Degree Project in Computer Science and Engineering

Second cycle, 30 credits

Exploring the Design of Wearable Haptic Devices for Promoting Relaxation

Investigating Pressure-Based Haptic Feedback for Stress Reduction

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Degree Programme in Computer Science and Engineering
Date: April 3, 2025

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Swedish title: En utforskning av designen av bärbara haptiska enheter för avslappning
Swedish subtitle: Undersökning av tryckbaserad haptisk feedback för stressreduktion

Abstract

Wearable haptic devices are an emerging field within human-computer interaction, offering innovative ways to enhance user experience through tactile feedback. Despite advancements in wearable technology, limited research focuses explicitly on designing pressure-based haptic wearable devices to promote calmness and relaxation. This study addresses this gap by investigating the design and testing of two wearable haptic prototypes: a servo motor device and an inflatable device, delivering pressure stimulation to reduce stress and enhance relaxation.

The project applied Research through a Design approach, combining first-person experimentation and participatory design methods in iterative prototype development and refinement. In the final study, feedback from ten participants was gathered through workshops to assess comfort, relaxation efficacy, and user preferences for various pressure patterns. Quantitative analysis included statistical techniques such as the Wilcoxon Signed-Rank test and Pearson correlation analysis, while qualitative data provided insight into user experiences and design suggestions.

The results showed that both devices achieved high ratings for comfort and relaxation, although the inflatable device showed a slight tendency to enhance relaxation compared to the other devices. Preferences for wave-like and pulsating pressure patterns stressed the importance of dynamic stimulation. A significant correlation between comfort and relaxation existed for the servo motor device, which underlined that comfort plays a critical role in effective relaxation. User feedback underscored the value of ergonomic design, material choice, and customizable pressure patterns in wearable haptic technologies.

This study offers insights into the development of wearable haptic devices by outlining an approach to evaluate pressure-based feedback and highlighting key user-centered design principles. The results highlight the potential of such devices in applications ranging from stress management to therapeutic interventions. Future research could explore limitations such as sample size, testing environments, and objective physiological measures, paving the way for developing more robust and adaptable relaxation technologies.

Keywords

Wearable Haptic Devices, Relaxation Technology, User-Centered Design, Comfort and Relaxation Ratings, Pressure Pattern Preferences, Ergonomic Design, Dynamic Pressure Mechanisms

Sammanfattning

Bärbara haptiska enheter är ett framväxande område inom människa-datorinteraktion och erbjuder innovativa sätt att förbättra användarupplevelsen genom taktil återkoppling. Trots framsteg inom bärbar teknologi har begränsad forskning specifikt fokuserat på utformningen av tryckbaserade haptiska bärbara enheter för att främja lugn och avslappning. Denna studie adresserar denna kunskapslucka genom att undersöka design och testning av två haptiska prototyper: en servomotordriven enhet och en uppblåsbar enhet, som båda levererar tryckstimulans för att minska stress och öka avslappning.

Projektet tillämpade en forskningsmetod baserad på design (Research through Design") och kombinerade förstapersonsexperimentering med deltagardrivna designmetoder i en iterativ process för utveckling och förbättring av prototyper. I den avslutande studien samlades feedback in från tio deltagare genom workshops för att utvärdera komfort, effektivitet för avslappning samt användarpreferenser för olika tryckmönster. Kvantitativ analys inkluderade statistiska tekniker som Wilcoxons teckenrangtest och Pearsons korrelationsanalys, medan kvalitativa data gav insikter om användarupplevelser och designförslag.

Resultaten visade att båda enheterna uppnådde höga betyg för komfort och avslappning, även om den uppblåsbara enheten visade en viss tendens att förbättra avslappning i jämförelse med den andra enheten. Preferenser för vågliknande och pulserande tryckmönster betonade vikten av dynamisk stimulans. En signifikant korrelation mellan komfort och avslappning identifierades för servomotorn, vilket underströk att komfort spelar en avgörande roll för effektiv avslappning. Användarfeedback framhöll betydelsen av ergonomisk design, materialval och anpassningsbara tryckmönster inom bärbar haptisk teknologi.

Denna studie ger insikter om utvecklingen av bärbara haptiska enheter genom att beskriva ett tillvägagångssätt för att utvärdera tryckbaserad återkoppling och belysa centrala användarcentrerade designprinciper. Resultaten understryker potentialen hos sådana enheter inom tillämpningar som stresshantering och terapeutiska interventioner. Framtida forskning kan utforska begränsningar som urvalsstorlek, testmiljöer och objektiva fysiologiska mätningar, vilket banar väg för utvecklingen av mer robusta och anpassningsbara avslappningsteknologier.

Nyckelord

Bärbara Haptiska Enheter, Avslappningsteknologi, Användarcentrerad Design, Komfort- och Avslappningsbedömningar, Preferenser för Tryckmönster, Ergonomisk Design, Dynamiska Tryckmekanismer

Acknowledgments

First and foremost, I extend my deepest gratitude to my supervisor, Caroline, for her unwavering support, invaluable expertise, and constant encouragement throughout this research journey. Her insightful guidance was pivotal in shaping this project, and her mentorship gave me the confidence to overcome challenges.

I am also profoundly grateful to my examiner, Mats Nordahl, for his thoughtful feedback and constructive suggestions. His expertise greatly enriched the quality and depth of this work, and I sincerely appreciate the time he devoted to reviewing my research.

To my beloved family—Afram, Hilla, Shamoun, and Simel—thank you for your unconditional love, patience, and steadfast belief in me. Your encouragement has been my anchor in moments of doubt, and I am endlessly thankful for the strength you have given me.

I also wish to thank all my friends, especially George and Rabi, for their unwavering support and the stimulating discussions that kept me motivated during challenging times. Your friendship has been a constant source of inspiration and a joyful reminder that this academic journey was not walked alone.

Finally, I express my sincere appreciation to the participants of this study. Your willingness to contribute was indispensable, and your insights were invaluable to this research. Without your involvement, this work would not have been possible.

(Mark 12:11)

Stockholm, April 2025
Gabriel Staifo

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Chapter 1

Introduction

The Introduction chapter lays the foundation for studying the design and evaluation of wearable haptic devices, specifically tailored for relaxation and stress management. It first presents a background that includes the increasing demand for effective stress management solutions and haptic feedback in wearable technology. The Problem Statement identifies lacunae in current research and practical applications that make this study necessary.

The study's purpose is to investigate user-centered design, evaluate relaxation efficacy, and enhance wearable relaxation devices. The Goals specify objectives such as assessing relaxation and comfort ratings, understanding user preferences, and examining the relationship between comfort and relaxation.

An overview of the methodology introduces the Research-through-Design framework, complemented by qualitative methods such as participatory design, first-person documentation, and data analysis. The societal implications and potential benefits of wearable haptic devices for relaxation are discussed, highlighting their importance in tackling stress-related issues. The delimitations detail the study's scope: it focuses on short-term effects, user experience, and controlled environments, excluding long-term and real-world usability assessments.

Finally, the Structure of the Thesis outlines the organization of the document, guiding the reader through the literature review, methodology, results, discussion, and conclusion. This chapter concisely introduces the study, highlighting its relevance, objectives, and contribution to wearable haptic technology.

1.1 Background

In today's fast-paced society, stress has become a prevalent problem with serious consequences on both body and mind. The World Health Organization (WHO) estimates that stress-related disorders rank among the leading causes of disability worldwide while contributing to chronic conditions such as hypertension, cardiovascular diseases, and anxiety disorders[1]. These increasing stress levels demonstrate the urgent need for innovative, accessible solutions to induce relaxation and stress management. Wearable haptic devices, which rely on tactile feedback to simulate sensations like pressure and vibration, are a promising avenue for addressing this challenge.

Wearable technology has evolved from single-purpose fitness tracking to advanced devices that combine health monitoring with therapeutic interventions. One particularly promising application is using haptic feedback for relaxation and stress relief. Tactile stimulation, research indicates, activates the parasympathetic nervous system to induce states of relaxation while reducing cortisol, a biomarker of stress [2, 3]. Research demonstrating that tactile stimulation activates the parasympathetic nervous system and reduces cortisol levels supports the positioning of haptic devices as a non-pharmacological tool for stress management.

Besides the physiological benefits, wearable haptic devices also reflect the trend of personalized health. Modern consumers are increasingly interested in technologies that can serve their specific needs and preferences, thus enhancing their sense of autonomy over their well-being. Wearable haptic devices have great potential in this respect, considering their possible customization and adaptability. For instance, pressure patterns, intensity levels, and design features can be tailored to individual preferences, enhancing user satisfaction and efficacy [4]. Integrating these devices into daily life—whether at work, during commutes, or at home—further underscores their potential to become indispensable tools for managing stress.

1.2 Problem Statement

Despite developments in wearable technology, very few research studies have focused on developing haptic devices for relaxation. Much research in wearables is centered around fitness tracking, general health monitoring, or rehabilitation systems [5, 6]. Although practical, such uses do not answer the increasingly important need for technology with mental health at the forefront. Without substantial empirical evidence regarding the efficacy of haptic devices in promoting relaxation, there is a noticeable literature gap that substantially reduces further efforts toward optimized designs and applications. Moreover, aspects like desired pressure patterns or preferences over device aesthetics are seldom focused on in user research and often narrow down the adaptability of these devices.

Considering the identified gap, here comes a relevant research question from this work: "*How can wearable haptic devices be designed to promote relaxation through pressure stimulation?*."

By comparing two different haptic devices—a servo motor device and an inflatable device—this research aims to provide valuable insights into the design features and user experiences contributing to effective stress management solutions.

1.3 Purpose

This thesis aims to explore the design and evaluation of wearable haptic devices specifically aimed at promoting relaxation. This research investigates two distinct types of actuation—one using servo motors and the other an inflatable mechanism—to identify the key factors influencing user comfort, relaxation effectiveness, and general usability. These findings add to exploring accessible and non-pharmacological means of stress management, addressing the ever-growing need in today's fast-paced society.

Beneficiaries and Impact

1. Device Users:
   (a) This study's findings will help individuals find new ways of relieving stress and give recommendations on how to have more functional and comfortable wearable devices.
2. Researchers and Developers:
   (a) These findings will help researchers and product developers understand the user's preferences for pressure patterns and design

features, which are input to the development and advancement of haptic technology.

3. Healthcare Sector:

   (a) This research may support the integration of wearable devices into therapeutic contexts and offers a potential complement to traditional treatments for stress-related conditions, such as anxiety or post-traumatic stress disorder (PTSD).

Broader Considerations

1. Ethical Implications:

   (a) The study prioritizes ethical practices by adhering to user-centered design principles, including obtaining informed consent, ensuring participant comfort during testing, and safeguarding the privacy and confidentiality of user data.

2. Sustainability:

   (a) Wearable devices must consider the environmental impact of materials and production processes. This study pinpoints how future device design might incorporate sustainable materials and energy-efficient mechanisms.

3. Social and Accessibility Implications:

   (a) By focusing on usability and comfort, the study furthers the accessibility of relaxation technologies to a wider group of people with limited mobility or who experience high-stress levels in demanding environments.

