the pneumatic system are developed within the project. Especially the software and wearable design integration worked towards rich and comprehensive wearable prototypes.

5.6 Textile integration

Wearable integration of a (pneumatic) mediated social touch wearable offers a hands-free solution that can actuate at any moment in various contexts. Integrating the actuator into fabrics brings challenges in factors such as comfort, durability, manufacturing, power, and safety. This chapter will discuss the process of overcoming such challenges, describes the final results on the textile end, and lists points for potential future iterations in textile integration.

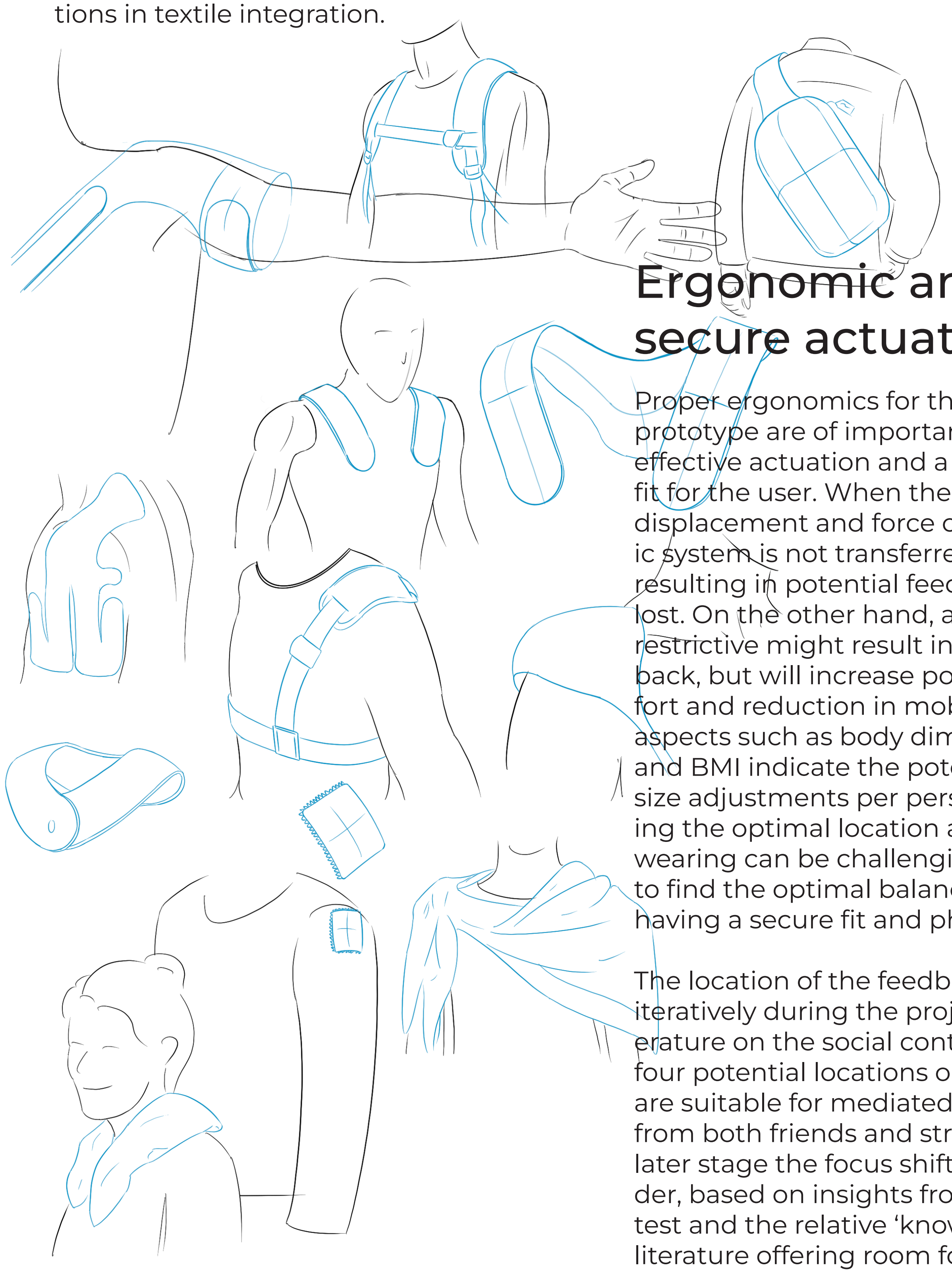


Figure 5.29: Textile integration sketches

Ergonomic and secure actuator fit

Proper ergonomics for the wearable prototype are of importance to have effective actuation and a comfortable fit for the user. When the fit is insecure, displacement and force of the pneumatic system is not transferred to the wearer, resulting in potential feedback being lost. On the other hand, a fit that is too restrictive might result in optimal feedback, but will increase potential discomfort and reduction in mobility. Individual aspects such as body dimensions, sex, and BMI indicate the potential need for size adjustments per person. Determining the optimal location and method of wearing can be challenging while trying to find the optimal balance between having a secure fit and physical comfort.

The location of the feedback developed iteratively during the project. Initially, literature on the social context determined four potential locations on the arm that are suitable for mediated social touch from both friends and strangers. At a later stage the focus shifted to the shoulder, based on insights from the first user test and the relative 'knowledge gap' in literature offering room for new insights. The final design offers feedback on the back of the shoulder, which is the result of various iterations from literature research and three user tests.

Manufacturing and sowing

The shoulder suspender design consists of four parts: the elastic band, clamps, shoulder pad, and embedded actuator. The bands and clamp are prototyped by modifying a conventional suspender. The sizing, adjustability, and wearing method changed to optimize for single-shoulder wearing with a variety of sizing options. The shoulder pad is made of breathable polyester offering a secure pocket for the electronics. The airbag and force sensitive resistor are covered by the pad and secured to the band by channeling them through a hole. Overall the prototype offers a solid foundation to offer pneumatic feedback on the shoulder while also offering interchangeability in components for prototyping purposes.

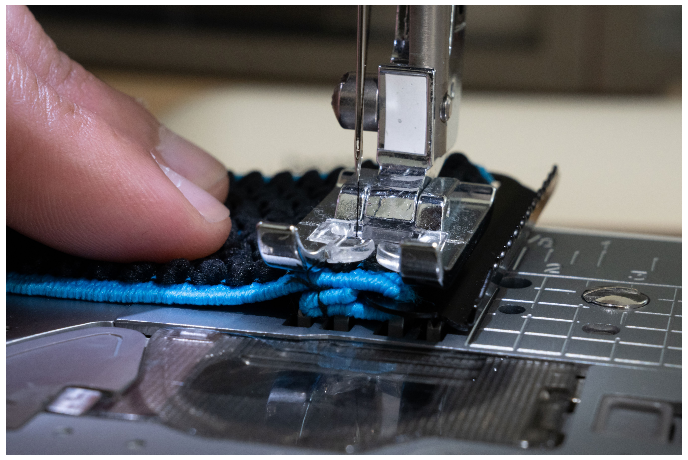


Figure 5.30: Components and integration of the wearable prototype

Final textile integration overview

The final design uses a suspender-style strap system over the shoulder (Figure 5.31). An elastic band is placed over the shoulder of the wearer and fastened to their pants on the front and back. A padded part on the band contains the wearable electronics part of the prototype and can be adjusted on the band to fine-tune positioning. Within the padding, the airbag, force sensor, and elastic band are layered on top of each other to offer a low-profile, flexible, and comfortable wearable solution.

Figure 5.31: Final prototype

The wearable design offers flexibility in wearing styles. During the user tests it was worn over a t-shirt and able to give enough feedback to create distinguishable patterns. It would also be possible to use the wearable underneath a t-shirt, which could offer a stronger experience of the feedback and opens the opportunity to hide the prototype. The tradeoff would be that it could be more difficult to put the wearable on initially. This project focused on wearing the prototype over a t-shirt to offer flexibility in various potential contexts, and also verifies the richness of a pneumatic feedback system with a fabric barrier that could limit the haptic experience.

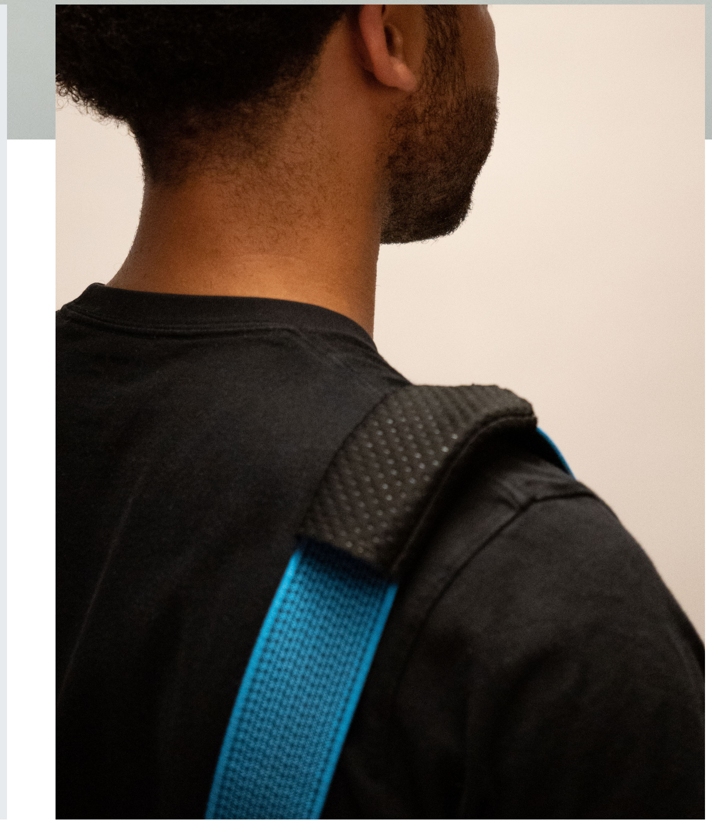


Figure 5.32: Final prototype worn on shoulder

Future possibilities on textile integration

While the embodiment of the prototype integrates the actuator in a wearable solution, there is room for advancement in further design iterations. Currently the rest of pneumatic control system is separated from the wearable and placed in a box, because this challenge was out of the scope of the project. Since the project defined the requirements of pneumatic actuation from a technical viewpoint, it could be valuable to optimize the prototype according to this. The prototype following from this could be used for further research introducing mobility to potential tests. Wireless connectivity and the addition of a battery might also be desired to facilitate this. The band offers room for hardware alongside both the front and back which could work towards a rather elegant solution.

Other than integrating more hardware in the wearable, it is also possible to further integrate the current actuator setup in the fabrics. The airbag could be sown on the textile, wiring could be integrated in thread, and the air channel tubing can be further covered with fabrics. However, it is important to consider the integration challenges and replacement in interchangeability for prototyping or in case a part fails.

Figure 5.35: Overview of components integrated in fabrics

Figure 5.33: PU airbags sown to various fabrics

Figure 5.34: Sewing over Silicone tube

Figure 5.36: Soundproofing box for the pumps and valves

6. User tests

6. User test validations

This chapter describes and gives an overview from the three user tests performed during the project. For further details on each user test, please refer to the Appendix.

6.1 First user test: Location and size of the airbag

Background and goals
At an early stage of the project a prototype was developed which could be used for an explorative user test. A qualitative test with seven total participants helped to scope the project on specifics for the location and size of the air container. The specific goals of the test were defined as:

1. To determine the optimal location to feel most pneumatic actuation on the arm
2. To understand the influence of contact area on the intensity and comfort experience
3. To understand how pneumatic actuation could be related to human interactions such as a poke or squeeze

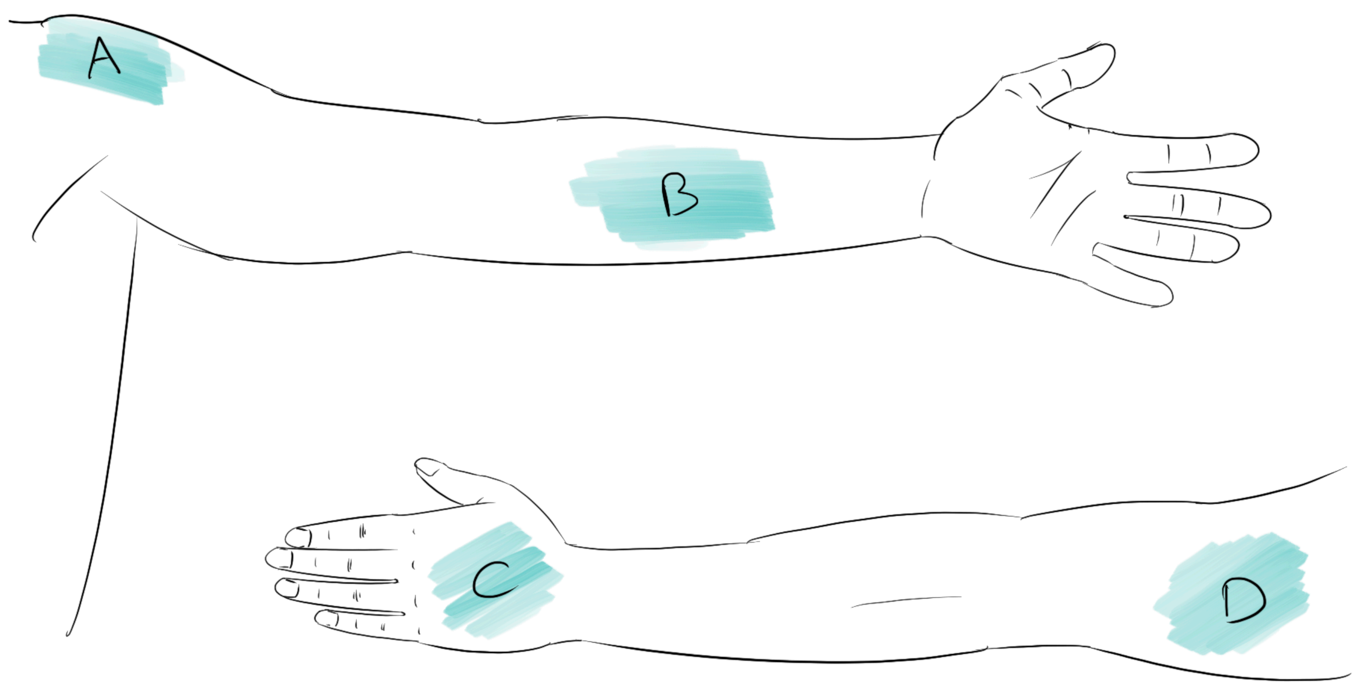


Figure 6.1: Overview of actuation locations in first user test

Method
Participants will have four air pockets placed on different locations on their arm, which will be automatically controlled by the pneumatic electronics. The participant will give insights in the feedback per location, and give scores comparing intensity and comfort of the actuation per location using a Likert scoring system. The location with the highest intensity score is further investigated by testing and rating four airbag sizes (5x5, 10x10, 20x20, 30x30 mm) on intensity and comfort.

Results

Table 6.1 displays the average intensity and comfort ratings for each tested location on the arm. It is interesting to see how the intensity rating seems to have a negative correlation with the comfort rating. Table 6.2 displays the impact of airbag size on the intensity and comfort ratings, which was only tested on the location with the highest intensity rating per participant. The focus of this test was to receive qualitative data and start initial explorations with seven total participants.

The interview gave valuable insights on each feedback location and the overall experience of the pneumatic actuation. Feedback on the hand was often considered slightly painful. This could be caused by the relatively high pressure, restrictive ergonomics of the strap, or a combination of either. The lower arm also received higher intensity ratings, but some participant stated they might felt a bit uneasy due to the location or potential setting in context.

Average rating per location (n = 7)

Location	Intensity (1-7)	Comfort (1-7)
Hand	5.71	3.00
Lower arm	5.43	4.29
Upper arm	4.29	5.29
Shoulder	3.43	5.14

Average rating per size (n = 7)

Size [mm]	Intensity (1-7)	Comfort (1-7)
5x5 XS	3.29	5.43
10x10 S	5.43	3.86
20x20 M	6.00	2.86
30x30 L	6.14	2.86

Table 6.1, 6.2: Average rating per location and size

The upper arm received higher comfort and lower intensity ratings, which aligned with the feedback from the interview. The shoulder received the lowest intensity rating and a similar comfort rating to the upper arm. While the strap design used in this test worked well for the other three locations, keeping the airbag in place on the shoulder showed difficulty with some participants. The lower intensity score might have been the result of a sub-optimal mount for some participants.

An increase in airbag size seems to have a positive correlation with intensity and a negative correlation with comfort. The smallest size of 5x5 mm received low intensity ratings and was sometimes difficult for participants to feel. Sub-optimal mounting or a smaller contact area (resulting in a smaller force being transferred since the system build pressure) could be possible causes. It is interesting to note how the medium and large airbags received similar ratings on both comfort and intensity.

Conclusion

This qualitative test explores the optimal location and airbag size for pneumatic actuation. After testing and rating the four locations on intensity and comfort with seven participants, followed by an interview, some conclusions can be made for further design decisions within the project. The ratings indicate how the hand and lower arm received a higher intensity score, at the cost of comfort. Opposing those results, the upper arm and shoulder received relatively high comfort- and lower intensity ratings. Sub-optimal mounting of the airbag on the hand and shoulder could be one of the main factors influencing intensity and comfort.

When considering the location with the highest intensity and comfort score, the upper arm seems to receive slightly better ratings compared to the other three locations. The test also indicates how the shoulder and hand could benefit from a more ergonomic design, which could improve their intensity and comfort ratings. The research potential also influences the design decisions for this project. Social touch wearables on the shoulder show potential in valuable research findings, compared to more commonly researched form factors on the hand or arm. Sub-optimal mounting should be overcome with iterations on the ergonomics of the design. Air gaps from sub-optimal mounting can be accounted for to some degree by increasing the size of the airbag. Air pressure should be kept under control during actuation to control the amount of force transferred to the wearer.

The test concludes with a focus on the shoulder and a large airbag size of 40x40mm. This can result in novel research solutions in the social touch wearables research field. With iterations on the ergonomics and pressure control a shoulder wearable can be designed which can offer both intense and comfortable pneumatic feedback.

Figure 6.3: Overview of airbag application during user test

6.2 Second user test: Pressure and pattering rating

Goals:
1. To understand the minimum needed pressure to reach the absolute detection threshold
2. To understand how various pressure levels influence comfort and intensity
3. To understand what pressure differences are needed to achieve a Just Noticeable Difference (JND)
4. To understand how frequency influences characteristics of various pressure pulses

Part 1: Absolute pressure threshold, intensity and comfort rating

1.What is the minimum needed pressure to reach the absolute detection threshold?

When looking at the graph below, it can be concluded that for some participants they are able to detect pressure at 50mbar, while some feel pressure at 75mbar. It is interesting to note that the static pressure before the system inflates hovered around 30 to 45mbar during the test, which means inflation time and pressure delta's slightly varied per participant.