1.4 Goals

The primary objectives of this study are achieved through a combination of Research-through-Design (RtD) and quantitative methodologies. These approaches collectively ensure a holistic exploration of the design, development, and evaluation of wearable haptic devices for relaxation. The specific goals are as follows:

1. Develop Functional Wearable Haptic Devices for Relaxation: Utilize iterative prototyping through the RtD process to design and refine two functional devices (servo motor and inflatable devices) that balance comfort, usability, and relaxation efficacy.

2. Evaluate Comfort and Relaxation Efficacy: I employed quantitative methods to measure each device's perceived relaxation and comfort. The study collects standardized user ratings to identify which device provides a superior relaxation experience, contributing to evidence-based insights.

3. Understand User Preferences for Pressure Patterns: Leverage RtD and participatory design to investigate preferences for different haptic pressure patterns, including constant, pulsating, and wave-like. This exploration informs future design decisions to enhance user satisfaction and adaptability.

4. Investigate Correlations Between Comfort and Relaxation Ratings: Employ quantitative analysis to study the relationship between comfort and relaxation ratings for each device. This investigation, complemented by insights from the RtD process, provides a deeper understanding of how perceived comfort influences the effectiveness of haptic stimuli in promoting relaxation.

By integrating iterative prototyping through RtD with robust quantitative analysis, this study bridges the gap between theoretical design principles and practical applications, fostering innovation in wearable haptic technologies for relaxation.

1.5 Research Methodology

This study employs a Research-through-Design (RtD) methodology, enhanced by qualitative methods and a user-centered research approach. This combination enables the study to navigate between hands-on design practices and empirical research, exploring the design and evaluation of wearable haptic devices for relaxation. The methodology incorporates iterative prototyping, first-person documentation, participatory design, and qualitative analysis, offering insights that bridge the gap between theoretical knowledge and practical applications in design and human-computer interaction.

The research is guided by a constructivist paradigm, assuming that knowledge is co-created through interactions between the researcher, participants, and the research context. This paradigm aligns with the RtD approach, emphasizing iterative design processes as a means to develop knowledge. By integrating subjective experiences, user feedback, and researcher reflection, this study adopts a holistic perspective that captures the interplay between design, user experience, and relaxation efficacy.

Research Methods:
The methodology consists of the following key components:

- First-Person Testing and Iteration: During this phase, I assumed the user's role in identifying design flaws and usability issues through systematic self-documentation. This approach enables early identification of design flaws and usability issues by documenting personal experiences and systematically iterating on prototypes. Such work can be effectively conducted well before involving any external participants, allowing the researcher to gain firsthand insights into the design of the devices.

- Participatory Design: In the second phase, participatory design sessions with college students offer direct user feedback on the refined prototypes. These one-on-one sessions provide valuable insights into user experiences, preferences, and the effectiveness of the devices in promoting relaxation. In contrast to the first phase, this step emphasizes evaluation rather than further iteration, ensuring that the project stays focused on delivering a deployable design.

- Research-through-Design (RtD): The overarching methodology integrates the iterative and exploratory processes of RtD, addressing complex design problems while simultaneously generating new knowledge.

- Qualitative Analysis of Participant Feedback: The feedback collected during participatory design sessions is analyzed to identify user preferences, evaluate usability, and assess the devices' relaxation impact.

This phased approach combines first-person and participatory design methods, ensuring a comprehensive exploration of wearable haptic devices for relaxation. While first-person testing provides foundational insights and iterative refinement, participatory design extends the evaluation to real-world applicability, bridging the gap between researcher perspectives and target user experiences.

The primary methodology utilized in this study is Research through Design (RtD), as it effectively blends theoretical and practical problem-solving within an applied design context. Given the complexity of this user-centered domain, there is a distinct requirement for iterative prototyping and feedback cycles that are integral to RtD, particularly in the realm of wearable haptic devices.

Qualitative methods were chosen to enhance the Research through Design (RtD) approach. They offer a comprehensive understanding of user experiences that are critical to assessing comfort, relaxation, and usability. This choice aligns with the study's objectives, which focus on evaluating devices and integrating user preferences into the design process.

Rationale for Chosen Methods:
While alternative methods, such as experimental or survey-based approaches, were considered, they were deemed less suitable for this study's goals.

- Quantitative Experimental Designs:
  - In such methodologies, the emphasis is usually on hypothesis testing and objective measurements that cannot detect the subtleties in participants' subjective experiences [7]. While applicable in other contexts, such methods are not well-suited to deliver the in-depth insights this user-centered design study calls for.
- Survey-Based Research:
  - While surveys can collect broad user feedback, they lack the iterative and participatory elements of RtD. Without direct participant involvement in the design process, surveys would not elicit the rich, actionable insight required to inform prototype creation and iteration [8].

By adopting a dual-phased approach integrating RtD, first-person testing, and participatory design, this study ensures a holistic understanding of user-centered design. It contributes actionable insights for the development of wearable haptic devices that effectively promote relaxation.

1.6 Societal Context and Impact

As discussed in the background, regarding increasing stress and anxiety in modern society, with a consequent dire health and financial impact (WHO; Chandola et al., 2006), this thesis addresses this urgent need for low-cost non-pharmacological interventions by discussing the design and effectiveness of wearables haptic devices for stress relief. The project contributes to the overall cause of mental health promotion and quality of life improvement by providing information and design recommendations for customized, portable stress reduction devices that may be incorporated into everyday lifestyles.

1.7 Delimitations

This study was designed to investigate wearable haptic devices that promote relaxation specifically; therefore, this study was developed under specific scope and with well-defined boundaries for a concentrated study. The following are the research delimitations:

- Scope and Boundaries:
  - The research targeted two kinds of wearable haptic devices: a servo motor and an inflatable device. These devices were selected based on their unique method of generating haptic feedback.
  - The research focused on user experience, focusing more on comfort and perceived relaxation efficacy than long-term physiological effects.
- Participants:
  - The participant pool was limited to relatively homogeneous adult college students. This controlled variability in user experiences but limited the generalizability of the findings.
- Testing Environments:
  - All tests were conducted in a controlled laboratory environment for consistency in data collection. Real-world test scenarios in workplaces or public spaces were not considered.
- Time Frame:

- The study focused on the short-term use of the devices and assessed participants' immediate feedback. Long-term efficacy or device usage patterns were beyond this study's scope.

- Methodology:
  - Data collection depended on self-reported measures, such as user ratings on a 1–10 scale, without objective physiological measures, such as heart rate variability or cortisol levels.
  - The research design was comparative, focusing on user preferences and device performance without being a randomized controlled trial.

1.8 Structure of The Thesis

The structure of this thesis is organized into different chapters, each addressing a critical aspect of the research process. Below is an overview of the content of each chapter:

- The **Background chapter** 2 presents the foundational concepts and recent advancements in wearable haptic technologies, focusing on their applications in domains like healthcare, gaming, and virtual reality. It highlights the psychological impact of pressure stimulation on relaxation and user responses while identifying gaps in existing research. Statistical methods and prior studies are also discussed to establish the basis for this study's methodological approach.

- The **Methodology chapter** 3 discusses the methodology employed in this research, the approach of Research through Design, the development of prototypes, and the collection of data. The rationale for the use of mixed methods, both qualitative and quantitative, in testing the devices is also discussed.

- The **Design and Development Process chapter** 4 describes the iterative design to develop the two prototypes, one with servo motors and the other with inflatable devices. It talks about design decisions, challenges, and refinements that were made to balance functionality with user comfort.

- The **Results and Analysis chapter** 5 provides quantitative and qualitative findings. It includes Statistical analyses of ratings regarding comfort and relaxation, preferences concerning pressure patterns, and user feedback. The collected data provides a rather detailed interpretation of the devices' performance.

- The **Discussion chapter** 6 interprets the findings in the context of the research objectives and the broader field of wearable technology. It explores the implications of the results, evaluates the strengths and limitations of the study, and suggests recommendations for improving future device designs.
- Lastly, the **Conclusions and Future Work chapter** 7 reflects upon the research achievements by summarizing the key insights and contributions. It discusses the limitations, suggests areas for further research, and provides recommendations for advancing wearable haptic technology.

1.9 Writing Style

This thesis adopts a mixed writing style to reflect the dual roles of the researcher in this study. First-person narration is used in sections related to the Research-through-Design (RtD) methodology, emphasizing the researcher's active role in iterative prototyping, self-testing, and personal reflections. In contrast, third-person narration is employed in sections presenting general findings, statistical analyses, and theoretical discussions to maintain an objective academic tone. This approach ensures clarity and aligns with the dual methodological focus of the study.

Chapter 2

Background

2.1 Introduction to Wearable Haptic Devices

2.1.1 Wearable Haptic Devices

Wearable haptic devices have emerged as a significant area of research in human-computer interaction, offering innovative ways to enhance user experiences with enriched tactile feedback. These devices can be attached to different body parts to stimulate pressure and other haptic technologies that supply sensory information. For example, a comprehensive review of wearable haptic systems for the fingertip and hand is presented by Pacchierotti et al., including applications related to virtual reality, teleoperation, and medical interventions [9].

The versatility of wearable haptics extends into domains such as fitness tracking, medical rehabilitation, and immersive gaming. Choi and Kuchenbecker [10] illustrate how vibrotactile feedback in wearable devices can enhance user performance in motor learning tasks, while Kapur et al. [11] explore wearable haptic systems for gait retraining in patients with movement disorders. Similarly, Wang et al. [12] investigate lightweight, unobtrusive haptic wearables that integrate seamlessly into daily life, addressing challenges like power efficiency and user acceptability. These developments signal a future where haptic feedback is fully integrated into technology interaction, enhancing sensory experiences in both virtual and physical worlds.

As the field progresses, contemporary wearable haptic devices have transitioned from experimental prototypes to commercially available products.

The precision of vibrations, exemplified by the Apple Taptic Engine, aligns seamlessly with the broader exploration of haptic feedback integration within mobile devices. Pasquesi and Gorlewicz introduce the concept of multi-touch vibrations, which, in contrast to single-point feedback, can generate spatially dynamic and multi-dimensional tactile experiences. This advancement enriches user interaction by providing more robust and versatile haptic feedback mechanisms [13]. As a result, it has established a benchmark for haptic feedback in wearable technology, demonstrating how tactile interaction can enhance usability and elevate user satisfaction.

Similarly, wearable haptic devices represent a very advanced application of force-feedback technology in MR. The wearable system proposed by Kudry and Cohen [14] enhances immersion with realistic, high-fidelity, tactile sensations while interacting with virtual objects by freely moving their hands or other body parts in any direction and smoothly integrating these with pass-through MR. Such progress will revolutionize gaming and entertainment and have significant implications in areas like training simulations, remote collaboration, and rehabilitation therapy.

2.1.2 Historical Context of Wearable Haptics

Wearable haptic devices represent thriving research and application, rooted in early explorations of tactile interaction within human-computer interaction. The concept of haptic feedback emerged from the need to simulate the sense of touch in virtual and physical environments, and early studies focused on force-feedback systems used in teleoperation and robotics [15]. These foundational efforts paved the way for miniaturized, wearable applications as advancements in materials science and electronics enabled the integration of haptics into compact, body-worn devices.

One of the first important events to mark the timeline in wearable haptics was the inclusion of vibrotactile actuators, which presented users with tactile cues in portable formats. Initial applications of these systems include assistive technology for people with visual impairments in their navigation [16]. In wearable haptics, as technology has evolved, this area has seen various other mechanisms: pressure stimulation, vibrotactile feedback, and electro-tactile stimulation-which contribute toward extensive applications in health care, gaming, and communication.

2.1.3 Somaesthetics and Embodied Interaction

Somaesthetics is one theoretical framework that underlines somatic awareness and body well-being; it is especially underlined when designing wearable technology. When integrated into designing a device, it develops instinctive, meaning-developing interactions that better place the user in his relationship with his body. Its application has been implicated across varied areas: In designing wearables fashion, it connects aesthetics with functionality for well-being [17].

2.2 Pressure Stimulation and User Responses

2.2.1 Psychological Theories Supporting Pressure Stimulation

Pressure stimulation has been shown to impact the parasympathetic nervous system, which promotes relaxation and reduces stress. For example, weighted blankets or compression garments have been associated with lower cortisol levels and increased serotonin production, thereby creating a calming effect [18, 19]. Such findings correspond with theories on sensory integration, which suggest that tactile input helps regulate the nervous system in cases where an individual has heightened stress or anxiety.

2.2.2 Factors Influencing User Responses

Various factors influence individual responses to pressure stimulation:

- Age and Gender: Women and younger individuals often report higher sensitivity to tactile feedback, which can influence their comfort with haptic devices [20].
- Cultural Differences: Societal norms around touch and personal space affect how users perceive pressure stimulation. Burleson et al. highlights that cultures with a higher tolerance for physical touch often show greater acceptance of pressure-based therapies [21].

2.2.3 User Experience and Individual Differences

Individual differences in comfort with touch and preferences for specific pressure patterns often influence the effectiveness of pressure therapy devices.

Research on the Automatic Inflatable Deep Pressure Therapy (AID) Vest found a significant relationship between comfort with social touch and reductions in self-reported anxiety [22]. These findings point to the need for pressure therapy technologies to be tailored to individual needs, ensuring that devices are practical and comfortable for diverse users.

2.2.4 Statistical Methods for Analyzing User Responses

Data analysis, both quantitative and qualitative, plays an important role in interpreting the user response to pressure stimulation delivered through wearable haptic devices. The use of robust statistical methods assures the reliability and validity of results, thus enabling the researchers to interpret user feedback, identify meaningful patterns, and draw evidence-based conclusions about the effectiveness of devices.

1. Shapiro-Wilk Test: The Shapiro-Wilk test tests the normality of distributions in datasets, such as ratings of relaxation and comfort. This test is fundamental in choosing which statistical test is appropriate. For example, many parametric tests, including the Pearson correlation, require normality assumptions. The Shapiro-Wilk test is especially suited to small sample sizes, as will be used here [23].

2. Wilcoxon Signed-Rank Test: This non-parametric test was utilized to compare paired data points-for example, the relaxation ratings associated with two different wearable devices, such as a servo motor and inflatable. Because this test does not require a normal distribution of data, it is very suitable for subjective ratings because one can never assume that those might come out of a normal distribution [24].

3. Chi-Square Test: The chi-square test is applied to examine relationships between categorical variables [25]. This test helps determine whether observed differences in preferences are statistically significant, offering insights into how users respond to various pressure stimuli.

4. Pearson Correlation Analysis: This involves a Pearson correlation coefficient for measuring the strength and direction of a linear relationship between two continuous variables [26]. Such determinations are crucial in knowing the way perceived comfort impacts relaxation effectiveness.

These are essential statistical tools in analyzing user responses to ensure the extraction of the subtle relationship between pressure stimulation and user experience. The research work, using the methods mentioned above, may provide a systematic evaluation of wearable haptic devices and help in their design in the future.

2.3 Methods and Mechanisms of Applying Pressure

2.3.1 Historical Context of Pressure Therapy

The idea behind pressure therapy is not new; weighted garments were used in the earliest times, as this can soothe a person's nerves and, therefore, calm the individual. A modern-day application would include weighted blankets, for instance, as this approach shows effectiveness in practice, as far as reducing anxiety and sleep improvement are concerned [27].

2.3.2 Methods of Applying Pressure

Several methods have been developed to deliver pressure stimulation, each with distinct benefits and applications. Weighted blankets provide all-over body pressure and have been associated with reduced anxiety and improved sleep quality [28]. Pressure vests, such as those studied by Grandin [19], apply targeted pressure to the torso and have been used in therapeutic settings. Inflatable devices, like the Automatic Inflatable Pressure Therapy (AID) Vest [29], offer portability and customizable pressure levels, making them versatile tools for deep pressure stimulation.

2.3.3 Technological Advancements in Pressure Therapy

Recent advancements in wearable technology have led to the development of more sophisticated pressure stimulation devices. Examples include the Snug Vest [30], the Hug Sleep Pod Move [31], and the AID Vest [22]. These devices are designed to deliver controlled, adjustable pressure, offering personalized interventions that cater to various user preferences and needs.

2.3.4 Future Trends in Pressure Mechanisms

Developments in both artificial intelligence and machine learning enable the development of adaptive pressure. Wearable soft robotic actuators with integrated biometric sensors that continuously monitor signals like heart rate or skin conductivity could also continuously update pressure levels according to an appropriate model for response [32]. Such approaches allow real-time personalized intervention, significantly improving wearable pressure therapy devices.

2.4 Pressure Application Sites

2.4.1 Body Positions for Pressure Application

The effectiveness of pressure stimulation often depends on the area of the body where it is applied. Common areas include:

- Torso: Using vests or weighted blankets.
- Limbs: Through compression garments or sleeves.
- Whole body: With tools like weighted blankets.

Studies suggest that applying pressure to larger areas, such as the torso, yields more significant calming effects than targeting smaller regions [22, 30].

2.4.2 Expanding Applications of Pressure on Limbs

While most research targets the torso, recent work emphasizes the potential of limb-based pressure devices. For instance, compression sleeves, which help athletes increase their blood flow and decrease fatigue, might be an example of broader applicability in relaxation and performance enhancement [33].

2.4.3 Emerging Research on Targeted Pressure

Targeted pressure application to specific muscle groups or acupuncture points has recently gained much interest. For example, Lee et al. reported significant improvement in relaxation and emotional response with deep pressure applied to the brachioradialis muscle [34]. These findings suggest that targeted pressure may combine benefits from traditional therapeutic practices with the convenience of wearable technology.

2.4.4 Studies on Pressure Application to the Arm

Pressure stimulation applied to the arms has been the focus of recent research. For example:

- Lee et al. [34] examined the effects of deep pressure on the brachioradialis muscle in the forearm, finding that deep compression at trigger points elicited stronger sensory and emotional responses compared to control points.
- Case et al. [35] investigated the perceived gentleness of compression sleeves, finding the most positive responses at a pressure of 70 mmHg.

These studies indicate that the arm is a viable and effective site for applying pressure, particularly in wearable devices designed for relaxation.

2.5 Challenges in Wearable Haptic Design

Wearable haptic devices face several challenges, including:

- Ergonomic Constraints: Ensuring comfort for prolonged use while maintaining functionality [9].
- Power Efficiency: Addressing the need for extended battery life without compromising device performance [36].
- Social Acceptance: Balancing aesthetics and functionality to create socially acceptable devices in public settings [37].

2.5.1 Consumer Behavior and Market Impact

Their success has dramatically changed customer expectations of wearable technology. People have come to relate haptic feedback with much better interactivity and a far more immersive experience [38]. This switch drove manufacturers to include haptic capabilities into an ever-growing number of devices, from fitness trackers and bright rings to VR headsets and gaming peripherals. However, battery life, size, and cost remain critical barriers to adoption, underscoring the need for continued innovation in this field.

2.6 Integration of Wearable Haptics into Daily Life

Wearable haptic devices are increasingly being integrated into everyday life, providing new opportunities for stress management and relaxation:

- Workplace Stress Relief: Devices designed to deliver calming haptic feedback during high-stress work scenarios [39].
- Rehabilitation Programs: Wearable haptics have shown promise in physical therapy, enhancing recovery for patients with motor impairments [11].
- Consumer Technology: Devices like smartwatches leverage haptic feedback to improve user interaction and enhance notification delivery [40].

Chapter 3

Methodology

3.1 Engineering Content and Process

3.1.1 Device Prototyping and Hardware Design

The development and testing of two wearable haptic devices for relaxation consisted of a servo motor and an inflatable device. Each was to apply controlled pressure, having its unique mechanism and structural feature.

The servo motor device uses a cylindrical fabric construction with integrated servo motors that apply precise pressure at exact load points. I refined the mechanical structure and ensured user comfort through iterative prototyping. In contrast, the inflatable device consisted of hidden balloons within an adjustable band to distribute uniform pressure across the wrist, focusing on ergonomic adaptability and even pressure application.

Both devices were mounted with FSRs to ensure precise pressure application and performance testing. The sensors recorded the applied pressure on the skin in the 18–110 units for the servo motor device and 44–171 units for the inflatable device. In addition, an air pressure sensor (MPRLS) was used on the inflatable device to measure internal air pressure. This pressure stayed within the narrow range of 24.62–24.67 PSI during all tests.

Integration of these hardware components was thus necessary to balance functionality and comfort for the user; indeed, these devices each settled into their final form with numerous re-designs. Such an approach jointly contributes to how innovative design meets exhaustive testing in wearables meant for relaxation.

3.1.2 Detailed Component Description

Servo Motor Device
To provide precise control and monitoring of the servo motor device, the following components were utilized:

- **Microcontroller**: The Arduino Uno was the microcontroller board employed, and it served as the central processing unit by managing the operation of the servo motors and accepting input from the force-sensitive resistor.

- **Servo Motors**: Two Hitec-HS-322HD servo motors with a 180-degree rotation range were used to give controlled pressure on the user's forearm. These motors were selected because of their precision, reliability, and compact size, making them easy to implement in the wearable system.

- **Force-Sensitive Resistor (FSR)**: A Force-Sensitive Resistor (FSR 400) was incorporated to measure the pressure exerted by the device on the skin. The force-sensing range of this sensor is 0.1 Newton to 100 Newton, with the advantages of being thin in size, shock-resistant, low power consumption, and having a fast response to force change [41].

- **Rotary Potentiometer**: A rotary potentiometer was employed to naturally and accurately control the rotation of the servo motor in a way that enables users to set the applied pressure according to their desire.

- **Additional Components**: The device was complemented with a breadboard for prototyping and insulated wire connections for ensuring reliable circuit connections.

Inflatable Device
To provide controlled inflation and pressure monitoring for the inflatable device, the following components were utilized:

- **Microcontroller**: The processing unit used was an Arduino Uno microcontroller board.