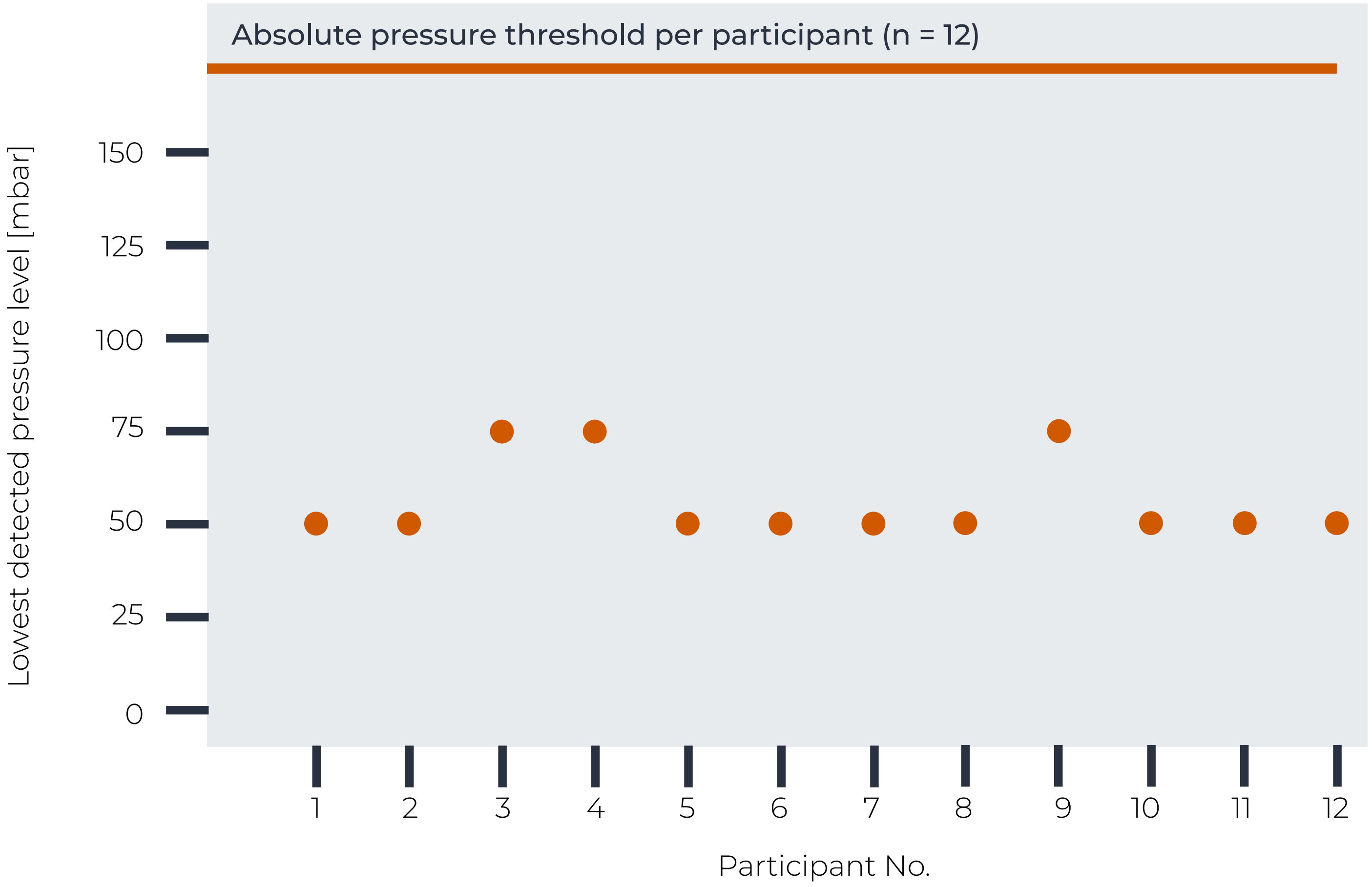


Figure 6.4: Absolute pressure threshold for each participant

2. How do various pressure levels influence comfort and intensity rating?
By looking at the mean intensity scores for both comfort and intensity for each pressure level, some insights can be made. The actuated pressure levels ranged from 25 to 500 mbar with steps of 25 mbar. The graph show how the intensity rating significantly increases at 125 bar, while the mean comfort score reduces at the same instance. Beyond those pressure values the intensiy and comfort ratings do not change much overall, but there is a slight trend toward a higher intensity and lower comfort rating at increasing pressure.
The graph below displays the relation between comfort and intensity score by pressure. It is interesting to note how the intensity and comfort lines intersect at 125mbar. When combining this insight with the insights from the two separate graphs before, two assumptions could be made: When actuating a pressure under 125 mbar, the wearer will experience a relatively high comfortable pulse with very low intensity. Pressure beyond 125 mbar does now show much change in the intensity and comfort ratings up to the higher pressure levels beyond 400 mbar.

Conclusion on part 1:

1. What is the minimum needed pressure to reach the absolute detection threshold?

A pressure target of 75 millibar pressure is needed for all participants to feel the pneumatic actuation on their shoulder

2. How do various pressure levels influence comfort and intensity rating?

Below 125 millibar the participants experience a relatively high comfort and very low intensity. Beyond 125 millibars up to the maximum pressure of 500 millibars, the intensity and comfort ratings stay close to the median (0 to 10 Likert scale) with overlapping error bars, suggesting that the comfort and intensity scores stay relatively neutral for this pressure range.

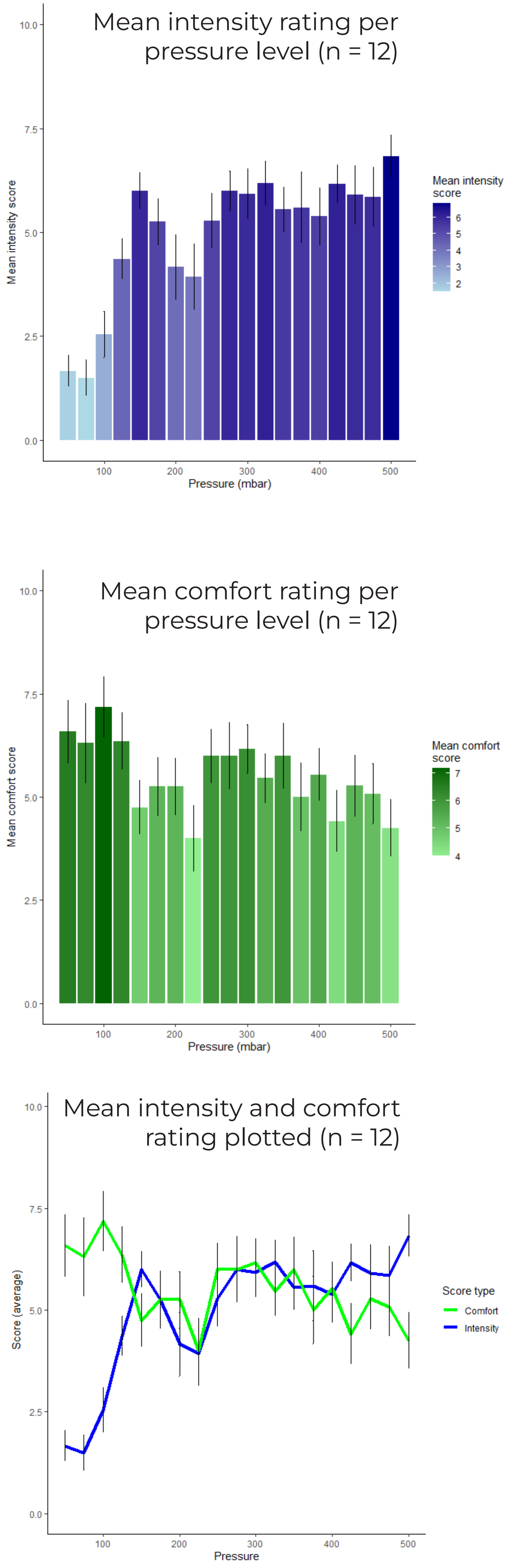


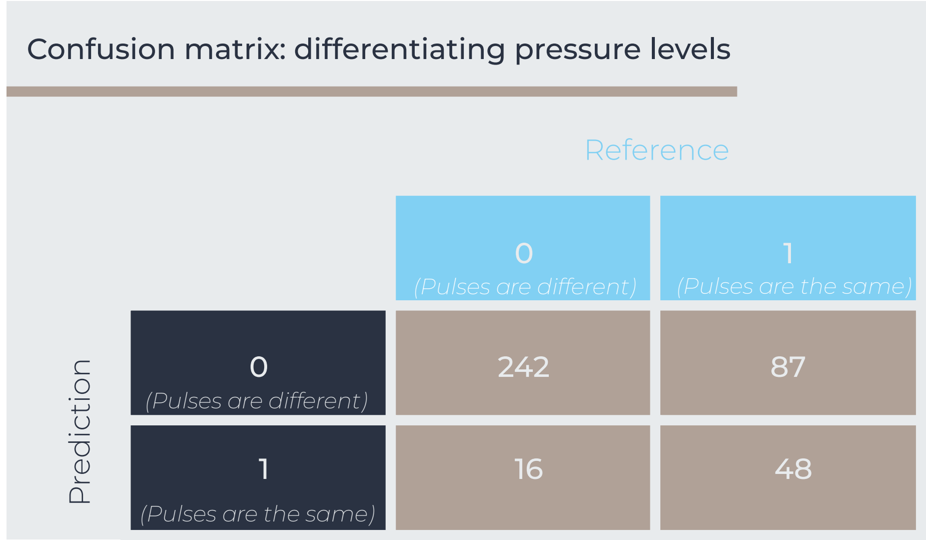
Figure 6.5 Intensity and comfort rating plots

Part 2: Just Noticeable Difference (JND)

While the system can distinguish and actuate up to a single millibar in resolution, the user might not be able to perceive this. The research question of this part of the test is as follows:

3. How well can users differentiate pressure levels, as indicated by the Just Noticeable Difference (JND)?"

By analyzing the 284 predictions by the participants, this research question can be answered. By comparing the reference pressure pairs (1 and 0 indicate same or different pressure respectively) to the predictions provided by the participants, a confusion matrix can be set up to gain more insight in user performance.



Confusion matrix: differentiating pressure levels

		Reference	
		0 (Pulses are different)	1 (Pulses are the same)
Prediction	0 (Pulses are different)	242	87
	1 (Pulses are the same)	16	48

Accuracy : 0.7379
95% CI : (0.6915, 0.7807)
No Information Rate : 0.6565

P-Value [Acc > NIR] : 0.0003203

Kappa : 0.3356

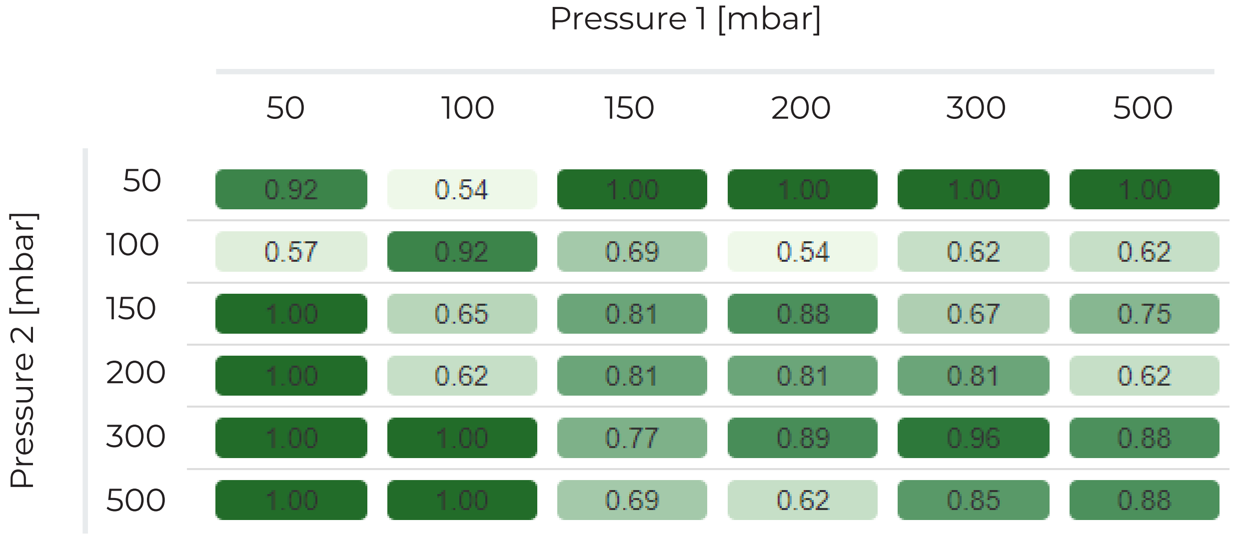
Mcnemar's Test P-Value : 5.3e-12

Sensitivity : 0.9380
Specificity : 0.3556
Pos Pred Value : 0.7356
Neg Pred Value : 0.7500
Prevalence : 0.6565
Detection Rate : 0.6158
Detection Prevalence : 0.8372
Balanced Accuracy : 0.6468
'Positive' Class : 0

Table 6.3: Confusion matrix for pressure differentiation test

Overall, the participants have moderate accuracy at 73.59%. The high sensitivity score at 93.12% indicated that the participants were good at identifying positive ("the pulses are the same") cases. However, the specificity is low at 34.74%, indicating that identifying negative cases ("the pulses are different") did not go as successfully. This could suggest that the participants are biased toward predicting positive cases, indicating that some used pressure levels are hard to differentiate.

The table below displays prediction success rate for each pressure combination the participants experienced. For example, 50mbar is easy to distinguish from 500mbar resulting in a high prediction success rate of 100%, while 100 and 200 mbar were harder to distinguish resulting in a rate of 55%. A slight diagonal trend of higher scores in the table can be related to the high sensitivity score discussed before. While 50 mbar shows a high succes rate in distinguishment from pressure levels from 150 mbar and beyond. It is also interesting to see how the sequence of pressures can influence the experience. A pulse of 100 mbar followed by 500mbar shows a 100% success rate, while the reverse order shows a 59% succes rate. Overall starting with the lowest pressure level of a pair resulted in a slightly higher successful identification rate.



Pressure 2 [mbar] \ Pressure 1 [mbar]	50	100	150	200	300	500
50	0.92	0.54	1.00	1.00	1.00	1.00
100	0.57	0.92	0.69	0.54	0.62	0.62
150	1.00	0.65	0.81	0.88	0.67	0.75
200	1.00	0.62	0.81	0.81	0.81	0.62
300	1.00	1.00	0.77	0.89	0.96	0.88
500	1.00	1.00	0.69	0.62	0.85	0.88

Table 6.4: Participant guess correct rate per pressure pair

Conclusion on part 2:

3. How well can users differentiate pressure levels, as indicated by the Just Noticeable Difference (JND)?”

The overall accuracy of the participants is 73.59%. Identifying pulses of the exact same pressure level has a relatively high success of 93.12%. Distinguishing different pressure levels can be very difficult for the participants, according to the specificity score of 34.74%. Pressure levels of 50 and 500 millibar have a relatively high success of being distinguished from the other pressure levels.

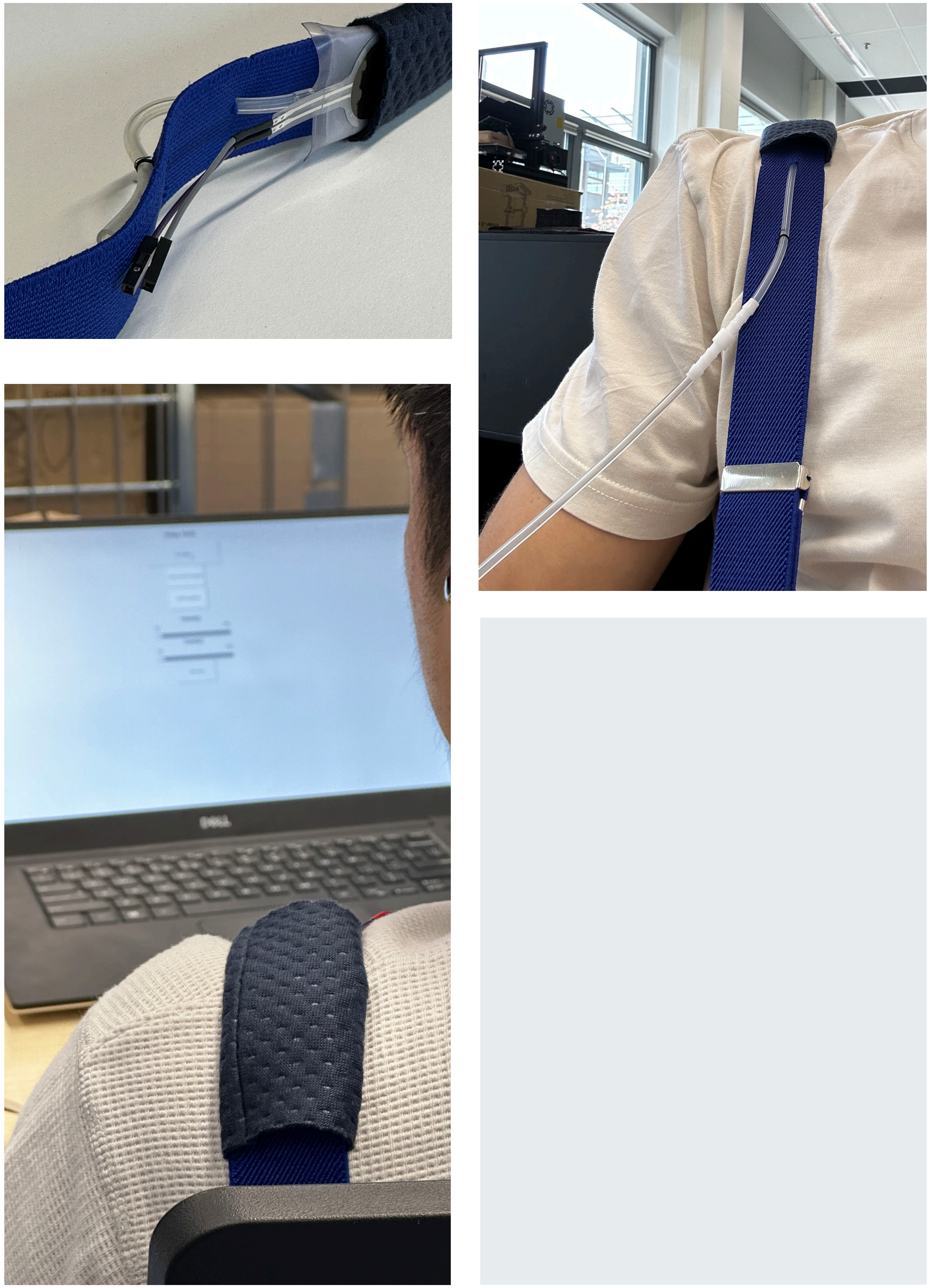


Figure 6.6: Overview of second user test setup

Part 3: Pulse pattern rating with variable speed

4. How are various pulse patterns their characteristics rated, and how does frequency influence these ratings?

When looking at the tables below displaying intensity, comfort, pleasant, and exciting ratings for each respective pulse type (heartBeat, shortLong, tripleLong, tripleShort), some insights can be made. It is interesting to see how the average ratings stay relatively close to the median, which could have various implications. The pulses used in the test might have felt too similar for the participants to have wildly varying ratings, sample size may have been too small, or the participant their shoulder may have been overstimulated since this was the final trial of test. Nonetheless, some interpretations can be made from the data.

Intensity scores for all pulse types and frequencies are rated quite similar, except for the triple short pulse which scores below the median at the highest speed (250ms delay). Patterns with varying pulse lengths have a relatively lower comfort rating, especially when repeated quickly at a 'short-long' pattern. Pleasantness ratings seem similar to the comfort score. The last rating on excitingness shows how an increased speed results in a higher exciting rating for a heartBeat and 'short-long' pattern, while 'tripleShort' stays around the median and 'tripleLong' below the median regardless of speed.

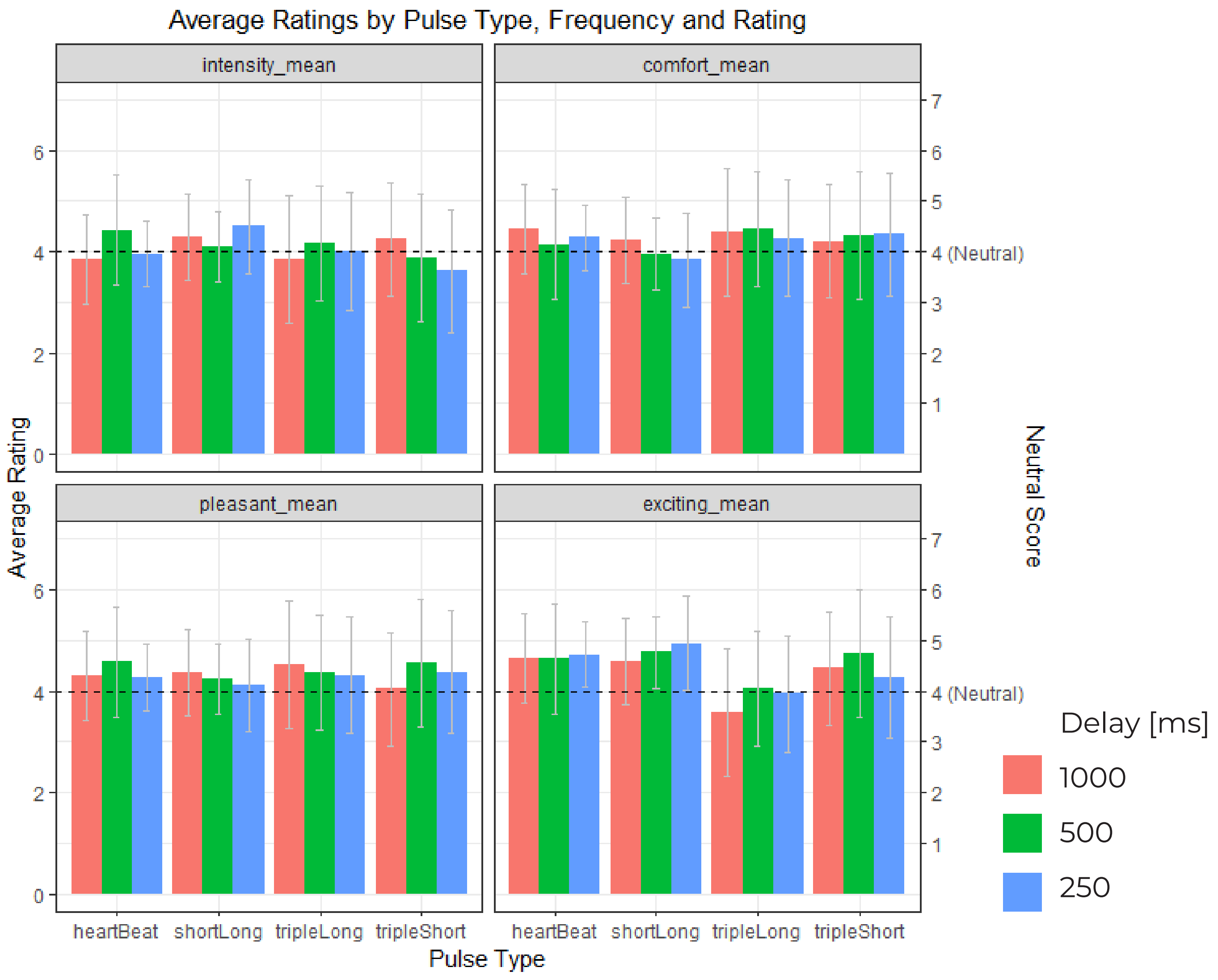


Figure 6.7: Average ratings for each pattern on three speed levels

Interview insights

Overall impressions on the pneumatic wearable actuation were diverse. Some participants noted how the pressure of the feedback was too much at times, while others noted they would like to feel more pressure. Pulse intensity and rhythm showed interest during the test. Some participants related the feedback to a squeeze, while others said it felt more akin to a tap.

Overall pulses with a high pressure level and high frequency were considered as noticeable pulses. Pleasant pulses were often considered short and soft, while feedback on comfortable pulses varied from soft and short to longer and higher pressure levels. In the case of ergonomics, there was some unfamiliarity with the suspender style of wearing, but there were no significant reports of discomfort. There were some slight challenges with the positioning of the device and the potential for it to slip, suggesting the value of a small adjustment in positioning to the back of the shoulder and fabrics that would slip less.

Overall suggestions for applications of such a pneumatic wearable would be in either professional settings for a different means of notifications, or for more intimate settings with a partner or relatives to convey social touch such as a hug over a distance.

Conclusion

The user test provided insights into characteristics for pneumatic actuation on the shoulder on by answering four research questions. The first research question on the Absolute Pressure Threshold concludes with a minimum pressure level of 75mbar for participants in order to feel pneumatic feedback. The second part of the research gives an overview of intensity and comfort ratings over the entire pressure range of the system. Below 125 mbar participants rate the pressure with a low intensity and high comfort rating. Pressure levels between 125 and 400 mbar received more neutral ratings close to the median no both pressure and intensity. Between 400 and 500 mbar show an increased intensity and lowered comfort rating.

The third part of the research on Just Noticeable Difference tests to what level participants can distinguish two pressure levels from one another. Overall accuracy was of 73.59%, the sensitivity score was 93.12% indicating a high success rating identifying pulses of similar pressure level. The participants did experience difficulty in telling pressure levels between 150 to 300 mbar apart from each other, with a specificity score of 34.74%.

Lastly, ratings on four characteristics (intensity, comfort, pleasant, exciting) brought insights into the characterization of four patterns on three actuation speed levels. Overall ratings stayed close the median, but tripleShort received a slighly lower intensity rating at a higher speed and tripleLong was considered less exciting at a lower speed.

Discussion

The user tests yielded significant insights on pressure levels that are suitable for the user, the identification of pressure levels, and how users rate these levels to some extent. However, the rating results could suggest that it may have been challenging for participants to identify different patterns. This challenge becomes more evident when considering the interview results from the test. A noteworthy factor that could potentially affect the test results is the mounting location on the shoulder. Slight inconsistencies in the placement of the device could have an impact on the sensations felt by the user and could have influenced their responses. The possibility of the system overshooting beyond the target pressure might have a slight influence on the results. While the pump power was set to the lowest level to minimize overshoot, lower pressure targets might show larget deviations in comparison to higher pressure targets. Lastly, factors such as sound or time to reach peak pressure might have an influence on the results, since potential sound leakage in combination with a longer time to inflate might indicate differences in actuation.

6.3 Third user test: Pattern identification and rating

Background and goals

Results from the second user tests emerged new research questions due to the similar ratings for each of the twelve previous patterns. Due to a lack of data on identifiability of each pneumatic pattern, it is difficult to assess whether the patterns were considered similar in characteristics, or instead if the participants could not distinguish the patterns in the first place. This test setup is is to resolve such questions, and introduces an iteration of pneumatic patterns built on the previous design. One of the major changes is the introduction of variable pressure per pulse, which could result in a more distinguishable actuation when looking at the interview notes from the previous test. The goals of this user research are:

1. To understand to what level pressure patterns with variable pressure are distinguishable
2. To understand how each pattern is rated on intensity, comfort, pleasantness, and exciting

Identification rate

8 Patterns are each actuated in a randomized order per participant. There are 16 trials in total, offering the participant two opportunities to identify the corresponding pattern while reducing the influence of guessing.

The specific patterns used during the test and their success rate in identification are shown in Figure 6.8 below. The patterns with the highest identification rate were ‘Triple short’ at 84.6% and ‘Heartbeat backward’ at 72%. All other patterns received an identification rate of 60% or lower. The lowest identification rates were for ‘Triple long’ and ‘Short staircase down’ respectively at 52% and 44%.

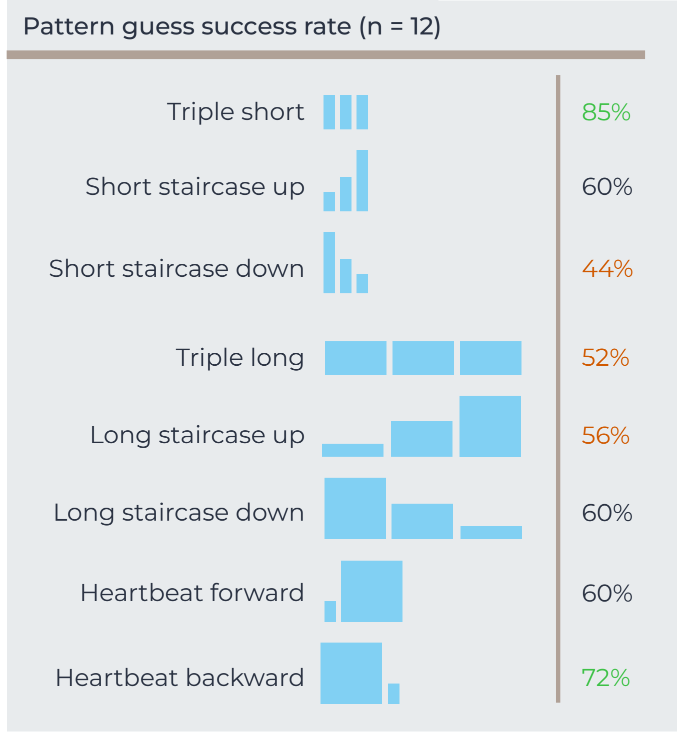


Figure 6.8: Pattern guess success rate

What patterns are confused for each other?

Since some patterns have a low identification rate, it can be of value to research what specific patterns the participants guessed for each pattern. The confusion matrix in Table 6.10 gives an overview of the participants their guesses and the patterns that were actuated in reality.

Some themes in the confusion matrix become clear when looking closely at the data. Patterns increasing in pressure are often confused for each other (short staircase up, long staircase up, heartbeat forward), and patterns decreasing in pressure show similar correlations in participants their guesses (short staircase down, long staircase down, heartbeat backward). This indicates that the participants did feel the pressure changes over time, but may have difficulties in distinguishing short from long pulses. An example of this would be 'Short staircase down' which is confused for 'Long staircase down' 9 out of 24 trials.

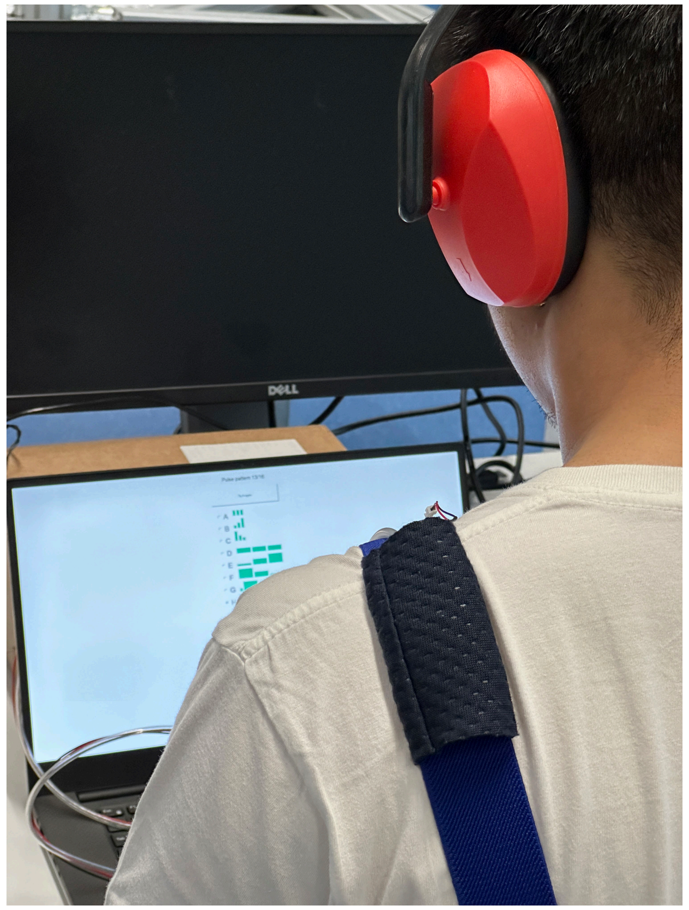
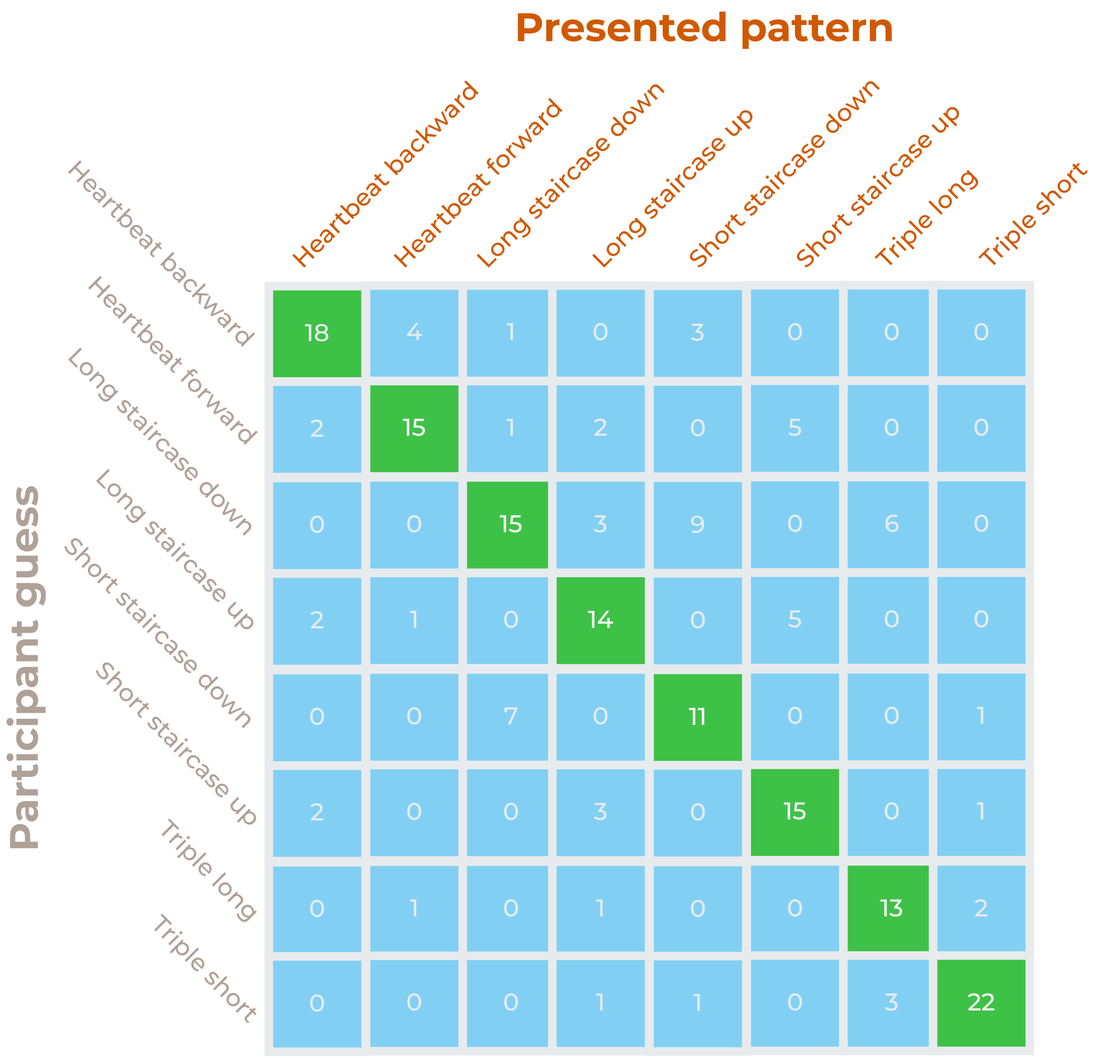


Figure 6.9: Overview of third user test



Participant guess \ Presented pattern	Heartbeat backward	Heartbeat forward	Long staircase down	Long staircase up	Short staircase down	Short staircase up	Triple long	Triple short
Heartbeat backward	18	4	1	0	3	0	0	0
Heartbeat forward	2	15	1	2	0	5	0	0
Long staircase down	0	0	15	3	9	0	6	0
Long staircase up	2	1	0	14	0	5	0	0
Short staircase down	0	0	7	0	11	0	0	1
Short staircase up	2	0	0	3	0	15	0	1
Triple long	0	1	0	1	0	0	13	2
Triple short	0	0	0	1	1	0	3	22

Table 6.5: Confusion matrix of pattern guesses from the third user test

Ratings on four characteristics

The second part of the test focuses on ratings of each pattern on intensity, comfort, pleasant, and exciting, which the mean values of are visualized in Figure 6.10. Overall rating stay close to the median similar to the previous test. Patterns including a longer peak hold time were rated slightly higher on intensity compared to those with only short pulses. Overall comfort ratings were neutral, but 'Heartbeat forward' and 'Long staircase up' scored above average. The pleasant rating scale show similar ratings to those of the comfort scale, and shows a higher pleasantness rating for 'triple short'. Lastly, 'short staircase up' and 'triple short' were considered a little more exciting than the other patterns.

Figure 6.10: Mean ratings for each pattern

Interview insights

A brief interview at the end of each test brought insights into the overall user experience and qualitative feedback on pattern characteristics and potential use cases.

Overall most participants found the study to be an interesting and unique experience. Participants stated to experience some challenges in relating the correct graph to the feedback they felt. Some related the feedback to something playful or a massage, and noted how they would have to get used to this new type of haptic feedback. High pressure levels over a prolonged time was considered most intense overall, and there might be a slight preference for longer pulses that increase in pressure over time when considering comfort.

On a social aspect participants considered context and intent important factors in relation to the acceptance of receiving feedback from a friend with such a wearable. The majority of participants were not comfortable with the idea of a stranger using such a system to interact with them.

Suggestions for potential applications of this type of pneumatic actuation stretched to applications in gaming, navigation, providing mediated social touch for people in long-distance relationships or quarantine, and posture correction. There were also unique suggestions for potential use with pets, intimate settings, or aiding those with disabilities.

Conclusion

This user study provided insights into how pneumatic patterns on the shoulder with variable pressure levels are perceived. The test shows to what level the patterns can be identified by the participants, and gives insights into how the patterns are characterized using four rating scales.

Specific patterns such as “Triple short’ and ‘Heartbeat backward’ demonstrated high identification rates (85%, 72%), while other patterns received a lower identification rate from 60% down to 44% (‘Short staircase down’). The confusion matrix shows how an increase or decrease in pressure levels was often identified correctly, but patterns sharing those characteristics were commonly confused for each other. This suggests that while users can detect changes in pressure, distinguishing between different pattern lengths was deemed more challenging in this test setup.

The participants’ ratings on intensity, comfort, pleasantness, and excitement stayed close to the median overall. Patterns with longer peak hold times were often associated with a mildly higher intensity. ‘Heartbeat forward’ and ‘Long staircase up’ received slightly higher comfort and pleasantness ratings, suggesting a preference for patterns with a progressive increase in pressure. Some participants noted similar feedback during the interview aligning with the ratings.

In terms of applications and user acceptance, interviews highlighted the importance of context and user intent. Participants expressed reservations about receiving tactile feedback from strangers but saw potential for the technology in personal settings and practical applications like gaming, navigation, social touch in long-distance relationships or quarantine conditions, and posture correction.

Discussion

Overall, the research provided valuable insights on pneumatic pattern identification, ratings and potential use cases in social contexts. Despite of that, the study shows limitations in the test itself and the potential of this type and iteration of pneumatic wearable.

The identification rate results from the test are lower than desired, but could have a variety of causes that could be resolved in the future. For example, participants had to accommodate to this new type of haptic experience during the trial. This in combination with the abstract interface might have made it challenging for participants what a short and a long pulse exactly means while experiencing the patterns for the first time. A test trial and more elaborate description of the patterns could resolve those issues.

Other potential improvements to the trial could be in the interface. At times the interface was slightly unresponsive which caused participants to accidently skip a trial in rare instances. The slider scaling and responsiveness could be improved as well, which might motivate the participants to move them further from the median.

It is also of importance to consider that the results are from a lab setting where the participants have limited distractions while performing the test. In mobile applications sensitivity to pneumatic feedback could be significantly lower, impacting the distinguishment of lower pressure levels (Pohl et al., 2017).

While one of the goals of this test setup was to receive more varied ratings by varying air pressure and avoiding desensitization, the ratings are still rather close to the median overall. The low identification rate and confusion between patterns could be a clarification, but ratings for patterns with a high identification rate such as ‘Triple short’ also stay rather close to the median. While the initial pulse designs are primarily based on the more positively received pneumatic patterns (leaving very unpleasant patterns out of the project scope), more variation in rating was expected initially. It could be the case that the research covers the extent of expressivity of pneumatic actuation on the shoulder. However, the interview shows more nuance to the experience of the pneumatic actuation, where context might have a large impact on the experience of these patterns. Therefore further research with a focus on various contexts could be insightful. Further research within these contexts with friends, acquaintances, strangers, and digital agents could show more insights on intent which closely relates to the experience and acceptability.