- **Air Pump**: A small air pump was utilized to inflate the pouches.

- **Air Pressure Sensor**: An MPRLS0025PA pressure sensor was utilised to gauge the air pressure of inflatable pouches.
- **Air Valves**: A total of eight miniature air valves (FA0520E) were utilized to control inflation and deflation of air pouches and exert precise control over the pressure applied on the wearer's wrist.
- **Force-Sensitive Resistor (FSR)**: Force-Sensitive Resistor (FSR 400) was also included to sense the pressure exerted by the device on the skin so that the pressure exerted is between the desired range.
- **Inflatable Pouches**: Small, inflatable, air-tight pouches were used to store the air.
- **Additional Components**: Prototyping involved the utilization of a breadboard, as well as secure wiring connections to ensure reliable circuit connections. The power supply utilized was 7.4 Volts to power the air pump and air valves. Pipes (hoses) were also utilized to offer connectivity from the air pump and air valves to the inflatable pouches.

3.1.3 Firmware Implementation

Servo Motor Device
The control logic for the servo motor device was implemented using the Arduino IDE with the C++ programming language.

Inflatable Device
Instead of using conventional firmware code, the inflation and deflation of the inflatable device were controlled using a "VMPK" (Virtual MIDI Piano Keyboard). By mapping specific keys to control signals, the virtual keyboard permitted direct and intuitive control of the air valves. Inflation of the balloons is done when keys 'q,' 'w,' 'e,' and 'r' are pressed on the VMPK interface, while deflation is accomplished when keys 'a,' 's,' 'd,' and 'f' are pressed. This method permitted convenient control of the air pressure within the pouches during examination and testing.

3.1.4 Mechanical Design, Electronics, and Materials Selection

In the servo motor device, this meant precise placement of servo motors inside the fabric structure, balancing their mechanical function with overall wearability. The inflatable device focused on a flexible yet secure band with hidden inflatable components. Both devices were to use materials suited for their functions: the servo motor device uses smooth, skin-friendly fabrics for comfort, while the inflatable device uses materials optimized for air retention and sensitive skin contact. It involves electronics systems: a button-controlled mechanism on the servo motor device and software-controlled inflation and deflation processes on the inflatable device for user-friendly operation.

3.1.5 Software Development

Exceptional software development was necessary to manage these devices effectively. The servo motor used an Arduino platform with customized C++ programming to control its movements, while the inflatable device was operated through keyboard inputs to regulate its inflation patterns. This setup allowed for flexible and precise adjustments.

3.1.6 Data Modeling and Analysis

Quantitative data modeling was incorporated into the study to analyze comfort and relaxation ratings and pressure measurements. Statistical analyses informed iterative design improvements and validated the devices' effectiveness in promoting relaxation.

3.2 Research Methodology

3.2.1 Overview of Research through Design (RtD)

In this project, I employed the principles of Research through Design (RtD) to iteratively refine wearable haptic devices, focusing on iterative prototyping and experimentation to solve complex design issues. In this project, RtD provides the underlying structure for developing wearable haptic devices by incorporating hands-on experimentation, iterative design, and user feedback into wearable haptic device development.

While Research-through-Design (RtD) provided the iterative framework for prototype development, the study also employed quantitative and qualitative methods to evaluate the prototypes' effectiveness. Quantitative measures, such as user ratings and pressure sensor data, ensured objective assessments, while qualitative feedback offered more profound insights into user experiences and preferences.

3.2.2 Dual-Phased Approach

The unique combination of Documentation of First-Person Experience and Participatory Design for comprehensive insight and improvement:

1. **First-Person Testing and Iteration**:
    - During the initial design and testing phase, I took on the user's role to refine the prototypes based on my experiences.
    - Several iterations are done through self-documentation, in which the researcher refines the prototype to achieve a satisfying level of functionality, comfort, and usability.
    - This helps the researcher to identify potential flaws in the design and improvements to be made before external participants are involved.
2. **Participatory Design for Final Evaluation**: The second phase leveraged quantitative results, such as participant ratings of comfort and relaxation, to validate the prototypes' performance in real-world scenarios:
    - The target demographic, college students, test the refined prototype in the second phase.
    - Their feedback will be on user experience, comfort, and efficacy of relaxation, thus offering valuable insight into the real-world application of the device.
    - An important note is that further iterations will not be part of this phase; participant feedback will be gathered only for evaluation purposes, ensuring the project stays focused on reaching a final, deployable design.

3.2.3 Justification for Methodology

While the first-person method provided in-depth experiential reflections, quantitative evaluation ensured measurable outcomes, offering a robust basis for assessing the devices' efficacy in relaxation. Therefore, this two-phase approach was followed for several reasons:

- **Efficiency**: During the first-person phase, I conducted internal iterations to identify and address potential design flaws before involving external participants. This method significantly reduces the likelihood of participant recursions, which could otherwise elongate the development process.

- **Experiential Reflection**: The first-person method enables researchers to extract experiential insights and reflections regarding technology design with greater depth and detail than traditional user studies or third-person approaches. This aligns with Jung's work [42], highlighting the importance of a first-person, somaesthetic perspective when exploring innovative haptic feedback modalities, such as deep touch pressure (DTP). By focusing on the subjective, lived experiences of the designer-researcher, this method ensures a comprehensive engagement with both the physical and emotional dimensions of interaction. These insights often remain elusive through third-person methods, providing a richer understanding of how DTP can promote relaxation and enhance body awareness.

- **Targeted Feedback**: The participatory phase gathers evaluation data from the target demographic, ensuring that the prototype aligns with user needs and expectations. This phase complements the first-person phase by validating the device's design from a real-world perspective.

- **Flexibility**: The iterative nature of the Research-through-Design (RtD) methodology allows for adjustments and refinements during the first-person phase, ensuring that the participatory phase is devoted to evaluating a refined prototype. This separation minimizes the need for further redesign and ensures that the device meets practical requirements effectively.

3.2.4 Alternative Methodologies Considered and Rejected

Several alternative methodologies were evaluated but ultimately rejected:

- **Traditional Experimental Research**: Robust for hypothesis testing but lacking in iterative design flexibility necessary for early-stage prototype development.

- **Observational Studies**: This methodology does not allow actual participation during the design phase and limits the possibility of drawing first-person accounts.
- **Randomized Controlled Trials (RCTs)**: Although an RCT provides sound evidence of efficacy, it was unsuitable for this project's highly exploratory and developmental nature.
- **Survey-Based Research**: This would not allow for the needed depth of insight for iterative improvements in design.

3.2.5 Data Collection Techniques

Data collection was performed through several integrated methods to gather an all-rounded insight into wearable haptic devices' functionality, comfort, and relaxation efficacy. These methods ensured a balance between personal experimentation and user-centered feedback:

- **Researcher Self-Documentation**: In the first stages of prototype development, I played the user's role, documenting my personal experiences to identify areas for improvement through testing and documenting personal experiences. This step provided the opportunity for detailed observations about usability, effectiveness, and areas of improvement that were iteratively used to refine the devices.
- **Prototype Testing**: Testing was an iterative process during development, ensuring continuous improvement of the performance and comfort of the device. Every test incorporated improvements from prior tests to systematically improve the design.
- **Individual Sessions**: The refined prototypes were tested through individual sessions with college students, the target population for these devices. These were conducted in a quiet library room in Södertälje to ensure the testing environment would be free of external interference. Participants thus provided qualitative feedback and gave quantitative ratings on comfort and relaxation. Using a standardized environment reduced response variation and made the data more reliable.

The following table summarizes the key methods, their intended purposes, and the corresponding outcomes to provide a clear overview of the methodologies employed in this study. This summary highlights the multifaceted approach taken to achieve the study's objectives.

Method	Purpose	Outcome
Research-through-Design	Iterative prototyping for functionality	Refined prototypes
Quantitative Analysis	User evaluation via ratings	Data on comfort and relaxation
Qualitative Analysis	Participant feedback	Insights into user preferences and design

Table 3.1: Summary of Research Methods, Their Purposes, and Outcomes in the Study

3.3 Methods

3.3.1 Prototyping Techniques

Prototyping was done using a modular approach to allow flexibility during testing and refinement. The servo motor device concentrated on integrating motor-driven pressure mechanisms into the wearable fabric, whereas the inflatable device concentrated on the versatility of pressure distribution using hidden balloons.

3.3.2 Experimental Design

Pressure Pattern Definitions and Implementation:
Three distinct pressure patterns were designed and tested: constant, pulsating, and wave-like. Each was designed to engage different perceptual and physiological systems, which can affect the user's sense of relaxation and comfort. The experimenter used and modulated these patterns over 30-second durations. The constant and pulsating patterns were chosen based on their use in previous studies [43, 44]. The wave-like pattern was derived from the pulsating pattern to explore a more gradual pressure application.

3.3.2.1 Mathematical Definitions and Graphical Representations

Pressure patterns can be represented mathematically as time functions, with $P(t)$ denoting relative pressure at time t between 0 (no pressure) and 1 (maximum comfortable pressure).

- Constant Pressure:

$$P(t) = P_0, \quad 0 \leq t \leq 30$$

Where P_0 is the constant pressure level determined to be comfortable for the participant.

- Pulsating Pressure:

$$P(t) = \begin{cases} 1, & \text{if } 2n \leq t < 2n+2 \\ 0, & \text{if } 2n+2 \leq t < 2n+4 \end{cases}$$

Where $n = 0, 1, 2, ..., 7$ (for the 30-second duration).

- Wave-like Pressure:

The wave-like pressure pattern was implemented to gradually increase pressure application times, incrising up to the participant's enjoyable pressure level. Let T be the time the participant's enjoyable pressure level is reached. The pattern can be described as a series of pressure applications and releases with increasing durations:

$$P(t) = \begin{cases} t/3, & \text{if } 0 \leq t < 1 \\ 0, & \text{if } 1 \leq t < 2 \\ (t-2)/3, & \text{if } 2 \leq t < 4 \\ 0, & \text{if } 4 \leq t < 6 \\ (t-6)/T, & \text{if } 6 \leq t < 6+T \\ 0, & \text{if } 6+T \leq t < 6+2T \end{cases}$$

Example: For a participant whose enjoyable pressure point was reached at 3 seconds, the cycle would be as follows:

- 0-1 second: Apply pressure from baseline (reaching 1/3 of enjoyable level.)
- 1-2 seconds: Release pressure to baseline.
- 2-4 seconds: Apply pressure from baseline (reaching 2/3 of enjoyable level.)
- 4-6 seconds: Release pressure to baseline.
- 6-9 seconds: Apply pressure from baseline (reaching full enjoyable level.)

- 9-12 seconds: Release pressure to baseline.

This 12-second cycle would repeat throughout the 30-second test period, resulting in 2.5 complete cycles.