Overall the participants responded with enthusiasm and surprise to the research and actuation from the prototype. After completing various tests with participants, the novelty and potential value in various use cases show promise for further research and development.

7. Conclusion

Conclusion

The goal of this project was to research and develop a form of affective touch that could bring valuable and potentially novel research results. Researching pneumatic actuation on the shoulder offered the opportunity to reach those goals.

The literature study and context definition framed the project and helped in developing the prototype iterations. It looked into social aspects from both a digital interaction and physical touch perspective. The value and impact of mediated social touch on social presence is described and connected to potential contexts. Studies on socially accepted touch directed towards the arm area for socially acceptable locations from strangers and acquaintances. Common instances to initiate social touch with those social-network members are greeting, parting, giving attention, and helping. Prior research with affective social touch wearables shows the ability of expressivity in multiple actuators which helped inspire development on both the embodiment of the prototype and the software integration controlling the actuators. While pneumatic actuation has been researched less in literature, prototypes show varied pump systems and airbag designs. This project worked with the Programmable Air development kit for its flexibility in prototyping and its relative performance.

The AffectiveAir prototype embodies a rich library of pneumatic actuations from multiple design iterations during the project. It is worn over the shoulder using a suspender-style mechanism that clips to the wearers' pants. This wearable form factor offers flexibility in size and movement while keeping the actuator secure on the body for optimal translation of force during actuation. The wearable part of the prototype is connected to external pneumatic control hardware to control airflow during prototyping and user research. The pumps offer inflation times under 1000- and deflation within 100 milliseconds. Three valves control the pneumatics and four additional valves offer future expansion. The airbag positioned on the shoulder offers a flexible soft actuator that is integrated into the textile, while the pressure sensor and thin force sensor measure the actuation to create a controlled feedback loop.

User tests functioned as a means to explore the possibilities of affective touch in a pneumatic shoulder wearable format and to verify its performance. The first explorative test determined showed potential in embedding actuation on the shoulder with an airbag of 40x40mm. The second test covered research on the absolute pressure threshold, just noticeable difference, and pattern ratings with variable speed. Participants felt the pneumatic actuation on their shoulder at a pressure level of 75 mbar. Below 125 mbar the actuation was characterised with a low intensity and high comfort. Between 125 and 400 mbar the ratings on intensity and comfort stayed close rather neutral, while pressures from 400 to 500 mbar showed high intensity and low comfort ratings.
Distinguishing different pressure levels from one another showed an overall accuracy of 73.59%. Identifying pressure levels of the same level showed relative success at 93.12% accuracy, while the specificity score of 34.74% indicates a low success in correctly identifying different pressure levels. Four preprogrammed patterns ('tripleshort', 'triplelong', 'heartbeat', 'shortlong') at three actuation speeds (250, 500, 1000 ms delay) showed overall neutral ratings on intensity, comfort, pleasant, and excitingness. 'Tripleshort' at a high speed received a slightly lower intensity rating, while 'triplelong' was considered the least exciting especially at lower speed.
The third user test researched pattern identification rate and further explored ratings by varying pressure levels instead of speed. Patterns such as 'tripleshort' and 'heartbeat backward' showed a high rating of 85% and 72% respectively, while 'short staircase down' received the lowest identification rate at 44%. Participants generally displayed the ability to distinguish between pressure increases and decreases. However, there was a tendency to misidentify the precise timing of the pulses, leading to instances where shorter pulses were mistaken for longer ones and vice versa. Overall ratings on intensity, comfort, pleasantness, and excitement stayed close to the median for most patterns similar to the previous test. Longer peak hold times resulted in a higher intensity rating overall. 'Heartbeat forward' and 'long staircase up' received a slightly higher comfort and pleasantness rating, which aligns with the feedback noted during the interview.

Overall participants responded with enthusiasm and surprise to the pneumatic actuation from the prototype. Multiple participants considered it a novel experience that shows promise in offering a new and soft means of feedback. The actuation was often related to human touch, possibly due to its location and characteristics from the programmed patterns. Overall AffectiveAir displays promising results in pneumatic affective social touch by demonstrating a library of unique sensations on the shoulder.

8. Recommendations

Recommendations

The project scope covered research on affective haptics, development of initial prototypes and user research to verify these first iterations. While the results of this project bring new insights in the field of affective (pneumatic) haptics, it simultaneously indicates the possibilities in case further research would be performed on this topic.

When examining the prototype used during this project, iterations on the hardware end would offer a richer prototyping system for future tests. As previously discussed, the air pressure sensor could be replaced with the MPX200GP to monitor a broader pressure range, thereby capturing the full range of pressures that the pumps can generate. Additionally, introducing a PID control system into the software could help manage overshoot, leading to quicker and more precise pneumatic actuation. The airbag design could implement separate inlet and outlet channels, to offer further control over the actuation by regulating the outlet flow. By integrating each of these proposals, a more extensive pneumatic library can be created with more diverse patterns.

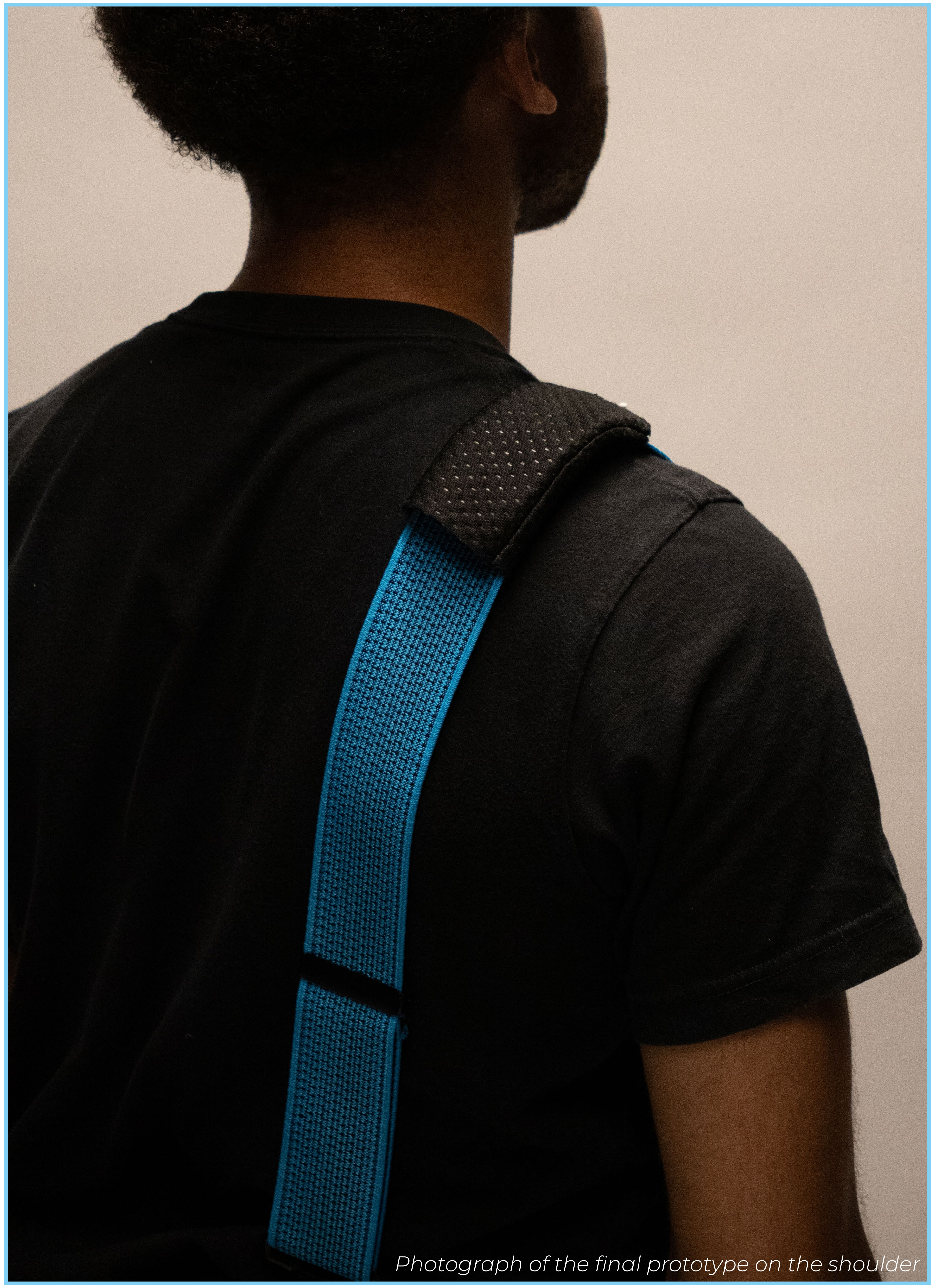
The current research used an initial prototype with new hardware, which resulted in some electrical components not being integrated within wearable textile components. While the user research within this test did not require a fully wearable solution, further iterations on wearable integration could enhance the user experience and broaden the applicability of the device.

Future iterations could also expand on the current hardware setup, by incorporating multiple airbags on the valve extensions. Sensations such as a lateral motion over the back or shoulder could be created. Another approach is to layer airbags, where one airbag could serve to cover possible air gaps between the wearable and the user, while a smaller airbag could provide more concentrated force, simulating the sensation of a fingertip.

Instead of expanding on the system and adding hardware, it is also possible to streamline the prototype by reducing the number of components to a single pump and three-way valve. This would allow the new prototype to offer actuations similar to the current version while reducing volume and weight. In order to establish a fully wearable solution, the integration of a battery and wireless communication may be necessary. Fortunately, the length of the elastic band affords sufficient space to accommodate these additional components.

Future research projects iterating on AffectiveAir could branch into several interesting research directions. It could be an interesting challenge to focus on integrating all components in a fully wearable solution. Additionally, expanding on the system and researching more pneumatic sensations by introducing multiple airbags could also bring valuable research insights. Further research in relation to the context can also bring insights into social acceptability and comfort, since the project did not cover user research with mediated interaction contexts. Other practical contexts, like navigation or notifications, may offer valuable insights into the usability of such a system in those situations.

Another appealing direction for further research involves incorporating two-way communication in user research. Since the sensor setup can detect when the user presses on the airbag, it would be possible to explore two-way communication, somewhat akin to a haptic Morse code. Overall, this research highlights promising new directions for future work on affective pneumatic wearable haptics.



Photograph of the final prototype on the shoulder

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Appendix

Appendix A: User test 1

User test 1: Location and size of the airbag

Finding the optimal location and contact area to feel most pneumatic actuation

Background

- Thesis project on social presence enhancing wearable
- Goal is to empower digital agents by increasing their social presence
- Social touch focus to facilitate social presence increase goal
- Pneumatic actuator to explore novel solutions
- Arm socially accepted location
- Specifics of arm location and contact area are to be explored in this test

Goal of the test (objective)

The goal of the test is to determine the optimal location and contact area to feel the most pneumatic actuation. Four predetermined locations with three different pneumatic actuator sizes will be tested by the participants. The maximum available pressure from the electronics is 50 kPa. A Likert scoring system in combination with qualitative feedback will give insight on what location and area on the arm is felt most.

Research questions:

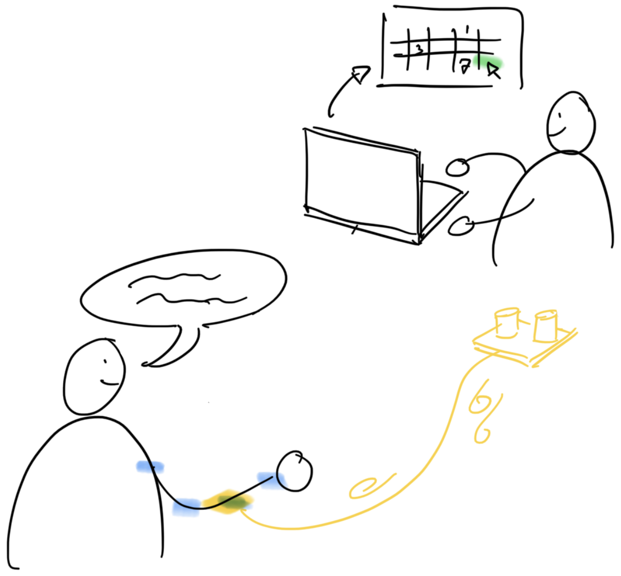
- At what pre-defined location do people feel the most pneumatic feedback?
- What pre-defined contact area has the highest recognition of pneumatic feedback?
- What pre-defined air container size feels similar to a human poke?

Materials

- Rectangular air containers in three sizes (1cm^2, 4cm^2, 9cm^2)
- Two strap types for wearing the TPU air pockets
- Programmable air kit
- Consent form

Test setup

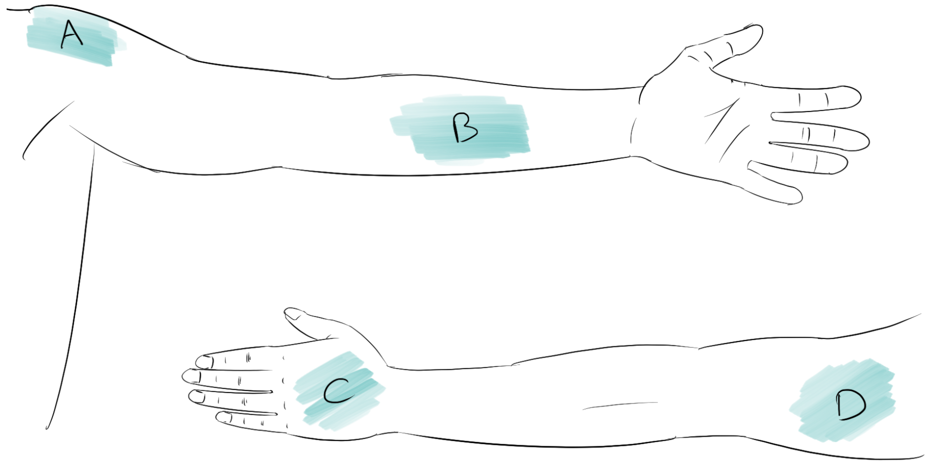
The Figure below shows an overview of the test setup. Participants will have four air pockets placed on different locations on their arm, which will be automatically controlled by the pneumatic electronics. The participant will give insights in the feedback per location, and give scores comparing intensity and comfort of the actuation per location.



Research plan

1. The participant will be briefly introduced to the topic and goal of the user test
2. Three air pocket sizes will be tested on four locations in a randomized order:
    a. Shoulder
    b. Lower arm (inside)
    c. Top of hand (dorsal side)

   d. Upper arm (outside)



3. The pneumatic actuation is controlled by a pump that will be operated manually by the researcher
4. The participant is asked to press a button when they start feeling actuation on their arm. This button press will be used to measure the time between when the pump starts, and when the participant can actually feel the actuation on their arm.
5. The participant rates each combination of location with contact area on a likert scale from 1 to 7 on two categories: intensity and comfort (1 = very low, 7 = very high). The participant can fill in their score on a keyboard for quick input of each combination.
6. While trying the different pneumatic actuations, a variety of questions will be asked for qualitative research insights.
   a. What do you think about each actuation location?
   b. What do you think about the different sizes?
   c. What would be your preferred actuation combination for optimal comfort?
   d. What would be your preferred actuation combination to feel the highest intensity?

An audio recording and handwritten notes will be used to keep track of the participants their feedback

Hypothesis

I expect a medium (2x2cm) air pocket on the lower arm to be one of the combinations which can be felt the most. The lower arm is relatively sensitive based on my personal experience with the prototype, and a medium air pocket may be the sweet spot of feeling directional actuation that does not try to cover the entire arm (and may lose too much force due to the pump specifications).

Ethical check

The participants will be informed of the risks and data processing by a consent form. While testing the prototype all possible risks were minimized. For further details, please check point B on the consent form.

Results

n=7

Averaged scores	**Intensity (1-7)**	**Comfort (1-7)**
Hand	5.71	3.00
Lower arm	5.43	4.29
Upper arm	4.29	5.29
Shoulder	3.43	5.14

Avg. score per size	Extra small (5x5mm)	Small (10x10mm)	Medium (20x20mm)	Large (30x30mm)
Intensity	3.29	5.43	6.00	6.14
Comfort	5.43	3.86	2.86	2.86

The interview gave valuable insights on each feedback location and the overall experience of the pneumatic actuation. Feedback on the hand was often considered slightly painful. This could be caused by the relatively high pressure, restrictive ergonomics of the strap, or a combination of either. The lower arm also received higher intensity ratings, but some participant stated they might felt a bit uneasy due to the location or potential setting in context.

The upper arm received higher comfort and lower intensity ratings, which aligned with the feedback from the interview. The shoulder received the lowest intensity rating and a similar comfort rating to the upper arm. While the strap design used in this test worked well for the other three locations, keeping the airbag in place on the shoulder showed difficulty with some participants. The lower intensity score might have been the result of a sub-optimal mount for some participants.

An increase in airbag size seems to have a positive correlation with intensity and a negative correlation with comfort. The smallest size of 5x5 mm received low intensity ratings and was sometimes difficult for participants to feel. Sub-optimal mounting or a smaller contact area (resulting in a smaller force being transferred since the system build pressure) could be possible causes. It is interesting to note how the medium and large airbags received similar ratings on both comfort and intensity.

Conclusion

This qualitative test explores the optimal location and airbag size for pneumatic actuation. After testing and rating the four locations on intensity and comfort with seven participants, followed by an interview, some conclusions can be made for further design decisions within the project. The ratings indicate how the hand and lower arm received a higher intensity score, at the cost of comfort. Opposing those results, the upper arm and shoulder received relatively high comfort- and lower intensity ratings. Sub-optimal mounting of the airbag on the hand and shoulder could be one of the main factors influencing intensity and comfort.

When considering the location with the highest intensity and comfort score, the upper arm seems to receive slightly better ratings compared to the other three locations. The test also indicates how the shoulder and hand could benefit from a more ergonomic design, which could improve their intensity and comfort ratings. The research potential also influences the design decisions for this project. Social touch wearables on the shoulder show potential in valuable research findings, compared to more commonly researched form factors on the hand or arm. Sub-optimal mounting should be overcome with iterations on the ergonomics of the design. Air gaps from sub-optimal mounting can be accounted for to some degree by increasing the size of the airbag. Air pressure should be kept under control during actuation to control the amount of force transferred to the wearer.

The test concludes with a focus on the shoulder and a large airbag size. This can result in novel research solutions in the social touch wearables research field. With iterations on the ergonomics and pressure control a shoulder wearable can be designed which can offer both intense and comfortable pneumatic feedback.

Interview notes per location (en/nl)

Hands
- Voelt meer als knijp effect, voel nergens een prik effect
- Voel het wel echt, maar niet vervelend ofzo
- Doet een beetje pijn
- hand wordt een beetje afgekneld, misschien als ie anders zit dat het fijner zit
- comfortable, niet pressing
- Heel naar (deelnemer schrok van feedback), idee dat ze harassed wordt
- Ook bloeddrukmeter vibes wanneer hij strak zit. Puur door die band afklemming
- Too much force, maybe less force is more comfortable
- Klinkt een beetje als op een computer tikken qua geluid, waardoor het voelt alsof er op je wordt geklikt
- Na een tijdje wel een beetje irritant
- Hand band restrict movement

Lower arm
- Voelt meer als knijpen, voelt veel een bobbel
- Niemand raakt je aan op je onderarm
- Prik voel je hier het meest
- Gevoelige plek, niet fijn
- Doet denken aan bloeddrukmeter, worden altijd net iets te omcomfortabel want net iets te strak
- Lower arm area feels more sensitive to the air pump, as opposed to the massage feel on the outside of the upper arm (upper arm is more comfortable)
- Raar om het het onderaan te voelen, omdat mensen in het echt ook niet poken onderaan de je arm
- Voelt bijna als een massage

Upper arm
- Voelde meer als tikken, want was niet zo hard
- voel je iets minder dan onderarm
- Kan een locatie zijn die heel vriendelijk overkomt
- Minder vervelend in verhouding tot onderarm. OOk al zou hij op typische plek bloeddruketer zitten
- More outside force, feels more like a massage
- Bij een bepaald punt zou het bijna pijn doen
- Voelt alsof iemand je grijpt
- Beetje naar
- Soms voelt het alsof de feedback van twee punten komt
-

Shoulder
- Zakt veel af, dus lastig vasthouden. Belangrijk om echt hoog te plaatsen
- Voelt meer als knijpen
- Later moment voelt als druk
- Vind het wel fijn voelen dat mijn schouder werd geknepen
- Kan een locatie zijn die heel afstandelijk kan zijn voor iemand die je minder goed kent
- Komt iets vriendelijke over
- Nog te veel afleiding dat hij strak trekt

Appendix B: User test 2

User test 2 data analysis

(Last export: May 4th 2023)

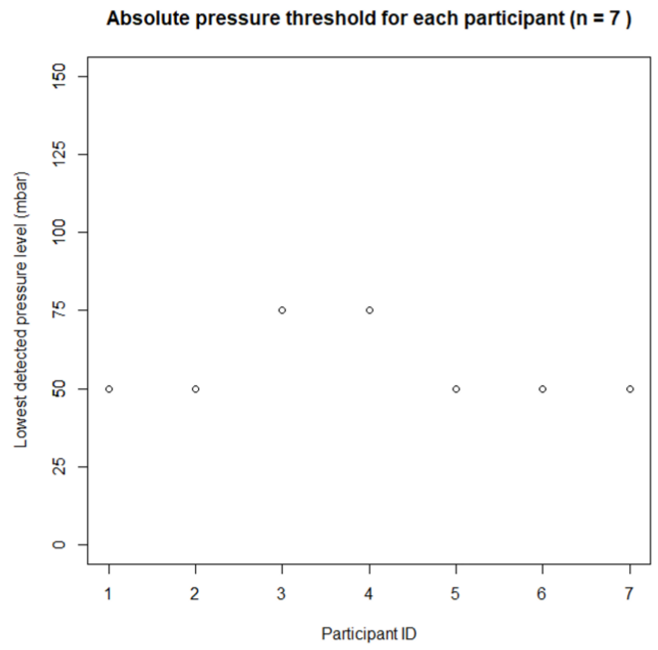
Goals:

1. To understand the minimum needed pressure to reach the absolute detection threshold
2. To understand how various pressure levels influence comfort and intensity
3. To understand what pressure differences are needed to achieve a Just Noticeable Difference (JND)
4. To understand how frequency influences characteristics of various pressure pulses

Part 1: Absolute pressure threshold, intensity and comfort rating over pressure

1. **What is the minimum needed pressure to reach the absolute detection threshold?**

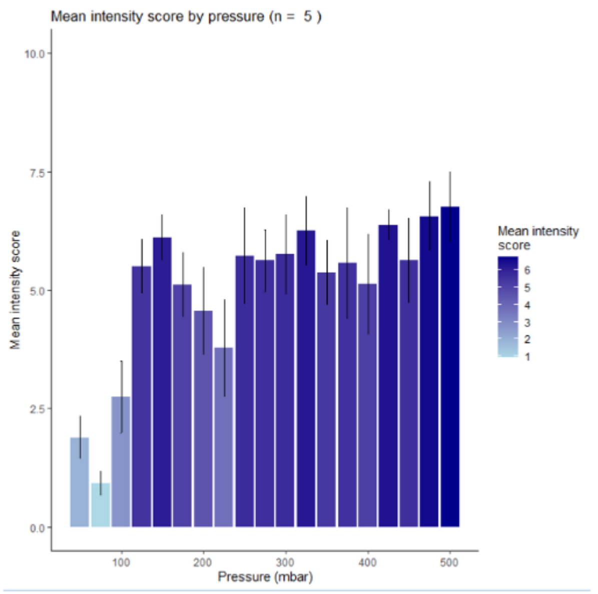
When looking at the graph below, it can be concluded that for some participants they are able to detect pressure at 50mbar, while some feel pressure at 75mbar. It is interesting to note that the static pressure before the system inflates hovered around 30 to 45mbar during the test, which means inflation time and pressure delta's slightly varied per participant.

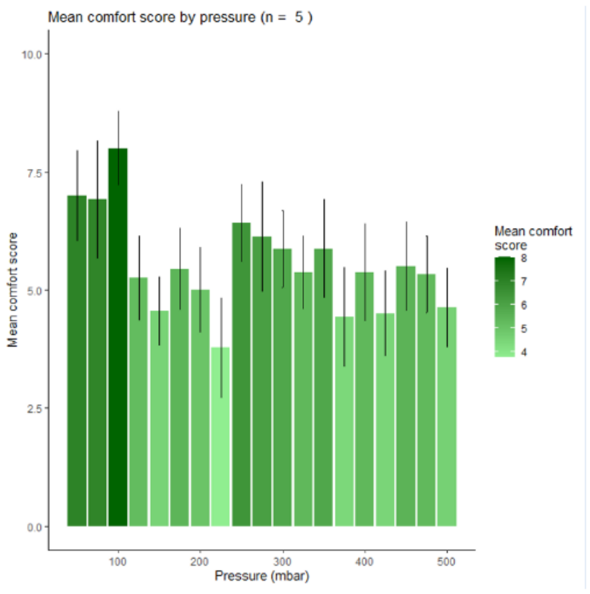


2. How do various pressure levels influence comfort and intensity rating?

By looking at the mean intensity scores for both comfort and intensity for each pressure level, some insights can be made. The actuated pressure levels in millibar were: 25, 50, 75, 100, 125, 150, 175, 200, 225, 250, 275, 300, 325, 350, 375, 400, 425, 450, 475, 500.

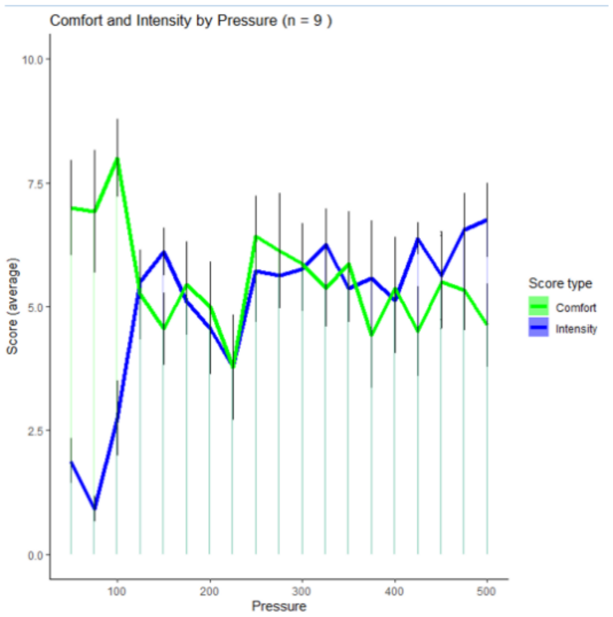
- Intensity score significantly increases at 125mbar.
- After 125mbar no significant deviation in score, suggesting intensity scores from 125 to 500 mbar is rated quite similar.
- Comfort score significantly decreased after 100mbar.
- After 100mbar there seems to significant change in comfort score. Maybe around 300mbar a higher comfort score (for some reason?)





The graph below displays the relation between comfort and intensity score by pressure. It is interesting to note how the intensity and comfort lines intersect at 125mbar. When combining this insight with the insights from the two separate graphs before, assumptions can be made on the following:

- When actuating a pressure under 125mbar, the wearer will experience a relatively high comfortable pulse with very low intensity.
- Pressure beyond 125mbar can increase intensity slightly, although the error bars suggest this varies per person or trial. Comfort stays relatively the same when looking at the line and error bars.



Conclusion on part 1:

1. **What is the minimum needed pressure to reach the absolute detection threshold?**

75 millibar pressure (target) is needed for all participants to feel the pneumatic actuation on their shoulder

2. How do various pressure levels influence comfort and intensity rating?

Below 125 millibar the participants experience a relatively high comfort and very low intensity.

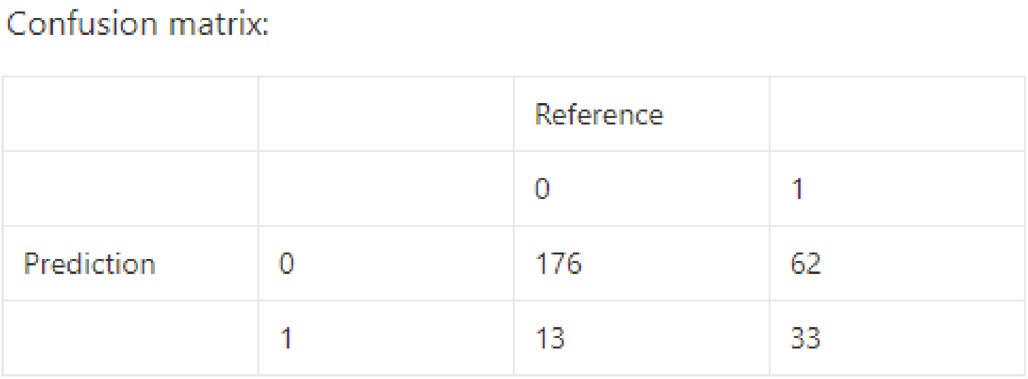
Beyond 125 millibars up to the maximum pressure of 500 millibars, the intensity and comfort scores float around the median of 5 (0 to 10 scale) with overlapping error bars, suggesting that the comfort and intensity scores stay relatively neutral for this pressure range.

Part 2: JND analysis

While the system can distinguish and actuate up to a single millibar in resolution, the user might not be able to perceive this. The research question of this part of the test is as follows:

1. **"How well can users differentiate pressure levels, as indicated by the Just Noticeable Difference (JND)?"**

By analyzing the 284 predictions by the participants, this research question can be answered. By comparing the reference pressure pairs (1 and 0 indicate same or different pressure respectively) to the predictions provided by the participants, a confusion matrix can be set up to gain more insight in user performance.



Confusion matrix:

		Reference	
		0	1
Prediction	0	176	62
	1	13	33

Accuracy : 0.7359

95% CI : (0.6806, 0.7862)
No Information Rate : 0.6655

P-Value [Acc > NIR] : 0.006332

Kappa : 0.3196

Mcnemar's Test P-Value : 2.981e-08

Sensitivity : 0.9312 Specificity : 0.3474 Pos Pred Value : 0.7395 Neg Pred Value : 0.7174 Prevalence : 0.6655 Detection Rate : 0.6197 Detection Prevalence : 0.8380 Balanced Accuracy : 0.6393 'Positive' Class : 0

Overall, the participants have moderate accuracy at 73.59%. The high sensitivity score at 93.12% indicated that the participants were good at identifying positive (”the pulses are the same”) cases. However, the specificity is low at 34.74%, indicating that identifying negative cases (”the pulses are different”) did not go as successfully. This could suggest that the participants are biased toward predicting positive cases, indicating that some used pressure levels are hard to differentiate.

The table below displays the specific pressure levels and successful prediction rates for each pair. A slight diagonal trend of higher scores in the table can be related to the high sensitivity score discussed before. The lowest and highest pressure levels have a relatively high success in being distinguishable according to the successful prediction rates in most cases. Pressure levels of 100 to 200 millibar seem to be more difficult for the participant to distinguish.

pressure1_level	50	100	150	200	300	500
50	0.93	0.56	1.00	1.00	1.00	1.00
100	0.61	0.93	0.69	0.56	0.64	0.56
150	1.00	0.62	0.69	0.93	0.71	0.75
200	1.00	0.64	0.81	0.81	0.88	1.00
300	1.00	1.00	0.69	0.83	0.94	0.88
500	1.00	1.00	0.56	0.62	0.88	0.88

Conclusion on part 2:

3. "How well can users differentiate pressure levels, as indicated by the Just Noticeable Difference (JND)?"

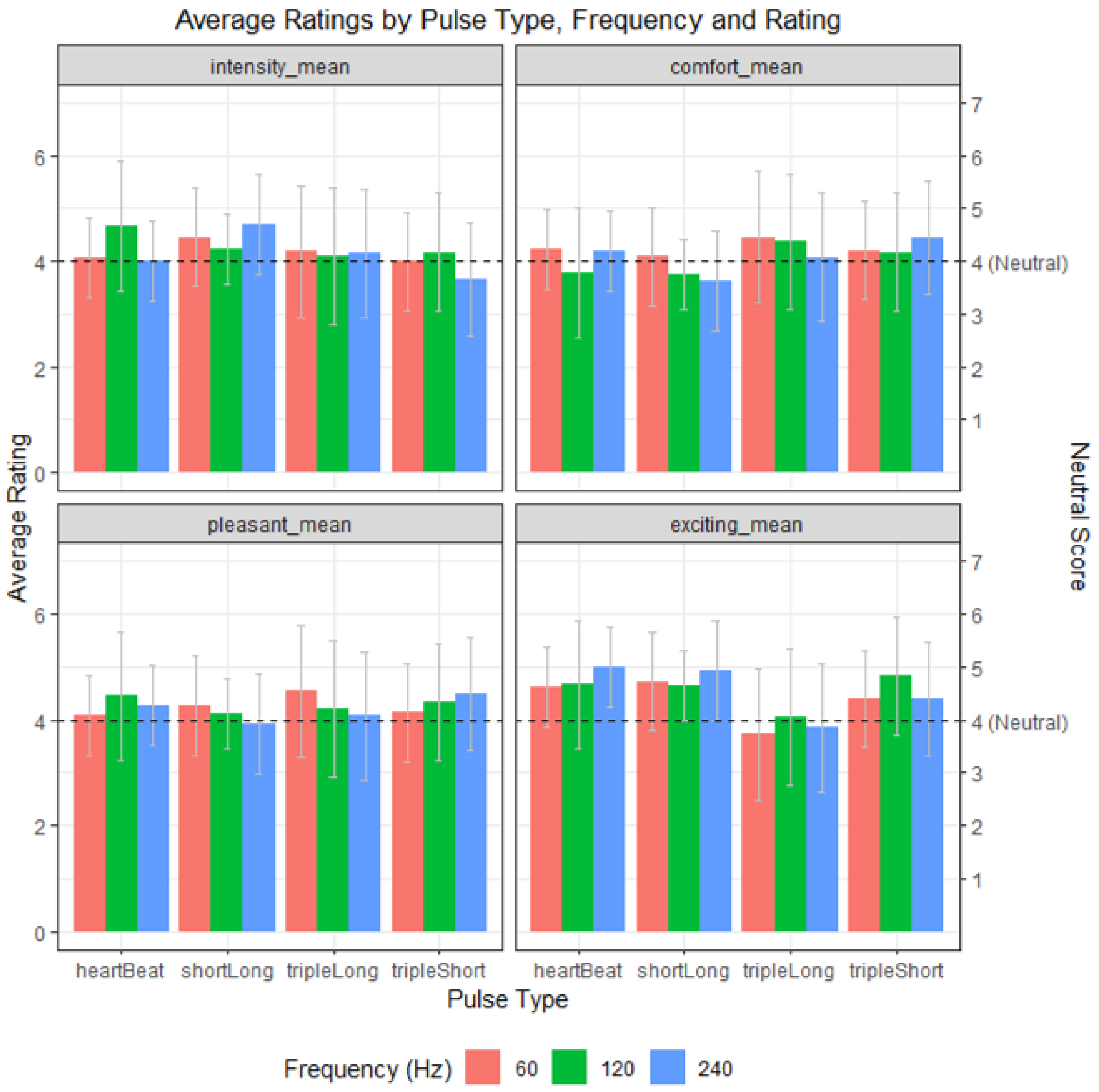
The overall accuracy of the participants is 73.59%. Identifying pulses of the exact same pressure level has a relatively high success of 93.12%. Distinguishing different pressure levels can be very difficult for the participants, according to the specificity score of 34.74%. Pressure levels of 50 and 500 millibar have a relatively high success of being distinguished from the other pressure levels.

Part 3: Pulse pattern rating and Frequency influence

4. How are various pulse patterns their characteristics rated, and how does frequency influence these ratings?

When looking at the tables below displaying intensity, comfort, pleasant, and exciting ratings for each respective pulse type (heartBeat, shortLong, tripleLong, tripleShort), some insights can be made. It is interesting to see how the average ratings stay relatively close to the median, which could have various implications. The pulses used in the test might have felt too similar for the participants to have wildly varying ratings, sample size may have been too small, or the participant their shoulder may have been overstimulated since this was the final trial of test. Nonetheless, some interpretations can be made from the data.

Intensity scores for all pulse types and frequencies are rated quite similar, except for the triple short pulse which scores below the median at the highest frequency of 240 hertz. Patterns with varying pulse lengths have a relatively lower comfort rating, especially when repeated quickly at a ‘short-long’ pattern. Pleasantness ratings seem similar to the comfort score. The last rating on excitingness shows how an increased frequency results in a higher exciting rating for a heartBeat and ‘short-long’ pattern, while ‘tripleShort’ stays around the median and ‘tripleLong’ below the median regardless of frequency.



Conclusion

The user test provided insights into characteristics for pneumatic actuation on the shoulder on by answering four research questions. The first research question on the Absolute Pressure Threshold concludes with a minimum pressure level of 75mbar for participants in order to feel pneumatic feedback. The second part of the research gives an overview of intensity and comfort ratings over the entire pressure range of the system. Below 125 mbar participants rate the pressure with a low intensity and high comfort rating. Pressure levels between 125 and 400 mbar received more neutral ratings close to the median no both pressure and intensity. Between 400 and 500 mbar show an increased intensity and lowered comfort rating.

The third part of the research on Just Noticeable Difference tests to what level participants can distinguish two pressure levels from one another. Overall accuracy was of 73.59%, the sensitivity score was 93.12% indicating a high success rating identifying pulses of similar pressure level. The participants did experience difficulty in telling pressure levels between 150 to 300 mbar apart from each other, with a specificity score of 34.74%.

Lastly, ratings on four characteristics (intensity, comfort, pleasant, exciting) brought insights into the characterization of four patterns on three actuation speed levels. Overall ratings stayed close the median, but tripleShort received a slighly lower intensity rating at a higher speed and tripleLong was considered less exciting at a lower speed.

Discussion

The user tests yielded significant insights on pressure levels that are suitable for the user, the identification of pressure levels, and how users rate these levels to some extent. However, the rating results could suggest that it may have been challenging for participants to identify different patterns. This challenge becomes more evident when considering the interview results from the test. A noteworthy factor that could potentially affect the test results is the mounting location on the shoulder. Slight inconsistencies in the placement of the device could have an impact on the sensations felt by the user and could have influenced their responses. The possibility of the system overshooting beyond the target pressure might have a slight influence on the results. While the pump power was set to the lowest level to minimize overshoot, lower pressure targets might show larget deviations in comparison to higher pressure targets. Lastly, factors such as sound or time to reach peak pressure might have an influence on the results, since potential sound leakage in combination with a longer time to inflate might indicate differences in actuation.