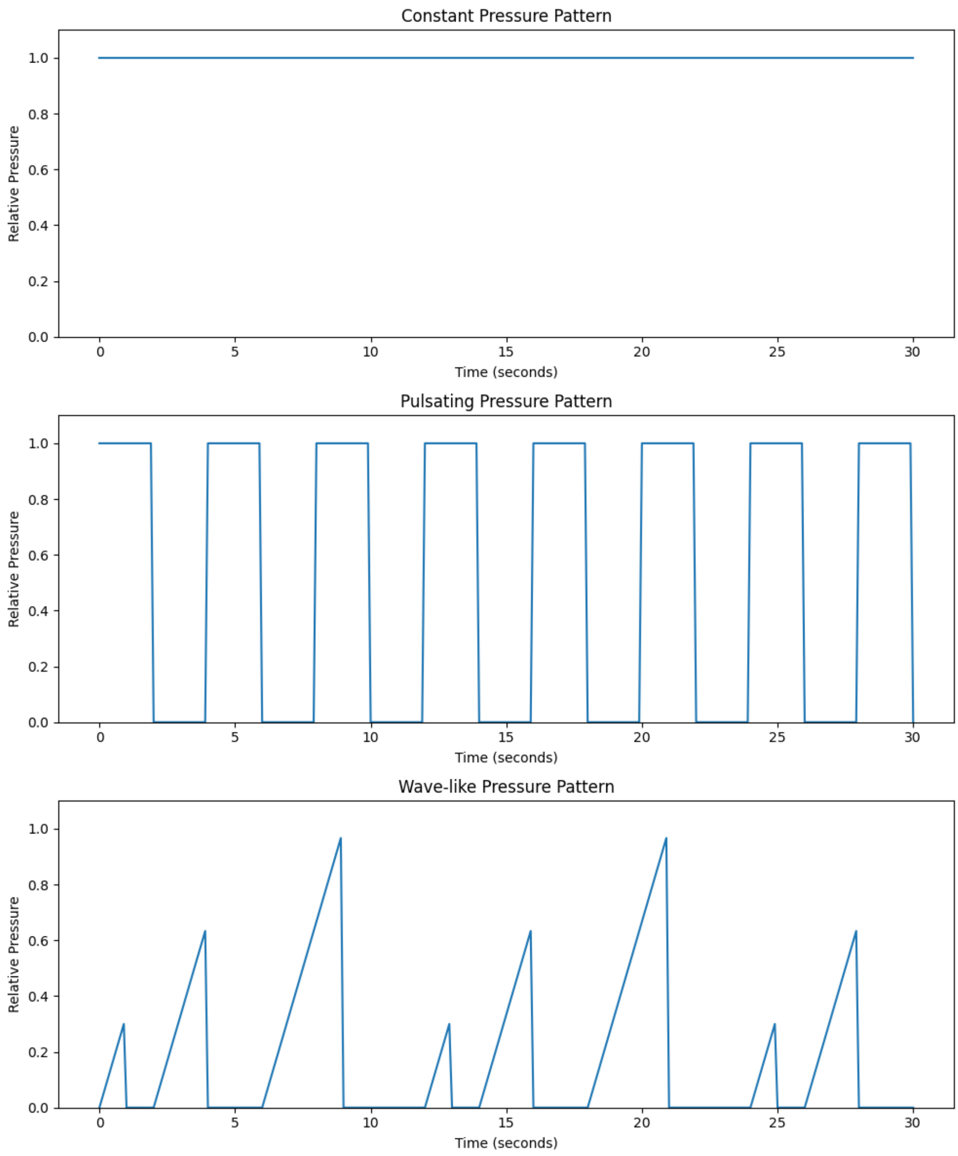

Figure 3.1: Graphical representations of the three pressure patterns over a 30-second period.

3.3.2.2 Implementation Details

Pressure patterns were customized for each device, and the researcher controlled the applied pressure as described below:

- **Servo Motor Device:** The servo motors' rotation was controlled with a rotary potentiometer and, therefore, controlled applied pressure directly. Based on the feedback from the participants, the researcher manually controlled the potentiometer.
- **Inflatable Device:** The device was controlled using keyboard inputs to inflate and deflate the air pouches. Specific keys on a virtual MIDI piano keyboard (VMPK) were mapped to control signals, allowing for direct manipulation of the air valves.

3.3.2.3 Timing and Duration of Pressure Patterns

Each pressure pattern was tested for 30 seconds, resulting in a total testing time of 90 seconds for all three patterns:

- **Constant Pressure:** The pressure was maintained consistently for 30 seconds.
- **Pulsating Pressure:** The pressure alternated every 2 seconds between maximum comfortable pressure and no pressure for the 30-second duration.
- **Wave-like Pressure:** The pressure changed in a cyclical pattern repeated for 30 seconds. For both the inflatable device and the servo motor device, the pattern was implemented as follows:
  - Apply pressure from baseline for 1 second (not reaching enjoyable level), then release for 1 second.
  - Apply pressure from baseline for 2 seconds (not reaching enjoyable level), then release for 2 seconds.
  - Apply pressure from baseline for T seconds (reaching enjoyable level), then release for T seconds.

  The value of T was determined individually for each participant based on their comfort level.

The 2-second interval for the pulsating pattern and the varying intervals in the wave-like pattern were chosen to align with typical breathing patterns, aiming to create a more natural and potentially more relaxing experience for the participants.

3.3.2.4 Ensuring Safe and Comfortable Pressure Limits

In order to ensure comfortable and safe levels of pressure, a feedback-based approach was adopted:

- The researcher gradually increased the pressure on both devices while verbally communicating with the participant. Participants were instructed to inform the researcher when the pressure reached an enjoyable level.
- Participants were encouraged to communicate discomfort immediately, allowing for real-time adjustments.

All testing sessions were conducted in one quiet room at the Södertälje library. This indoor environment was controlled to ensure session consistency and minimize variables that could affect user feedback. While the patterns were designed to represent diverse contexts, the study's limitation is the absence of real-world simulations, such as outdoor environments or active workplaces.

This allows for a standardized evaluation of the devices while gaining fundamental insight into the different pressure patterns that affect relaxation and comfort. Future studies should extend the scope of testing in naturalistic settings for wider applicability.

3.3.3 Measurement and Data Collection

This study adopted a dual-method approach. Research-through-Design (RtD) drove iterative development, while quantitative measures objectively validated the devices' performance. These methods worked in tandem to refine prototypes and evaluate their effectiveness in delivering comfort and relaxation.

3.3.3.1 Quantitative Measures

Quantitative data focused on the measurable aspects of the devices' performance. After using each device, participants rated their comfort and relaxation experiences on a scale of 1 to 10. These ratings provided a numerical foundation for comparing the two devices and identifying patterns in user responses.

Additionally, Force-Sensitive Resistor (FSR) sensors were integrated into the devices to record pressure measurements during operation. These sensors captured the pressure applied to the skin for both the servo motor and inflatable devices, offering objective insights into their functionality. An air pressure sensor (MPRLS) was also used to measure the inflatable device's internal air pressure.

Quantitative analysis utilized statistical methods, such as the Wilcoxon Signed-Rank Test, to compare the devices and identify trends. These methods added precision to the evaluation process, complementing the qualitative insights gathered.

3.3.3.2 Qualitative Measures

Qualitative data collection focused on understanding user experiences and preferences. The participants gave very valuable feedback on design aspects, usability, and areas of improvement that could be made to the devices. This information will provide valuable feedback on how the devices meet user expectations and what elements could be used to enhance their effectiveness and comfort. Individual sessions were used to discuss open-ended questions about ease of use, perceived relaxation, and preferred pressure patterns.

Integrating quantitative and qualitative research methods allowed for a comprehensive validation of wearable devices. Quantitative tests provided objective benchmarks for device performance, while qualitative responses gave more profound insights into subjective user experiences. This combined approach drove the iterative design process internally and laid the path for future improvements and possible field applications of the devices at the end.

3.4 Theoretical Foundation

3.4.1 Body-Centric Design Principles

The design of wearable haptic devices in this study is based on the principles of body-centric design, informed by the theory of Somaesthetics and Human-

Computer Interaction. These frameworks provided the theoretical foundation for creating devices that promote relaxation by enhancing bodily awareness and facilitating intuitive interactions.

Somaesthetics

Somaesthetics underlines the importance of body consciousness for perception and well-being in general through the engagement of the body's sensible surface. For wearable designs, this implies an intention to bring to the first planar how a device couples with and rests on or even against the body to promote meaningfulness and comfort. Conceived in somatic awareness-tactile engagement, the inspiration for the haptic design of such devices is their controlled-pressure delivery as part of promoting relaxation. It does so by recognizing that such bodily feelings, like pressure, might greatly influence one's emotional state and stress levels.

The study's somatic aesthetics informed the designs that not only should work efficiently but also merge with the user's body to better link the physical sensations and relaxation outcomes. The focus on somatic engagement led to the development of devices that could eventually increase the users' awareness of their body states and levels of stress for the betterment of their overall well-being.

Human-Computer Interaction (HCI) Principles

Human-computer interaction, on the other hand, provided complementary insights into the design of user-friendly and intuitive devices. The principles of HCI are focused on creating interfaces and interactions that are easy to use, understand, and integrate into daily routines. In the context of wearable haptic devices, this means comfort, unobtrusiveness, and responsiveness to user input. In this study, HCI principles informed key design choices, such as:

- **User Feedback Integration**: Iterative prototyping and participatory design ensured users' experiences and preferences shaped the final prototypes.
- **Ease of Use**: The devices were designed with straightforward control mechanisms, such as button-based inputs for the servo motor device and keyboard-based controls for the inflatable device.
- **Daily Routine Compatibility**: By making the devices portable and wearable, the design was for ease in integrating into users' daily lives to make relaxation more accessible and consistent.

3.4.2 Integration of Theoretical Concepts in Device Design

This project combined somaesthetic insights with HCI principles to develop adaptive, intuitive wearables that engage tactile and emotional user responses to foster relaxation.

3.5 Social and Ethical Considerations

3.5.1 Accessibility and Inclusivity

The project aims to increase accessibility to stress management tools by designing wearable haptic devices that are affordable, portable, and user-friendly. The user-centered design approach enables these devices to cater to a broad range of users, including individuals with limited access to traditional stress relief methods. While inclusivity was not fully realized in this study, the combined use of first-person methods and participatory design offers potential for future research to focus on specific groups of users with unique physical and psychological needs. By tailoring the design process to these groups, future iterations of wearable haptic devices could better address diverse requirements, enhancing their accessibility and impact.

3.5.2 Ethical Challenges and Mitigation

Some of the ethical challenges identified and addressed throughout the project were the safety, inclusivity, and effectiveness of developing wearable haptic devices. These considerations balanced user comfort, ensured data privacy, and maintained participant well-being during testing.

Balancing Comfort and Effectiveness
Various ethical issues connected with the safety, inclusion, and effectiveness of developing wearable haptic devices were present within this research. Significant actions taken included user comfort, protection of data privacy, and the maintenance of the well-being of participants during testing. **Balancing Comfort and Effectiveness**: One of the ethical priorities was balancing comfort and effectiveness. Pressure mechanisms had to provide relaxation and not cause discomfort or injury. Pressure sensors such as Force-Sensitive Resistors (FSR) and MPRLS air pressure sensors have been incorporated into the devices to avoid this. This action allowed the levels of applied pressure

to be monitored and controlled so as not to exceed unsafe limits. Including such precautions ensures the study minimized any discomfort or physical harm while upholding a commitment to exemplary ethics in design, even as the devices focused on inducing relaxation.