User test 2: notes

1. **What is your overall impression of the various pulses you experienced?**

1. Interesting, it shifted a bit a times. Sometimes it felt like something was squeezing. A lower pressure felt more like a top. I did hear the sound sometimes.
2. It feels like a new experience
3. The feedback is softer than I initially expected. But I did feel some pulses
4. I don't really like the constant pressure on my shoulder, but the actuation itself is okay by me.
5. Some of the pulses were quite soft. Sometimes it did take some time before I felt anything. Sometimes it was difficult to distinguish different pulses from one another. High pressure levels were definitely noticeable to me
6. Multiple pulses felt way more noticeable. Felt like the airbag was pushing up more. Sound isolation was not perfect.
7. The diversity in the pressure intensity was noticeable. Some were too intense while others were subtle
8. Large spectrum in intensity. Does not really feel like a real squeeze, due to the duration. Longer pulses do not feel really human. Rhythm could be intersting
9. Cool. I could feel the personalities of the various poking on my shoulder. Tightness does not influence how much I felt it.
10. Surprising to me how similar they felt. Difficult to distinguish the pulses. Sequential pulses are a bit more noticeable
11. Most of the patterns did not feel pleasant to me
12. The feedback felt quite similar to me. Intensity was quite varied however. Patterns felt the same to me

2. **Which pattern did you find most noticeable? Why? Was it distracting? Why?**

1. I did feel the intense ones most. Inconsistent patterns felt unpleasant to me
2. Variation within a pattern was noticeable to me
3. The ones that started with a long hold time and gave a short pulse afterwards
4. Some of the patterns were quite slow, and the fast touches felt more human-like to me
5. Long hold times, hard or soft are both fine. Repetition was also noticeable
6. Rapid change, high frequency, reminds me of a buzzing phone or alarm
7. the ones that gradually increased in pressure
8. The patterns in creasing in pressure. Deflation felt more noticeable to me of the pulse. Heartbeat was also noticeable
9. High frequency. Really soft as well sometimes
10. High frequency. Two steps was nice from soft to hard. I was also not caught by surprise on those instances
11. Quick and high pressure
12. Alternating pressure levels. At the end of the test I did not feel much anymore

3. **Which pattern did you find most pleasant? Why?**

1. Short, long, low intensity, consistent patterns
2. Long and slow patterns
3. The ones that started with a long hold time and gave a short pulse afterwards
4. Soft short first, followed by a harder longer pulse. Not too slow
5. A short tap
6. None of them felt pleasant to me. Overall I think they felt quite neutral.
7. ower intensity more pleasant
8. Pulses with a lower intensity
9. I liked the ‘big’ pulses
10. Single soft pulse
11. Subtle but noticeable and slow
12. The ones with the lowest intensity

4. **Which pattern did you find most comfortable? Why?**

1. The same as in the previous question.
2. Long holding patterns
3. The ones that started with a long hold time and gave a short pulse afterwards
4. Not to hard, especially when it is the first pulse I feel.
5. Soft presses. In case the pressure is high, rather a short pulse
6. Nothing exceptional, so overall I would rate them as ‘good’
7. middle pressure level was the most comfortable to me
8. Depends on the setting, and differs per person I would interact with. Maybe the middle pressure level of what I felt.
9. All the pulses were comfortable to me
10. Smother increase in pressure. Some pulses were too hard
11. Subtle but noticeable and slow
12. The lower the intensity, the higher the comfort

5. **What do you think about the ergonomics of the prototype?**

1. I have to get a bit used to wearing suspenders
2. It was a little bit slippery to me and a bit ticklish. Maybe I would prefer to put something over my shoulder instead of having this constant pressure
3. Ergonomics are fine to me. Wearing it is fine. The clamps did fly off once however. Maybe the elastic band could have been a little bit more tight.
4. Good. it is rather comfortable to me. Not too tight. Pressing of the actuator is also not unpleasant to me.
5. I did not really notice the band over my shoulder. But I did feel the airbag when it started inflating. As if my clothes were inflating.
6. The prototype was sliding a bit off the shoulder at times. Maybe the pressing forces in the airbag and band can be more balanced out
7. New to me and I had to adjust a bit
8. After putting it on I don’t notice it much. Suspenders are new to me and could be in the way when I visit the restroom. I am also a bit afraid of damaging my pants.
9. Really easy to wear. Wasn’t sure if I tightened it enough, so maybe the intensity could be higher?
10. Comfortable pressure on my shoulder
11. My pants were pulled upwards a bit due to the elastic band
12. Elastic band pressure is okay I would say. Location is a bit sensitive for me.

6. **Is the location of the feedback where you would want it to be?**

1. Sometimes the feedback shifted a bit to the front. But on the back of my shoulder it did feel pleasant!
2. I would rather have the feedback a little bit to the back of my shoulder
3. Feedback on the back of the shoulder was nice. Otherwise a massage near the neck could be pleasant to me.
4. Depends on what I would like to convey. What kind of metaphor should I be thinking of
5. It feels like a strong shoulder massage at times, like my dad used to give me. Due to the sensitivity I could feel the different pulses well however.
6. Too high up on the shoulder in my opinion during the test, so I could not feel much of hte pressure (avoid the bone to feel more pressure changes).
7. I am okay with the feedback on the back of my shoulder
8. Back of the shoulder is fine by me. I am missing the “thumb” of the press on the shoulder however.
9. Sometimes it felt a bit like a squeezing hand or palm over one shoulder. Maybe it could be more centered on my back
10. Good location for the feedback in my opinion
11. Shoulder is fine, but maybe I would have preferred to have the strap on either side for a more balanced feel.
12. Depends on the context. Could be very intimate quickly. Maybe on the upper arm it could work.

7. **Do you see yourself using such a wearable in daily life? If yes, in what scenario?**

1. I might forget to put it on. It might be nice to have this type of feedback when I’m isolated. Otherwise when I am contacting people much I would see no need for it myself
2. I think there is a low threshold for me to wear it, as long as I don’t have to charge it often. Maybe it is nice for online meetings or a massage over a distance
3. Not in a professional context, but rather in a more personal setting with family to give a hug for example
4. Desk context, to help get a posture correction

5. Remote working, notifications when using noise cancelling headphones. Soft method to get someone their attention. Email notifications. I don’t like the notification of my phone because they can be abrupt and hard, maybe this is a less annoying alternative.
6. In a conference setting this might be nice. I wouldn’t want to use this at times because it feels like a teacher squeezing my shoulder to make sure I don’t zone out
7. Maybe for gaming or an immersive movie
8. With the trend of the metaverse I could see an application in gaming (VR). Maybe on a festival to feel the bass.
9. Maybe when I am using slack or working online. I could feel the urgency in the poke
10. Office setting (or remote), when I have a headset on for example to be notified
11. No
12. Maybe useable for a long distance relationship

8. **Are there any specific patterns you would see yourself using in everyday life?**

1. A means to convey a firm handshake
2. I think it would depend on the situation for me. But maybe more of a preference for longer hold pressures. Or maybe I can draw my own waveform.
3. Massage like actuations. Slow, strong and sometimes soft to create an overall intense experience
4. Short soft followed by a longer harder pulse. Higher urgency should be with a higher pressure
5. Short, repetition, not too hard, not too soft, so middle of the pressure levels I experienced. Triple short tap was nice.
6. Repeated patterns would get my attention fast.
7. Maybe a massage or way of saying hello
8. Maybe something massage-like or sensual with a partner. Gamification could als obe interesting. Or maybe something with music.
9. Varies per instance. Can’t remember each pattern clearly.
10. Maybe something similar to a shoulder tap where it is tapped twice
11. -
12. Maybe a stroking sensation

9. **Any other comments or suggestions?**

1. -
2. The test setup really made me focus on fulfilling the test itself.
3. Chill
4. More pressure distributing maybe for more wearing comfort. And very long waveform pulses could be nice
5. When I wear a dress I cannot wear the wearable!
6. -
7. -
8. I am wondering on the social aspect: who is giving the squeeze?
9. -
10. -
11. Try to keep the feedback as natural as possible. Suspender style is fine by me because of the freedom in movement.
12. -

Conclusion

Overall impressions on the pneumatic wearable actuation were diverse. Some participants noted how the pressure of the feedback was too much at times, while others noted they would like to feel more pressure. Pulse intensity and rhythm showed interest during the test. Some participants related the feedback to a squeeze, while others said it felt more akin to a tap. Overall pulses with a high pressure level and high frequency were considered as noticeable pulses. Pleasant pulses were often considered short and soft, while feedback on comfortable pulses varied from soft and short to longer and higher pressure levels. In the case of ergonomics, there was some unfamiliarity with the suspender style of wearing, but there were no significant reports of discomfort. There were some slight challenges with the positioning of the device and the potential for it to slip, suggesting the value of a small adjustment in positioning to the back of the shoulder and fabrics that would slip less.
Overall suggestions for applications of such a pneumatic wearable would be in either professional settings for a different means of notifications, or for more intimate settings with a partner or relatives to convey social touch such as a hug over a distance.

Appendix C: User test 3

User test 3 setup: Distinguishable pulses with variable pressure

1. General information

Goal:

1. To understand to what level pressure patterns with variable pressure are distinguishable
2. To understand pleasantness rating for each pressure pattern

Participant pool:

- Age 20-30s
- 12 participants consisting of nearby friends and acquaintances

Recruitment process: Invitations through social media, in person approaching
Timeline:

- Pilot: Friday May 26th - 2 participants
- Real: May 30th, 31st, June 2nd - 12 participants

Place: IDE faculty
Language: English for most data input, qualitative data can be in Dutch if the participant prefers.
Materials: Prototype, Laptop, audio recording equipment
Preparatory tasks: Informed consent form
Data to be collected:

- Data input from questionnaire and qualitative feedback
- Audio recording of the interview
- Transcript of the interview

2. Protocol: activities overview

Total number of blocks: 5 (Introduction, static pressure test, just noticeable difference

Step 0: Choose interviewee

Step 1: Introduction to the research topic, placement of wearable and headphones (5min.)

- The participant has a brief introduction to the research project
- The wearable prototype is placed on the shoulder
- Headphones playing brown noise are used to minimize noise interference from the prototype

Step 2: Pattern rating and identification (15min.)

- 8 Patterns are each actuated in a randomized order per participant. There are 16 trials in total, offering the participant two opportunities to identify the corresponding pattern while reducing the influence of guessing.

Step 3: Brief interview (5min.)
(To gain qualitative feedback on the various patterns)

Total time: 25min

3. User test questions:

Research questions:

1. To what level can the participants successfully identify the designed pulse patterns?
2. Are specific types of patterns confused with each other?
3. How pleasant is each respective pattern rated?

Basic information:

- Name / Gender / Age / Weight / Height

Part 1: Introduction to the test

- The participant will sit at a table in front of a computer
- The participant equips the prototype and hearing protection
- The strap length of the prototype is measured
- The control electronics are placed in a noise canceling box connected to 1m tubing

Part 2: While performing pattern rating and identification

- Which pattern did you feel?
- How intense does the feedback feel? → Likert 1-7
- How comfortable does the feedback feel? → Likert 1-7

Part 3: Interview

1. What is your overall impression of the study?
2. What pattern felt most intense to you? Why or why not?
3. What pattern felt most comfortable to you? Why or why not?
4. How would you feel if a <u>friend</u> could touch you with such an actuation?
5. How would you feel if a <u>stranger</u> could touch you with such an actuation?
6. Do you see any applications in your day-to-day life for such a wearable?

User test 3: interview notes

Q1: What was your overall impression of the study?

1. Clear, did need some time to get used to it
2. Difficult, felt there was something, but somewhat difficult to translate to the graphs. At the start the feedback felt quite exciting
3. Overall it comes across as a prototype (little bit slow and loud). Somewhat more intense feedback compared to vibrations.
4. Difficult to rate pleasantness
5. Cool! Feels as if there are ‘feelings’ accompanying the feedback. Feedback has something spontaneous, fun experience. Short feedback felt more human and therefore more comfortable. But I had more difficulty feeling the pressure levels.
6. Difficult to give ratings. High pressure felt nice, like a massage
7. Everything felt fine. I didn’t feel much intensity. The sound was well isolated.
8. Funny. Feels quite natural. It feels kind of cool (nice). I did have to get used to it a little bit though.
9. Felt nice overall, especially the 3x short tap
10. Feels unique
11. Hard to distinguish pulses
12. First difficult to feel intensity. At first it felt like a located touch on the shoulder, later like something that rolls a bit over the shoulder. The intensity felt somewhat nagging, kinda of adhd-like characteristics.

Q2. What pattern felt most intense to you? Why or why not?

1. Decreasing in pressure
2. Constant intensity
3. Triple long ,long staircase down, reverse heartbeat. High pressures felt intense as well. Sudden high pressure also helped to make the feedback feel more intense
4. High pressure. Long staircase up is not too bad, Long staircase down felt more intense.
5. Short high pressure
6. Heartbeat forward, which also felt the most pleasant. Low pressure was not really noticeable, especially regarding the length of the pulse
7. Longer pulses with increasing pressure (long staircase up)
8. Faster increasing feedback with increasing pressure, which also felt more exciting to me
9. Long and high pressures
10. Long and high pressures (squeezing)
11. High initial pressure
12. High initial pressure such as heartbeat backward. (starts intense, later soft)

Q3. What pattern felt most comfortable to you?

1. Building in pressure, long hold times
2. Long staircase down
3. Increasing pressure. Fast might be nice. Maybe low high low
4. High pressure and increasing pressure
5. Short pulse
6. Difficult to say
7. They felt similar on this regard
8. Long/slow feedback with the same or decreasing pressure
9. Triple short
10. Fast increase in pressure buildup, followed by a decreasing pressure
11. Intense feedback felt more like a hug, which may be comfortable to me (high pressure)
12. Longer pulses

Q4. How would you feel if a friend could touch you with such an actuation?

1. Context is important. Unique interaction. Maybe intent is also important
2. Hard to imagine. Maybe during a difficult conversation this could be used to show support. During a normal conversation rather not. Overall the feedback is nice and makes the interaction feel more ‘real’ and ‘close’.
3. Weird. I would rather have something which would feel more like a handshake. But I don’t really see the need for such feedback
4. Convenient. However, I would like to know who would have touched me in such context.
5. Triple short or short staircase up would be nice. Could be fun or cool. Depends on my mood.
6. Depends on the context. Is is serious, calm, etc? Could be fun while gaming
7. Gives an extra dimension. Could be quite intimate.
8. Could be funny. I am not used to receiving a tap on the shoulder during a conversation.
9. Could be funny. Decent solution. Convenient.
10. I would consider it unpleasant. Would rather not have something like this
11. Why and at what moment? Who is this person? Maybe it is weird? Maybe it is okay depending on the moment (such as greeting someone).
12. Depends on who you’re calling with. A longer pulse could be comfortable

Q5. How would you feel if a stranger could touch you with such an actuation?

1. I wouldn’t want that. Especially the increasing pressure touches I’d rather avoid. Maybe a short pulse could be applicable
2. I wouldn't want that. I would probably be surprised by it
3. Maybe it has pros and cons. For intrusion it could be beneficial and low-effort. But there could also be misused. It could also be quite funny
4. For a presentation it could be beneficial. Other than that I am not sure
5. I think I would be okay with it. Feels more professional/distant to me compared to touch in real life
6. Depends on how well/little I know the person. If it is a complete stranger rather not
7. I would have to get used to it.
8. Bit weird. It is an active choice so that could influence my impression of the touch
9. Would be fine by me
10. Could be annoying
11. Maybe a bit weird.
12. Could be a funny way to acknowledge someone

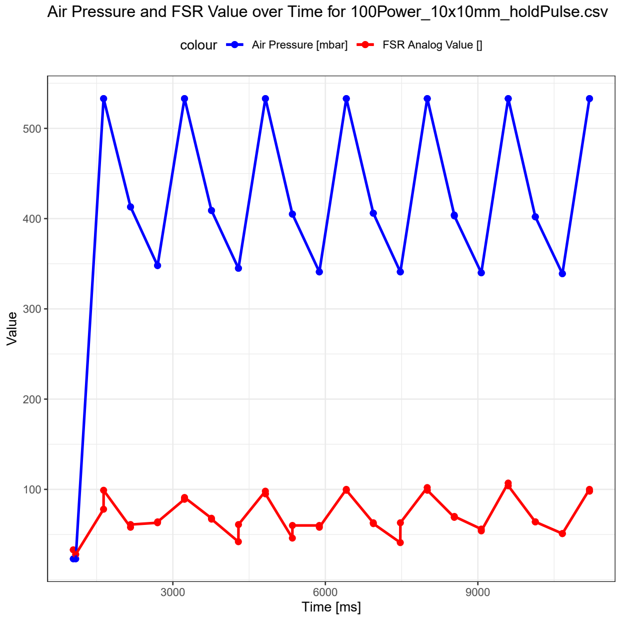
Q6. Do you see any applications in your day-to-day life for such a wearable?

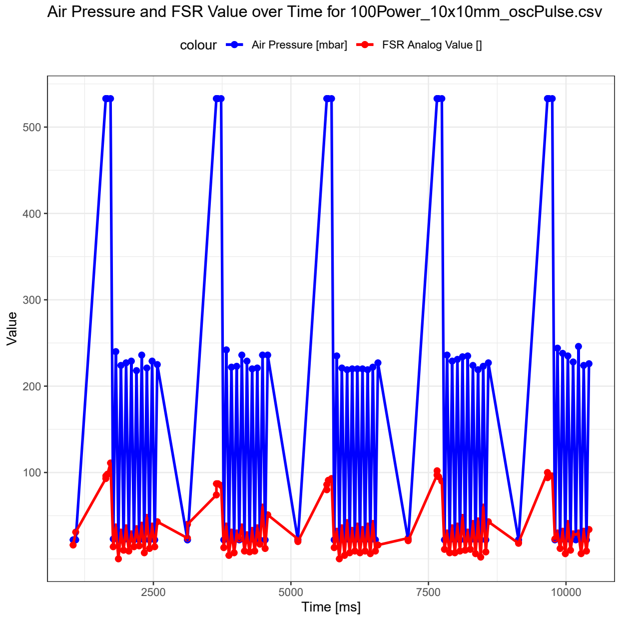
1. Interactive gaming
2. Long distance touch with friends and family who are abroad for example, to show support
3. Navigational purposes, notifications.
4. While running or cycling: navigation
5. Depends on the context. While I am studying it could be an alternative way to display smartphone notifications. Could be a study timer. Or maybe just for a shoulder massage
6. Maybe for long distance video calling social touch with my partner
7. More immersion during movies. Gaming.
8. Solve loneliness. Maybe while someone is quarantined to give social touch
9. Posture correction
10. Online gaming. Other than that I think seeing and hearing is fine for me.
11. Navigational purposes. Connecting to my dog to know how they feel
12. Presentation: notifying I would like to ask a question. Phone navigation (no vr glasses necessary). Supporting disabled people who have one hand. Sexual pleasure. Therapy.