Privacy Concerns
Although this study did not collect biometric data such as heart rate or cortisol levels, privacy remained a central concern. I implemented the following measures to ensure the ethical handling of participant feedback:

- All data collected was anonymized; no personally identifiable information was retained.
- Participant feedback was utilized only to enhance the designs of the devices, following all ethical research considerations.
- Transparency was maintained to ensure participants were fully informed about the purpose of the study, the nature of the data collected, and its intended use. For future iterations, particularly those involving physiological data collection, the devices will incorporate robust security measures for data storage and management, along with comprehensive consent procedures to safeguard participant trust and privacy.

Avoiding Bias and Achieving Depth in Testing g
The study utilized complementary methods to balance the goals of achieving an in-depth understanding of the experiential aspects and ensuring diverse, unbiased perspectives:

- In the first-person method, the focus was on obtaining a rich, detailed understanding of the experiential aspects of using wearable haptic devices. This method allowed the researcher to refine the prototypes by engaging deeply with their functionality, comfort, and usability.
- For the final participatory phase, participants with diverse backgrounds and preferences were recruited to capture a wide range of perspectives and ensure that the findings reflect varying user experiences.
- The data collection process emphasized candidness during one-on-one sessions, creating an environment that minimized social and environmental influences.

- The testing process was designed to focus solely on the comfort and relaxation effectiveness of the devices, avoiding the introduction of external stressors or leading questions

Avoiding Stress During Testing
Given that devices should contribute to relaxation, it was important to ensure that the very process of testing would not lead to unnecessary stress or discomfort. To that end:

- All testing sessions were conducted in a quiet, controlled environment to minimize distractions and external stressors.
- The testing could be stopped or paused at any moment if the person felt uneasy, and all instructions were given clearly.

By keeping the participant-centered approach, ethical integrity was further ensured regarding the testing process of these devices for their intended use.

Mitigation Strategies
To address these challenges, the study employed several key strategies:

1. The iterative design and testing phases ensured that the devices were both safe and effective prior to their use by participants.
2. Clear communication regarding testing procedures and potential risks was provided to all individuals involved.
3. Feedback from users was processed ethically, with measures taken to anonymize responses and utilize them solely for the purpose of enhancing the devices.

By addressing such ethical challenges, the project remained committed to developing wearable haptic devices that are functional, effective, safe, inclusive, and respectful of participants' rights and well-being.

3.5.3 Testing Environment Limitations

In this study, the testing environment was intentionally controlled to minimize external variables that could affect the results. All sessions were conducted in a quiet, private room within the Södertälje library. This setting was chosen because it would be quiet and free from distractions, allowing participants to focus entirely on the wearable haptic devices and the testing process.

Advantages of a Controlled Environment

1. **Consistency Across Sessions**: Using the same environment for all testing sessions minimized the variability that could be introduced by external factors such as noise, lighting, or interruptions. This environment would ensure participant feedback was based on their experience with the devices rather than external influences.

2. **Focus on Immediate Feedback**: It is clear that the quiet room allowed them to focus solely on their interaction with the devices, ensuring clear and detailed qualitative and quantitative feedback regarding comfort and relaxation.

Limitations of the Testing Environment: While the controlled environment offered several advantages, it also introduced limitations that impacted the generalizability of the findings. For instance, the study did not include outdoor environments or scenarios that might simulate workplace or study settings; therefore, the effectiveness of the devices in dynamic or real-life contexts associated with stressors remains unexplored.
Short-Term Interaction: The controlled setting focused on immediate user feedback rather than long-term usage patterns, which are crucial for understanding how these devices integrate into daily routines over time.

Recommendations for Future Research: To address these limitations, future studies should:

1. Include field testing in various environments, such as workplaces, outdoors, and public areas, to assess the performance of devices under different conditions.

2. Include longitudinal studies assessing how participants adapt to and integrate the devices into daily life, providing insight into long-term usability and effectiveness.

3.6 Evaluation

3.6.1 Evaluation and Performance Assessment

The wearable haptic devices were evaluated by a structured approach that combined controlled testing environments with comprehensive feedback collection to ensure reliable performance assessment. This approach provided quantitative and qualitative insights into the devices' functionality, comfort, and relaxation efficacy.

Quantitative Metrics
After using each device, the participants rated their comfort and relaxation experiences on a 1–10 scale. These ratings quantitatively provided the numerical basis for comparing the two devices. Additionally, pressure measurements were recorded to test the consistency and safety of the devices.

Qualitative Feedback
Participants provided in-depth feedback on various aspects of the devices, including:

- **User Experiences**: Insights into comfort, usability, and effectiveness in inducing relaxation.
- **Pressure Patterns Preferences**: Constant, pulsating, and wave-like pressure patterns were compared.
- **Design Suggestions**: Recommendations on improving the devices' design, functionality, and wearability.
- **Real-Life Application**: Participants gave suggestions of situations in which they think the devices would be most useful for them.

3.6.2 Criteria for Success

The effectiveness of the devices will be evaluated based on the following criteria:

- **User Comfort**: Participants will rate their comfort level on a scale of 1-10 for both devices.
- **Relaxation Efficacy**: The ability of each device to promote relaxation will be assessed using a 1-10 scale.
- **Device Usability**: Feedback will be collected on the ease of use and potential integration into daily routines.
- **Wearability**: The devices will be evaluated for comfort during extended wear periods.

- **User Preference**: Participants will be asked to indicate their preferred device, providing insights into overall effectiveness.

3.7 Visualization

3.7.1 Research Process and Data Workflow

A comprehensive visual representation of the research process highlights the cyclical nature of the Research through Design (RtD) methodology. The flowchart includes the following key stages:

1. **First-Person Experimentation**: The researcher conducts initial prototype testing, documenting usability, comfort, and performance issues. This stage is crucial for gathering hands-on insights that guide early design decisions.

2. **Prototype Iteration**: A cyclical process where prototypes are refined based on self-documented feedback from the researcher. This iteration loop continues until a satisfactory prototype is achieved, ensuring the design meets the intended functional and comfort goals.

3. **Participatory Design**: College students engage in one-on-one design sessions after finalizing the prototype through iterations. These sessions focus on gathering personalized feedback on the devices' comfort, usability, and effectiveness.

4. **Data Collection and Analysis**: Quantitative measures, such as comfort and relaxation ratings, and qualitative feedback from participatory design sessions are integrated to evaluate the performance of the devices and inform conclusions.

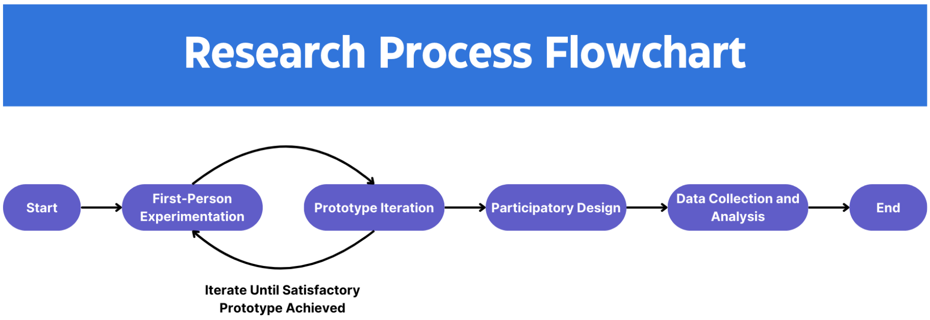

Figure 3.2: Research Process Flowchart: Iterative design and evaluation workflow for wearable haptic devices

To enhance the research process, the researcher uses a data collection workflow diagram outlining the sequential steps in gathering user input. These steps include:

- Implementation of self-documentation techniques.
- Recruitment of participants.
- Facilitation of individual sessions to capture feedback on usability and comfort.
- Data analysis employing statistical methods.

Together, these visuals clarify the research methodology and highlight the interdependence of the design, testing, and evaluation phases.

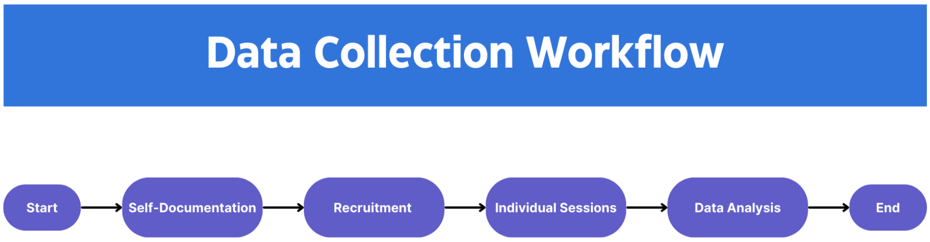

Figure 3.3: Data Collection Workflow: Sequential steps from researcher self-documentation to participant recruitment, individual feedback sessions, and final data analysis

3.7.2 Device Design and Construction

Detailed diagrams of wearable haptic devices—one servo motor and one inflatable—provide an overview of the mechanical and electronic components. Each of the device diagrams shows:

- Servo Motor Device:
  - The servo motors, positioned for external testing, conceptualize their alignment with pressure application zones.
  - The integration of components, including the Arduino UNO, breadboard, rotary potentiometer, and Force-Sensitive Resistor.
  - The system is designed to deliver targeted pressure feedback through button-controlled mechanisms for ease of use.

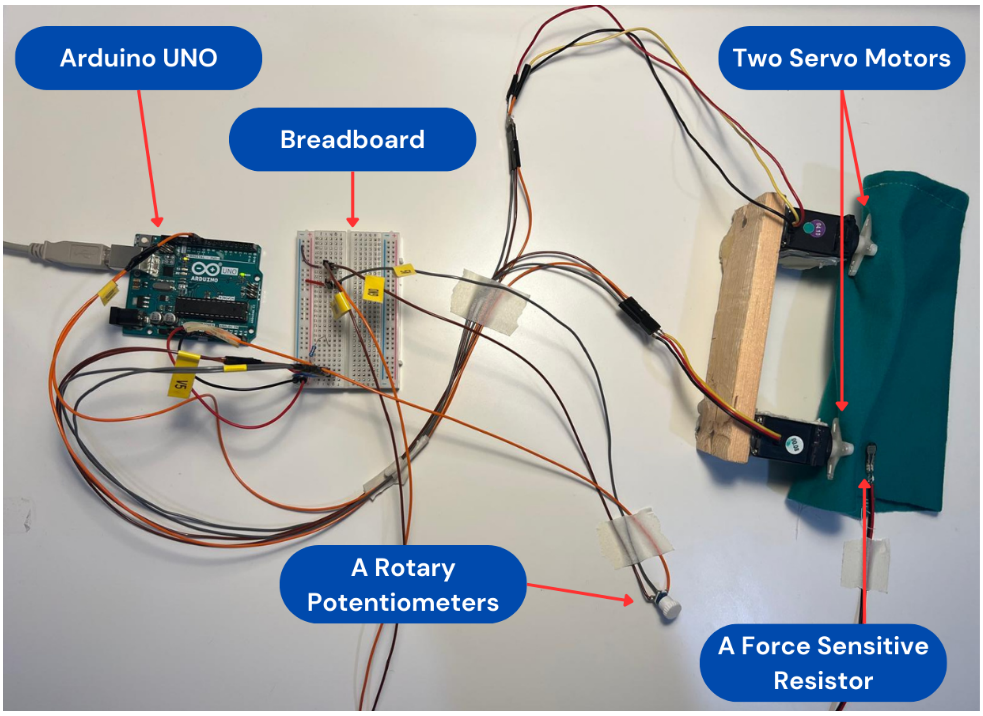

Figure 3.4: Components of the Servo Motor Device: Arduino UNO, breadboard, rotary potentiometer, servo motors, and Force-Sensitive Resistor.

- Inflatable Device:
  - The adjustable band contains hidden balloons for uniform pressure distribution, conceptualized for therapeutic effect.
  - The integration of an MPRLS pressure sensor and its connection to the inflation mechanism.
  - Software-controlled inflation and deflation systems for precision.

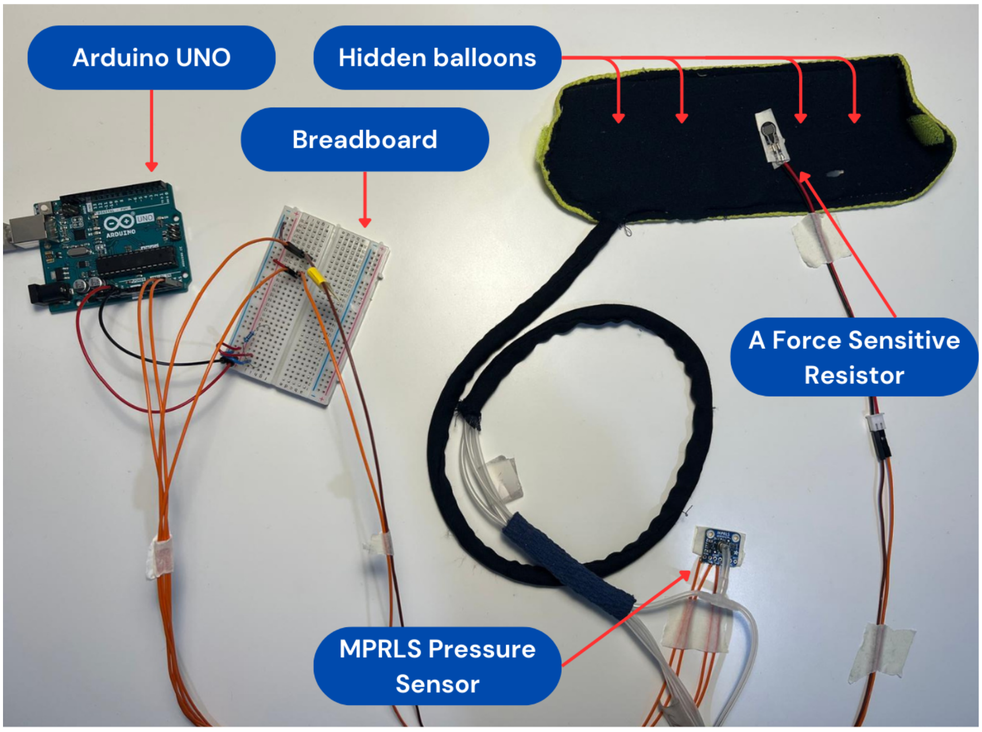

Figure 3.5: Components of the Inflatable Device: Arduino UNO, breadboard, hidden balloons, MPRLS pressure sensor, and Force-Sensitive Resistor.

These diagrams, supplemented with labeled annotations, provide clarity on each device's components and design intent. While external elements are visible for testing purposes, key features—such as the pressure alignment zones or inflation control mechanisms—are conceptualized to illustrate their intended functionality.

3.7.3 Comparative Analysis of Device Performance

Several comparative analysis charts were performed to assess the two devices' efficiency. These include:

1. **Bar Charts**: Showing the average ratings of comfort and relaxation for both devices will give a clear vision of the user's preference.
2. **Box Plots**: These illustrate the range and dispersion of ratings. It gives consistency in the response from users for each device.
3. **Preference Distribution**: A bar chart showing participant preference for pressure patterns (constant, pulsating, wave-like) across devices.

These plots summarize the key results but also provide information about each device's specific strengths and weaknesses.

3.8 Limitations and Constraints

3.8.1 Sample Size and Diversity

This research had a small sample size of college students, limiting its generalizability to wider populations. While this provided rich, detailed data, future research should expand to larger, more diverse participant groups.

3.8.2 Testing Environment

Testing was conducted in a controlled indoor setting, which may not fully represent naturalistic usage scenarios. Future studies should also conduct field testing in natural environments to capture more variations in user experiences.

3.8.3 Duration of Testing

The project focused on short-term use and immediate effects; thus, long-term efficacy and user adaptation were left unexplored. Longitudinal studies are recommended to investigate the sustained impact of the devices on relaxation.

3.8.4 Physiological Measurements

The ratings are subjective, while objective physiological measures such as variability in heart rate or cortisol level were not taken. Future designs can embed biometric sensors to obtain comprehensive reviews.

3.8.5 Single Researcher Perspective

The initial steps were heavily based on self-documentation, which made them biased. However, they were later complemented and balanced in participatory design sessions with students by obtaining diverse feedback from the users.

Chapter 4

Design and Development Process

This chapter details the iterative design, development, and testing process of creating two wearable haptic devices: a servo motor device and an inflatable device designed for relaxation and comfort, using an RtD approach. In this manner, I assumed the dual roles of both researcher and user in balancing first-person documentation with participatory design to refine each prototype iteratively. Reflecting on the development process, I realized that each step was essential for understanding the challenges and opportunities in designing wearable haptics.

4.1 Prototype Development

Servo Motor Device
I iterated on the servo motor device through four prototyping stages, with each version building on the knowledge gained from the previous one. In the first iteration, I used non-elastic fabric, which was too rigid and uncomfortable while functional in exerting pressure. I noted in my documentation, "The first version was functional, but the discomfort was glaringly obvious due to the chosen fabric." This observation highlighted the critical importance of material choice in ensuring usability and comfort. The band also failed to conform well to the shape of my arm, creating noticeable gaps. I reflected, "Because the circular shape of the band did not perfectly fit my arm, it affected the overall wearability."

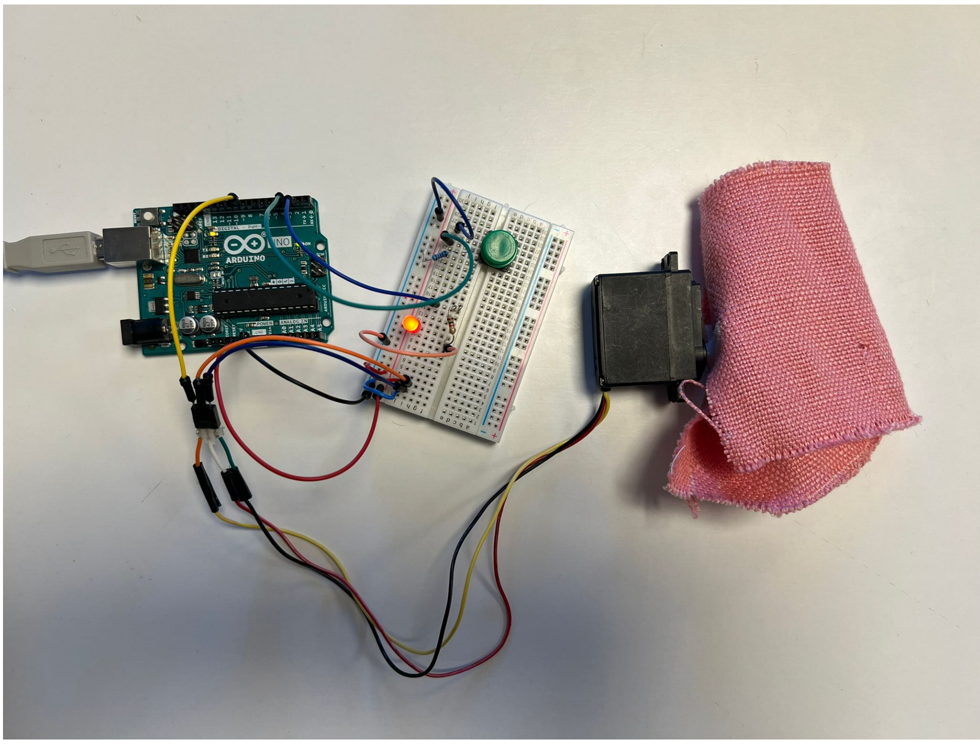

Figure 4.1: teration 1: Initial Prototype of the Servo Motor Device

To resolve these issues, I added elastic material in the second version. This adjustment improved the device's conformation to the arm's shape, but it introduced new challenges. While the increased elasticity improved wearability, it still fell short of providing a complete fit. Additionally, the elasticity caused excessive pressure on the arm, highlighting the need for further refinement.

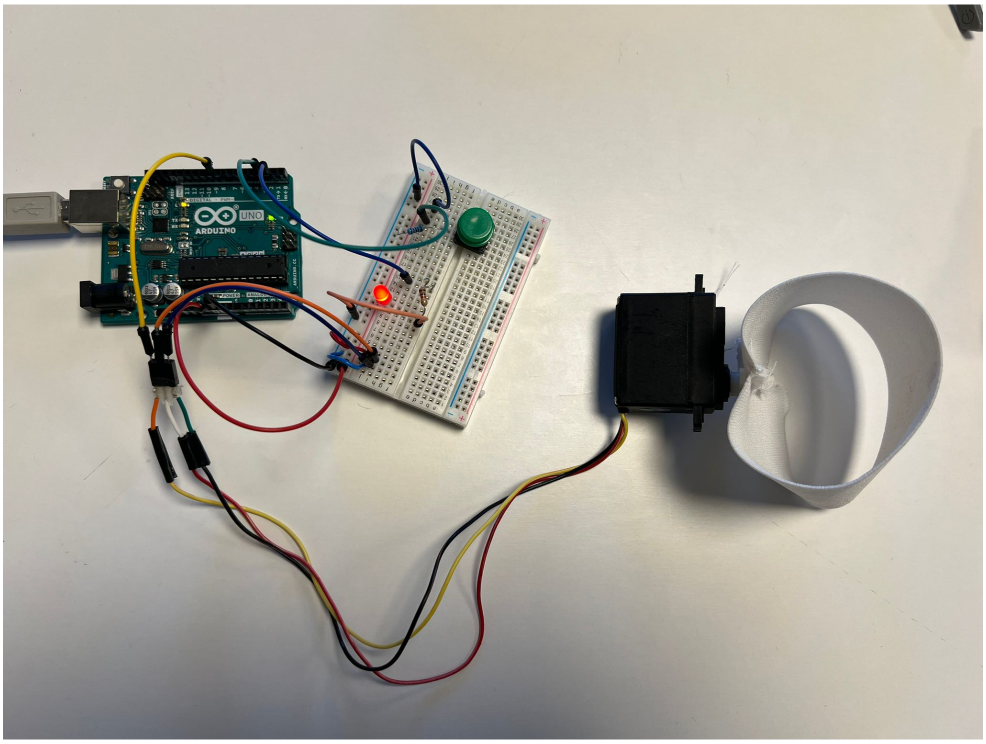

Figure 4.2: Iteration 2: Introduction of Elastic Materials

The third iteration marked a significant step forward. I incorporated skin-friendly fabrics into the design, which provided a proper fit without gaps and significantly enhanced user interaction. I noted with satisfaction, "This version fits perfectly, and I love having it on my arm where there are no gaps at all." However, during prototype testing, I noticed that while the pressure applied was even, it was not strong enough to create a noticeable relaxation effect. Reflecting on this, I wrote: "The applied pressure is not very noticeable, which diminishes the device's effectiveness."