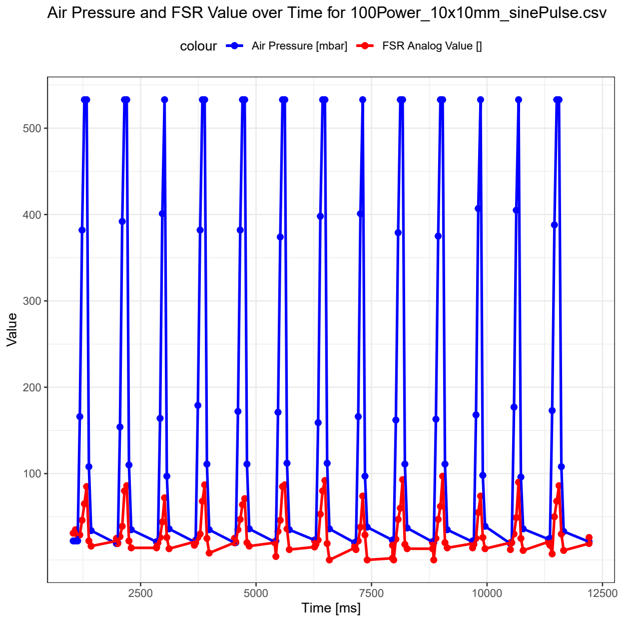
General data per participant

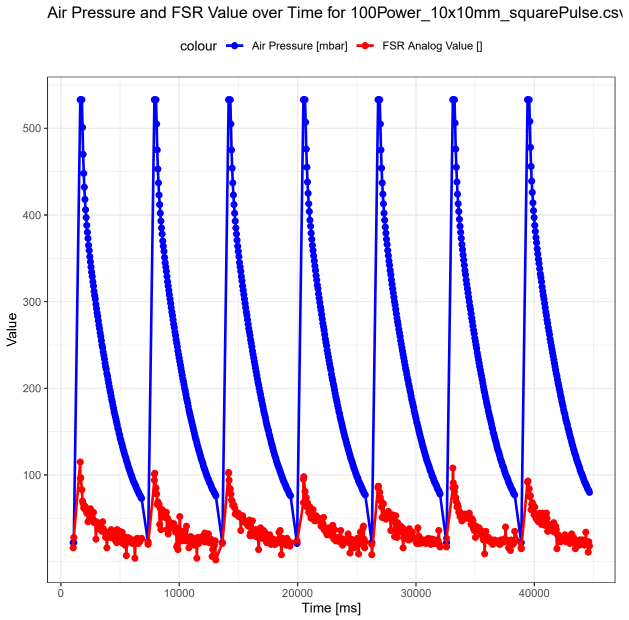
Participant No.	Gender	Age	Weight (kg)	Height (cm)
1	Male	26	70	170
2	Female	23	68	178
3	Male	25	77	182
4	Female	24	92	170
5	Female	24	62	177
6	Male	25	80	185
7	Female	25	58	163
8	Female	25	62	178
9	Female	18	60	173
10	Male	21	67	172
11	Female	25	70	180
12	Female	28	57	163

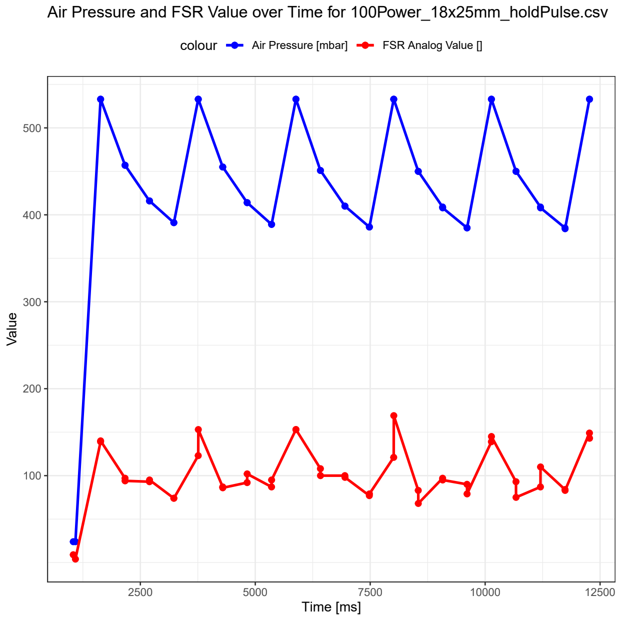
Appendix D: Benchmark

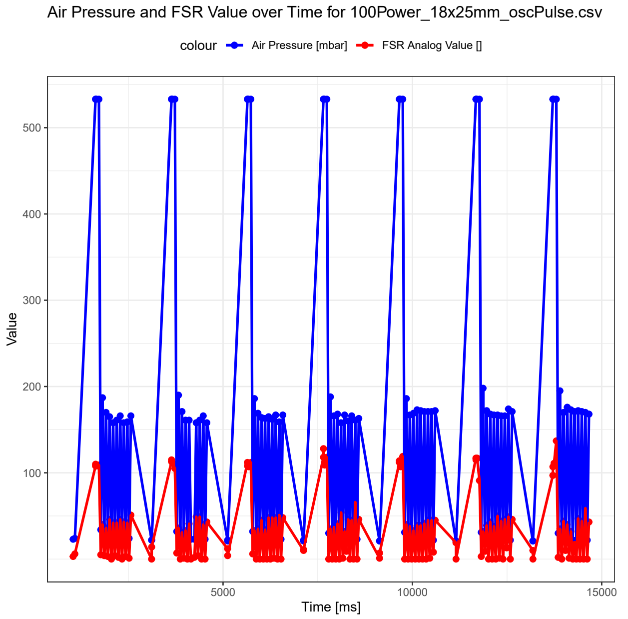


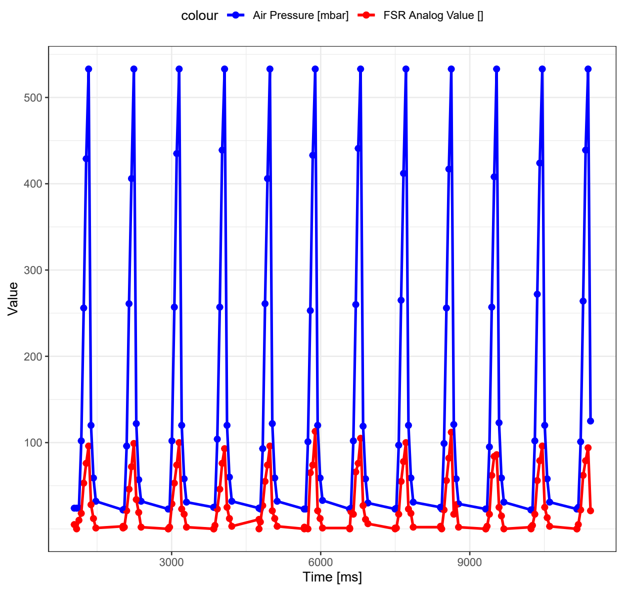








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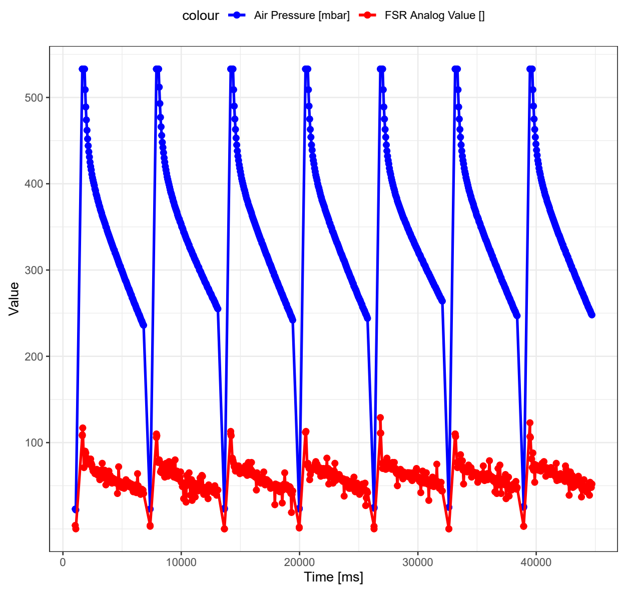
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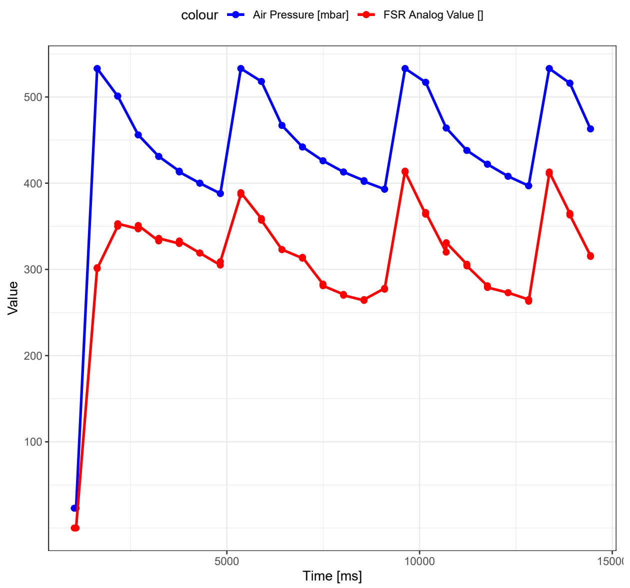
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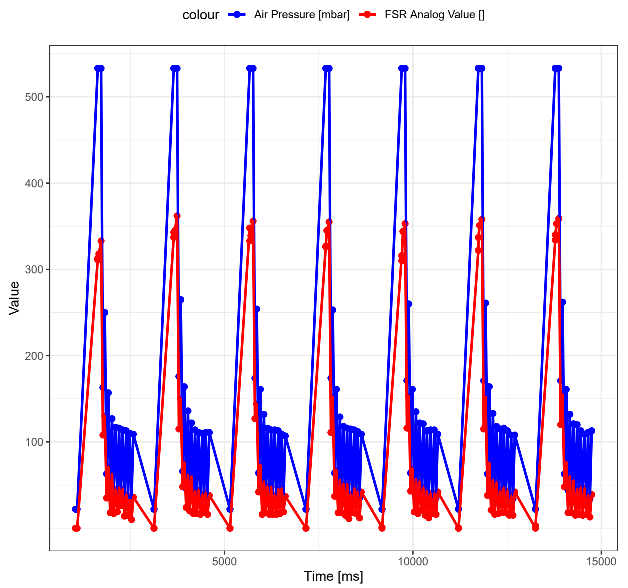
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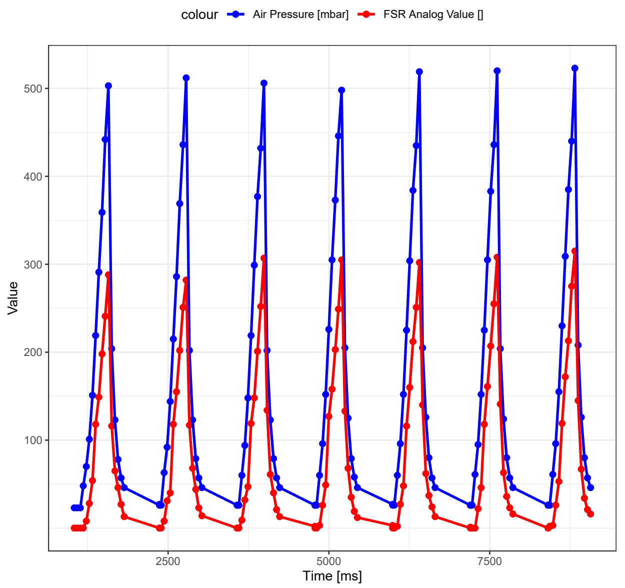
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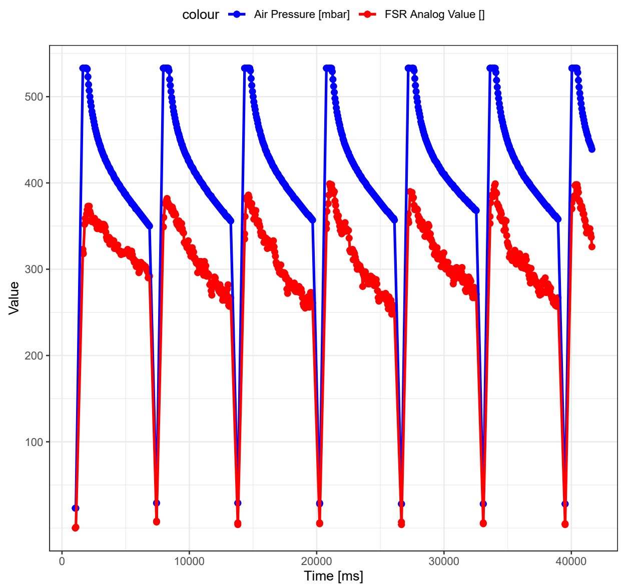
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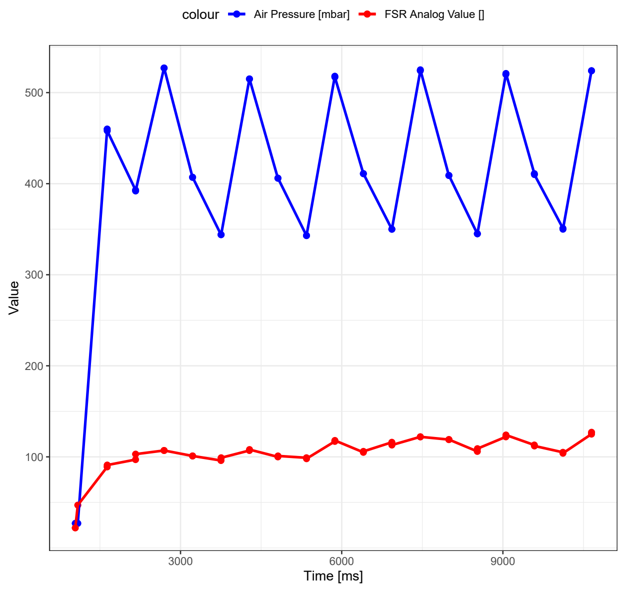
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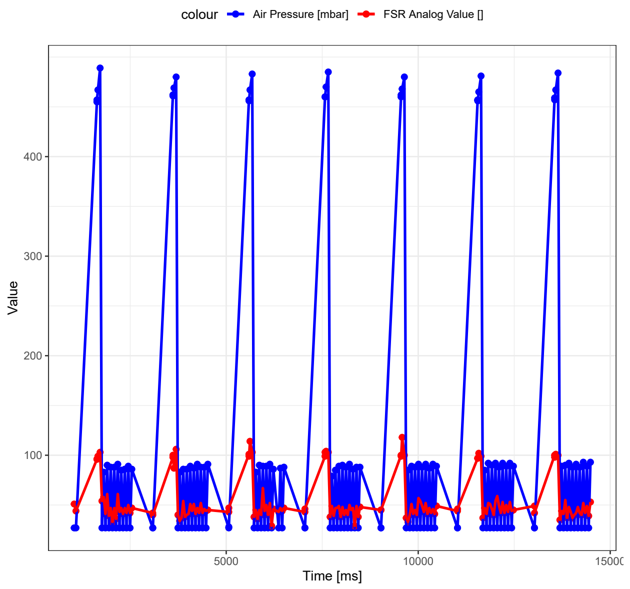
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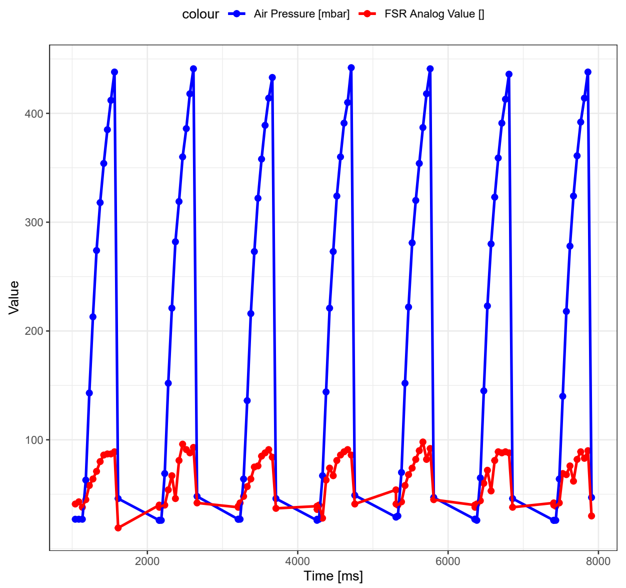
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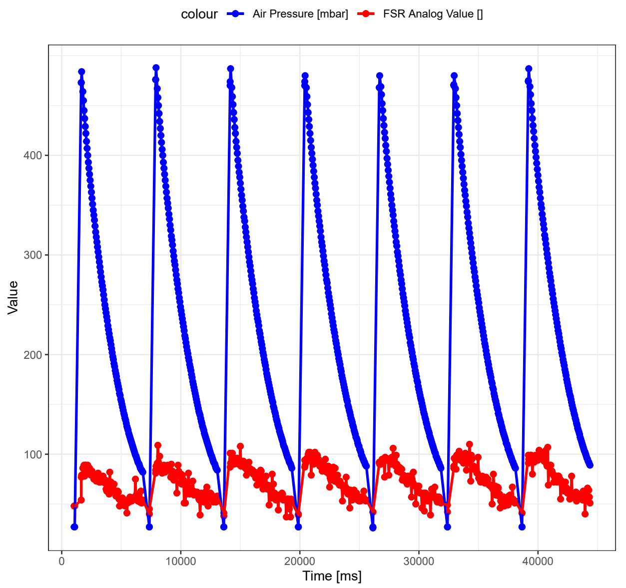
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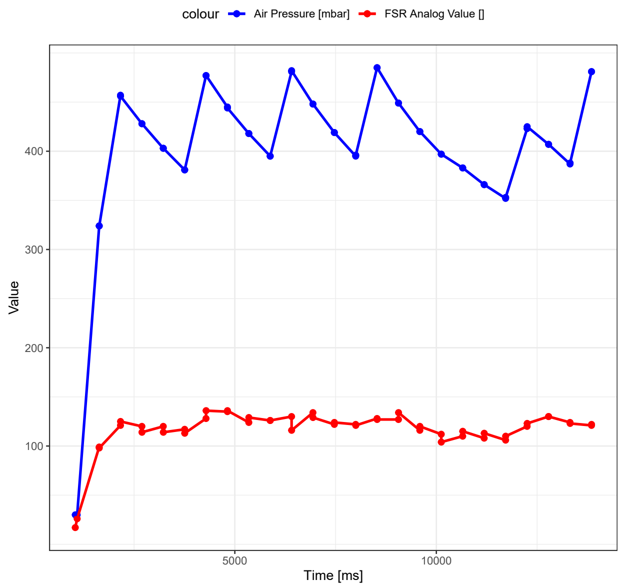
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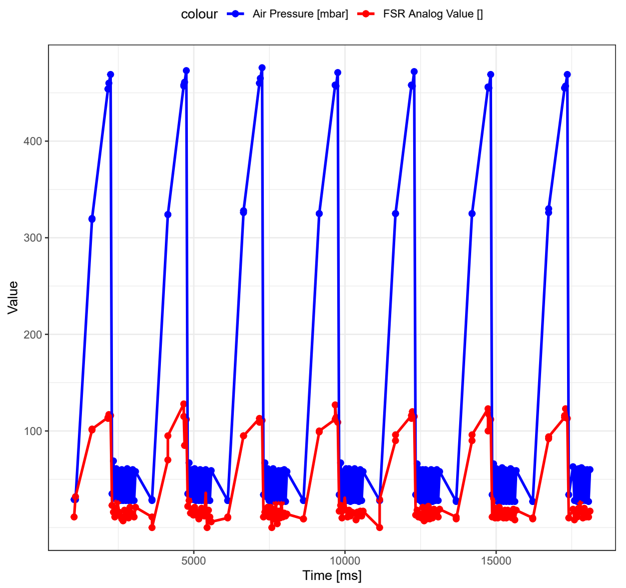
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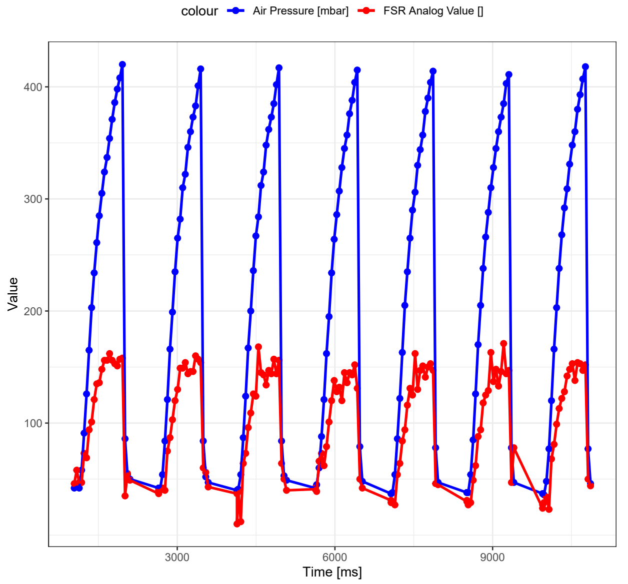
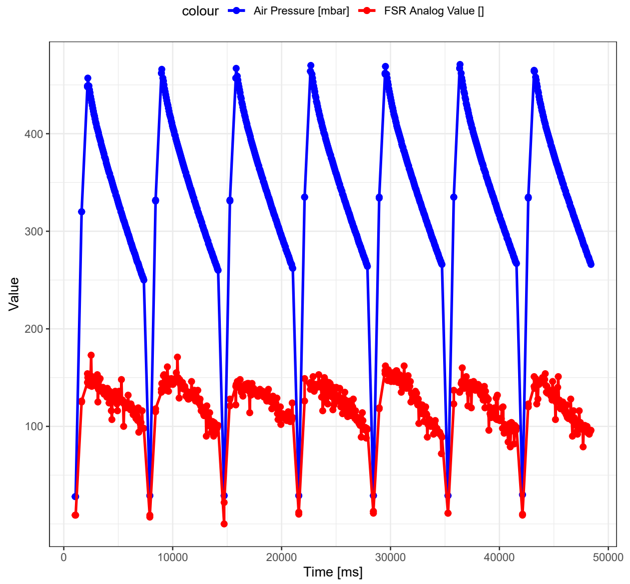
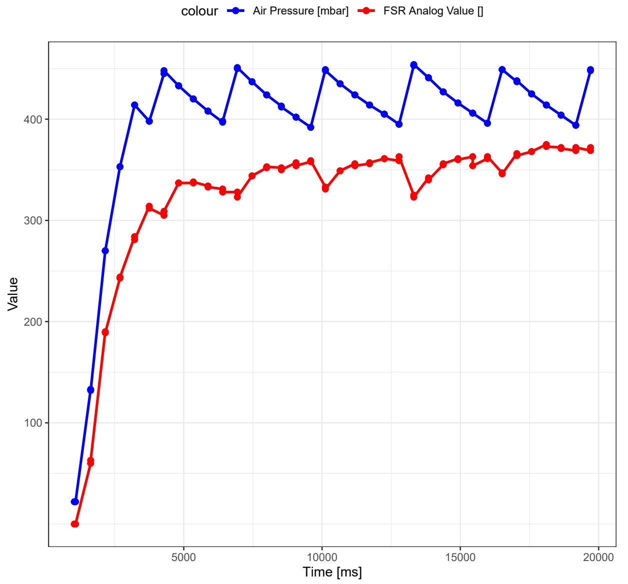


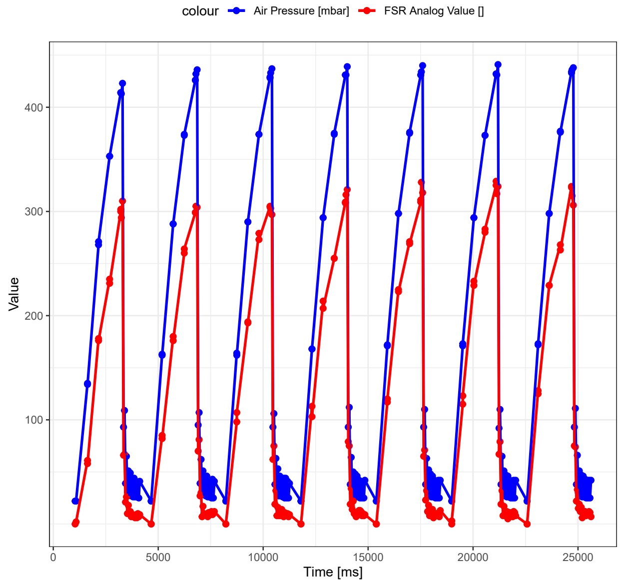
Air Pressure and FSR Value over Time for 30Power_18x25mm_squarePulse.csv



Air Pressure and FSR Value over Time for 30Power_35x35mm_holdPulse.csv



Air Pressure and FSR Value over Time for 30Power_35x35mm_oscPulse.csv



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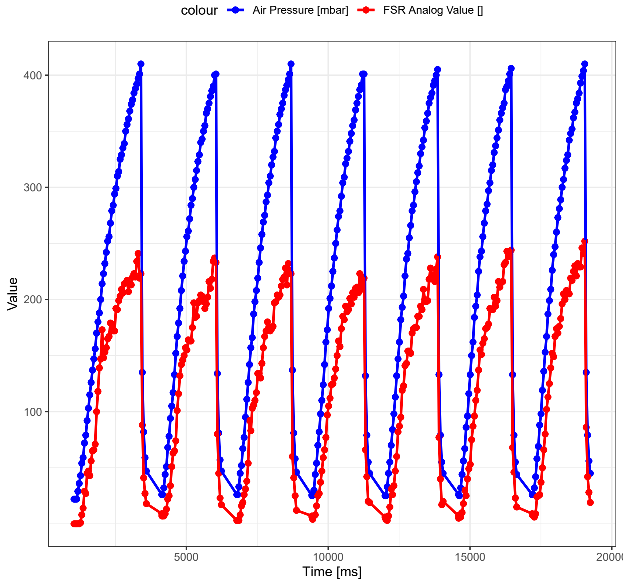

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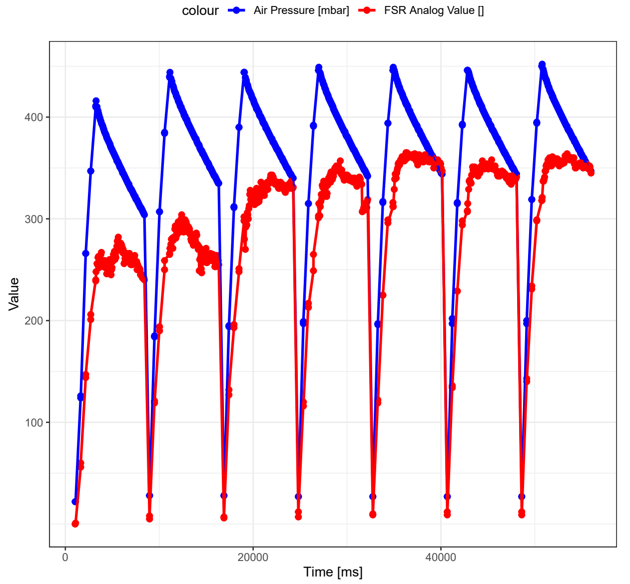
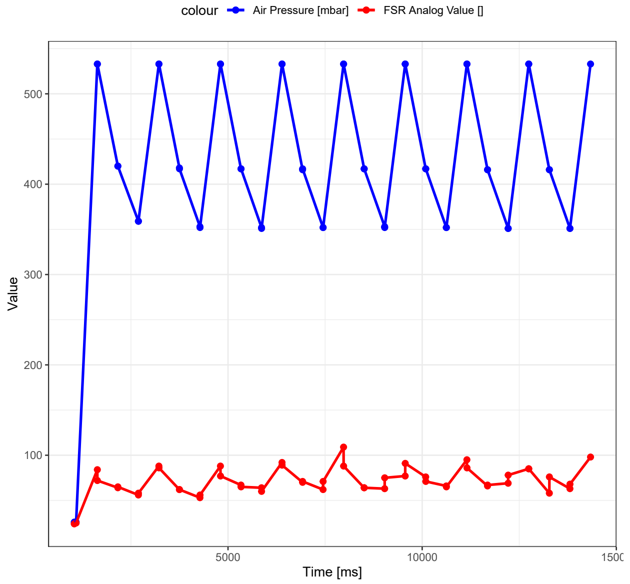


Air Pressure and FSR Value over Time for 65Power_10x10mm_holdPulse.csv



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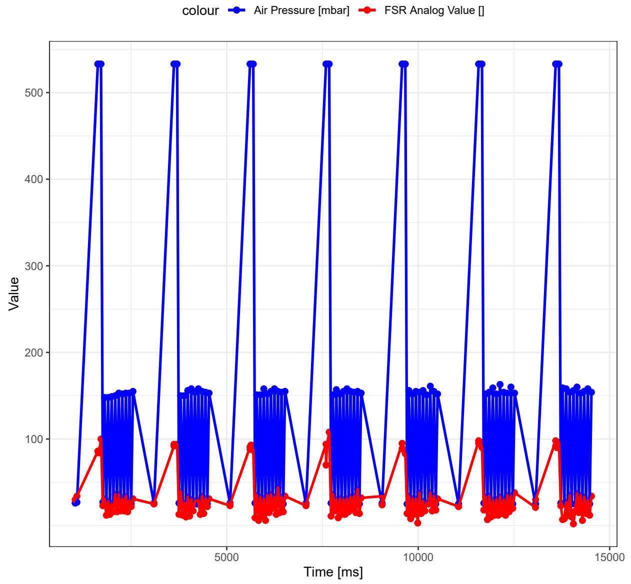

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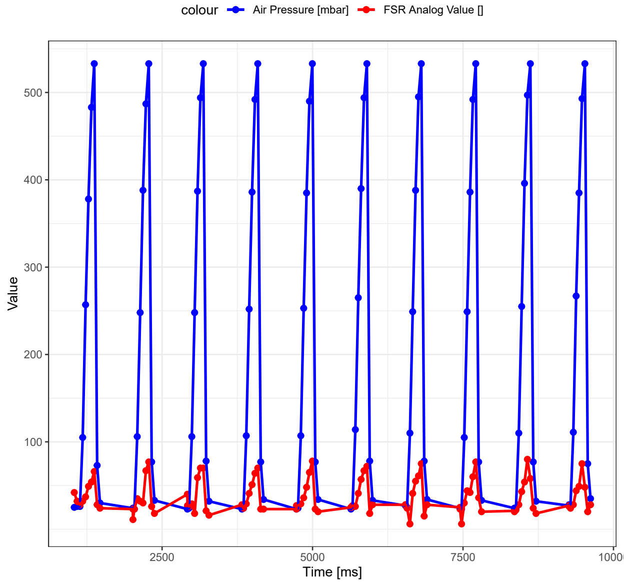

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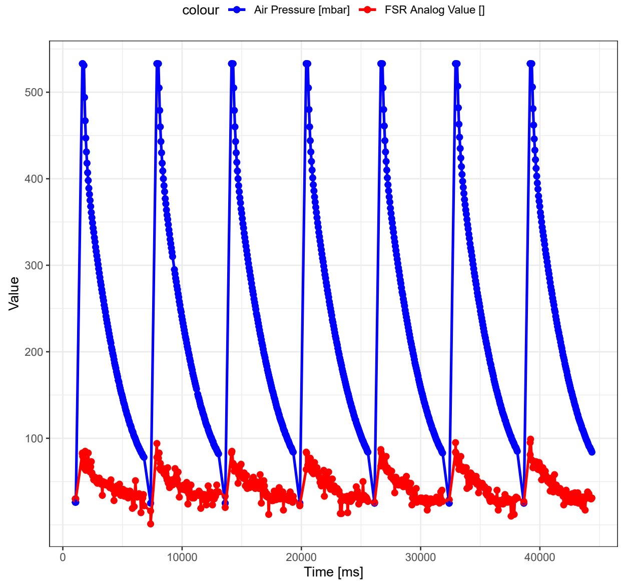

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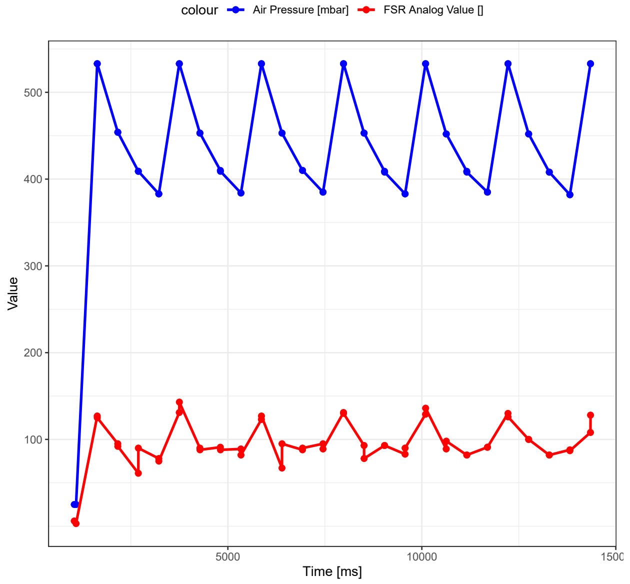

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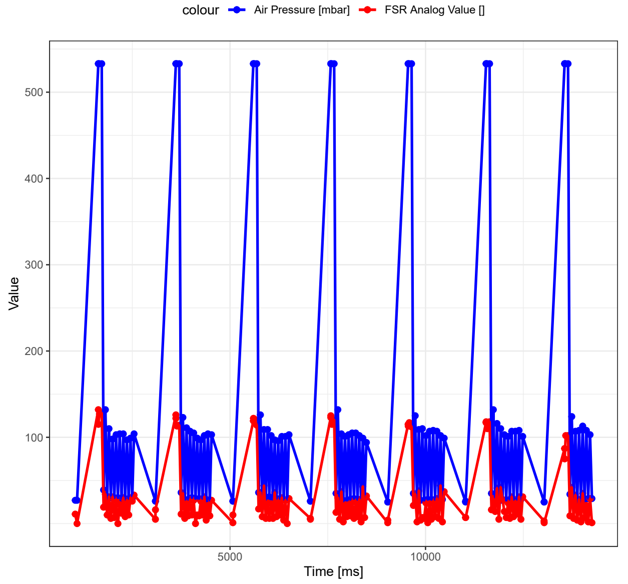
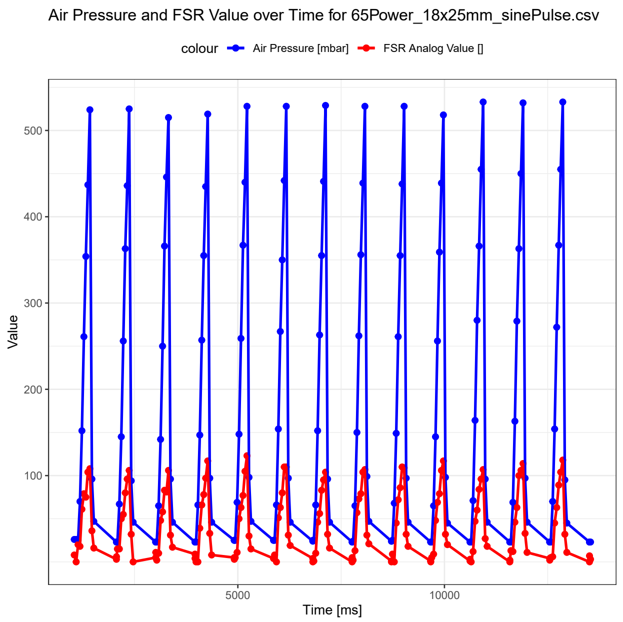
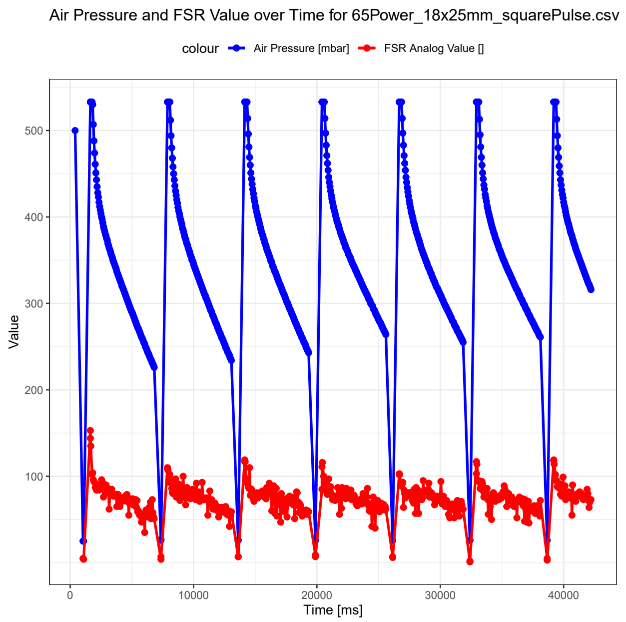



Air Pressure and FSR Value over Time for 65Power_18x25mm_sinePulse.csv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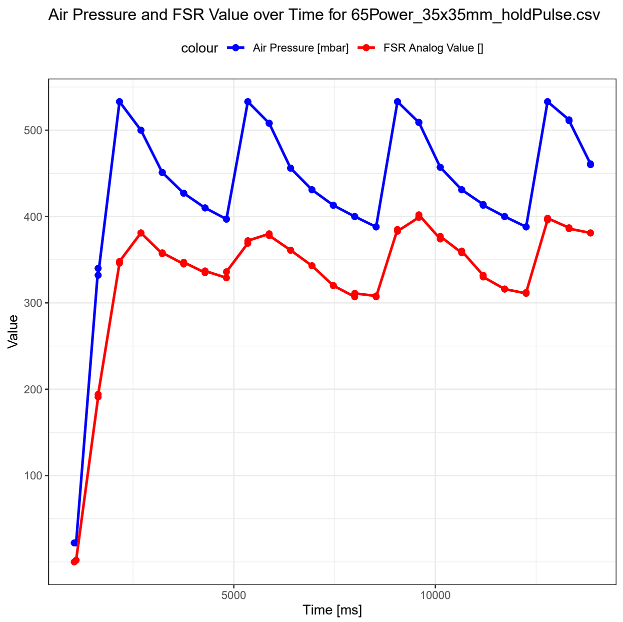
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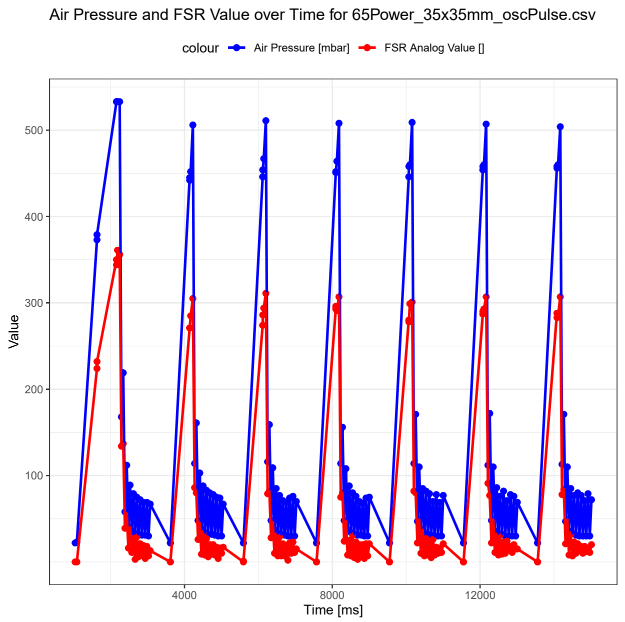
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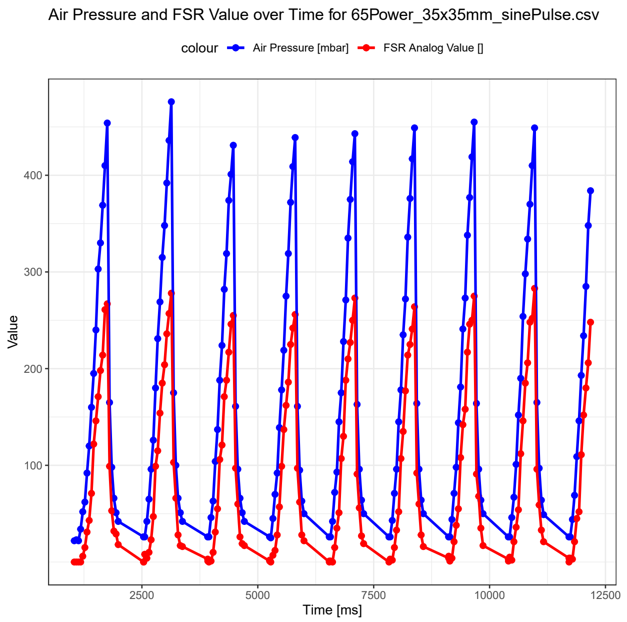
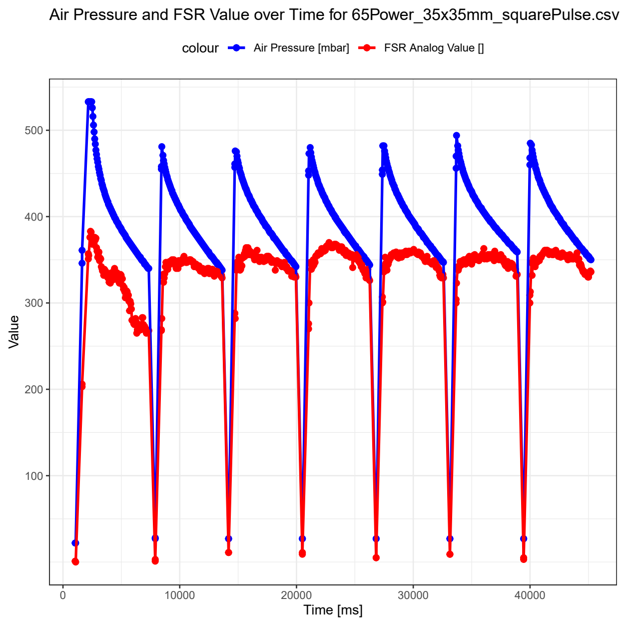

Air Pressure and FSR Value over Time for 65Power_35x35mm_sinePulse.csv


Air Pressure and FSR Value over Time for 65Power_35x35mm_squarePulse.csv