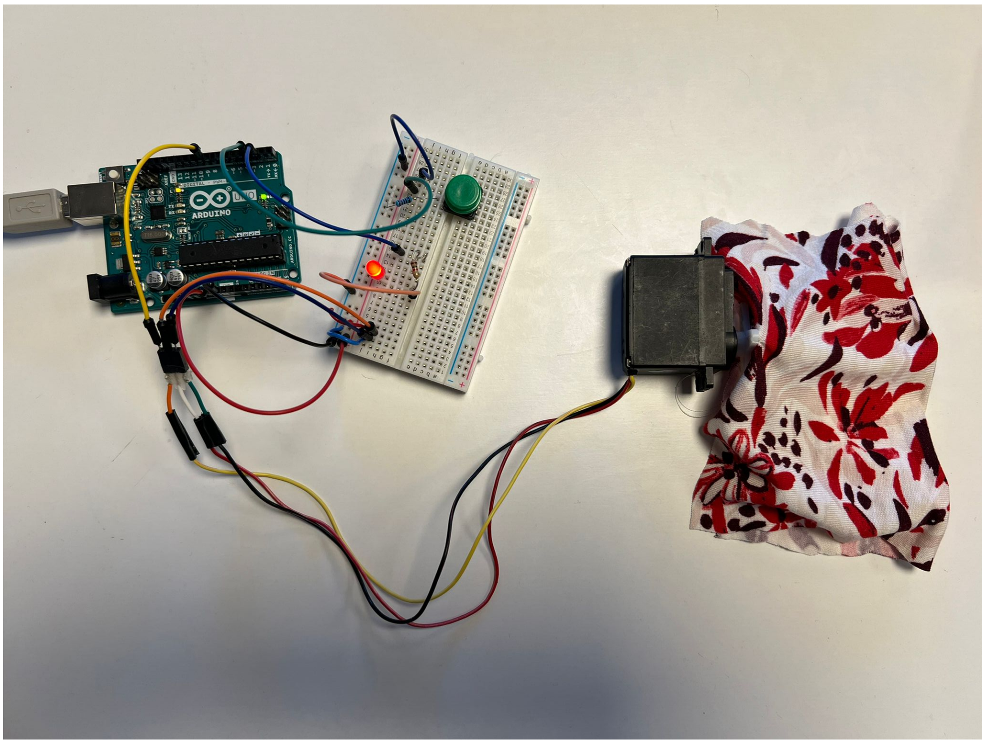

Figure 4.3: Iteration 3: Skin-Friendly Fabric and Enhanced Fit

In the fourth and final iteration, I integrated dual servo motors to balance comfort, functionality, and practical pressure application. I strategically placed the motors to ensure consistent and noticeable pressure without compromising wearability. I further refined the materials, ensuring they provided a soft, comfortable touch against the skin. This iteration addressed all the identified issues and fulfilled the key design criteria. Reflecting on this final version, I wrote: "The fourth iteration finally felt cohesive—a device that worked as intended while being comfortable enough for long-term use. All three sides of the comfort triangle (pressure, temperature change, and soft touch) are fulfilled by this design."

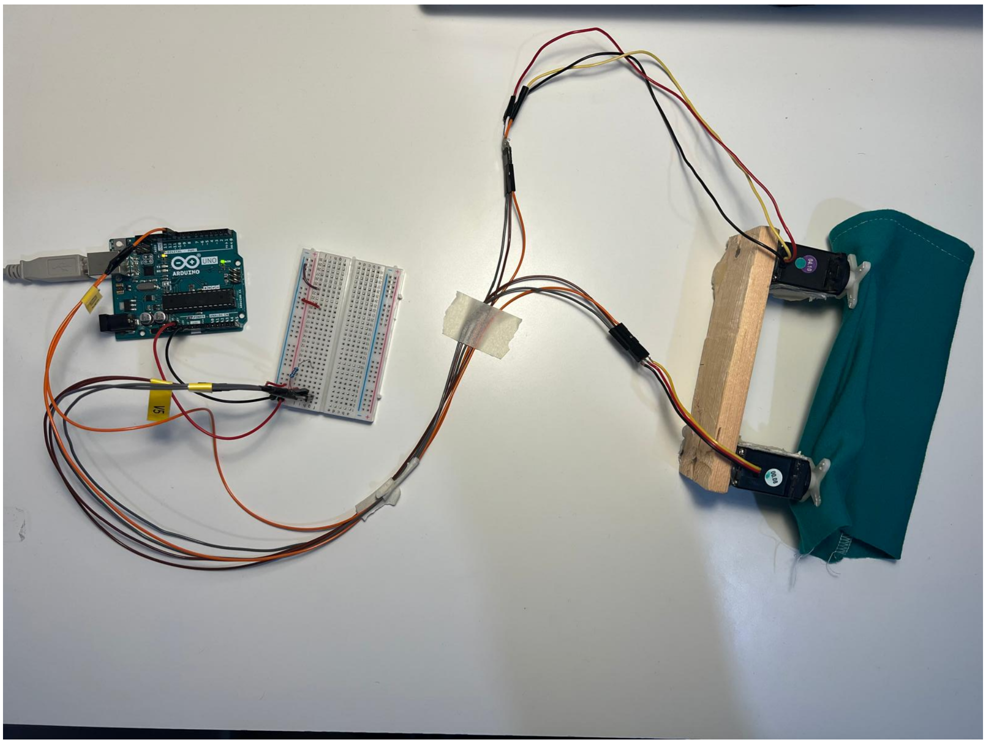

Figure 4.4: Iteration 4: Dual Servo Motors for Balanced Pressure

After achieving a satisfactory prototype, I made two additional modifications to enhance the device's functionality and usability further. First, I replaced the button with a rotary potentiometer to control the servo motor's rotation. The rotary potentiometer allowed users to adjust the motor's angle more intuitively and precisely. Second, I integrated a Force-Sensitive Resistor (FSR) into the design to measure the applied pressure on the skin. This addition simplified the device's control interface and enabled testing with more precise data collection.

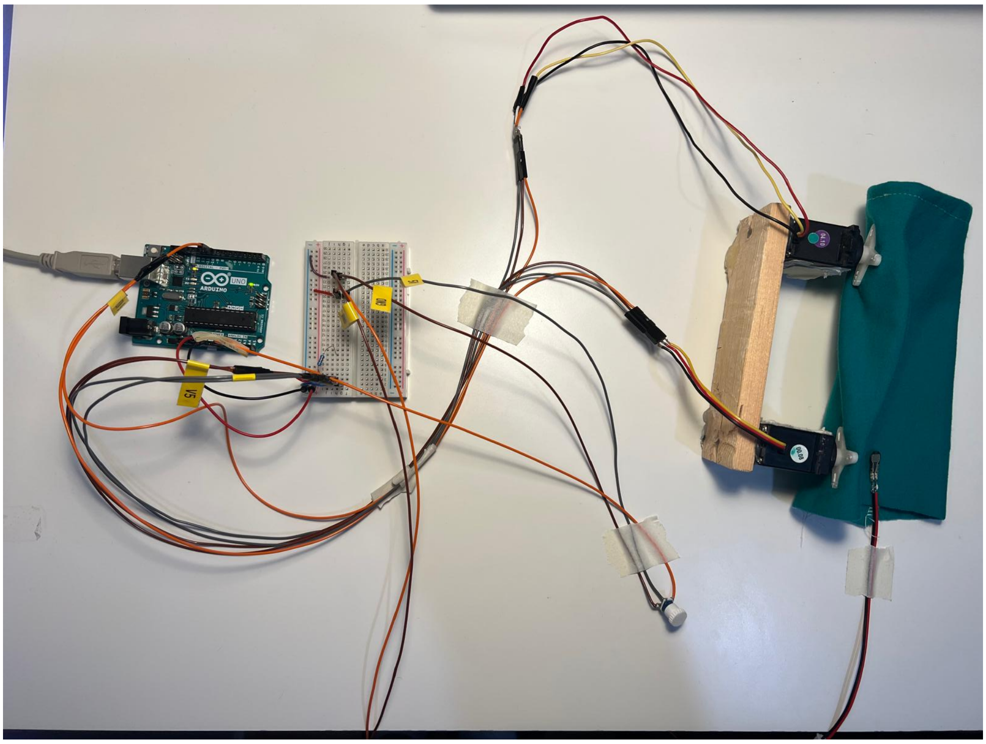

Figure 4.5: Final Prototype: Enhanced Servo Motor Device with Additional Features

This iterative process demonstrated the value of meticulous refinement in wearable haptic device design. Each iteration informed the next, resulting in a device that balanced functionality and comfort while meeting the project's objectives. The evolution of the servo motor device underscored the importance of material selection, mechanical design, and iterative user feedback in developing effective wearable technologies.

Inflatable Device

The development of the inflatable device followed a more linear path than the servo motor device. From its earliest prototype, it met the primary functional requirements. I documented my observations: "The hidden balloons provided even, adjustable pressure, and the materials were soft and breathable." This early success reduced the need for extensive iterations, as the device effectively addressed three primary benchmarks for relaxation: (1) delivering consistent and practical pressure application, (2) ensuring comfort with a soft touch, and (3) enabling subtle temperature changes during use.

While the servo motor device required multiple iterations to refine its design, I decided not to develop additional versions of the inflatable device. This decision was informed by the prototype's early success in meeting the design goals. Reflecting on this, I wrote: "Sometimes, you have to know when a design works and not over-complicate it." The simplicity of the inflatable device, combined with its functionality, became one of its strongest features, making it ready for user testing with minimal adjustments.

The only modification I made was to add two sensors to extend its functionality. I integrated a Force-Sensitive Resistor (FSR) to measure the pressure applied to the skin and an MPRLS sensor to monitor air pressure inside the inflatable pouches. These additions ensured precise measurement capabilities, allowing for comprehensive data collection during testing.

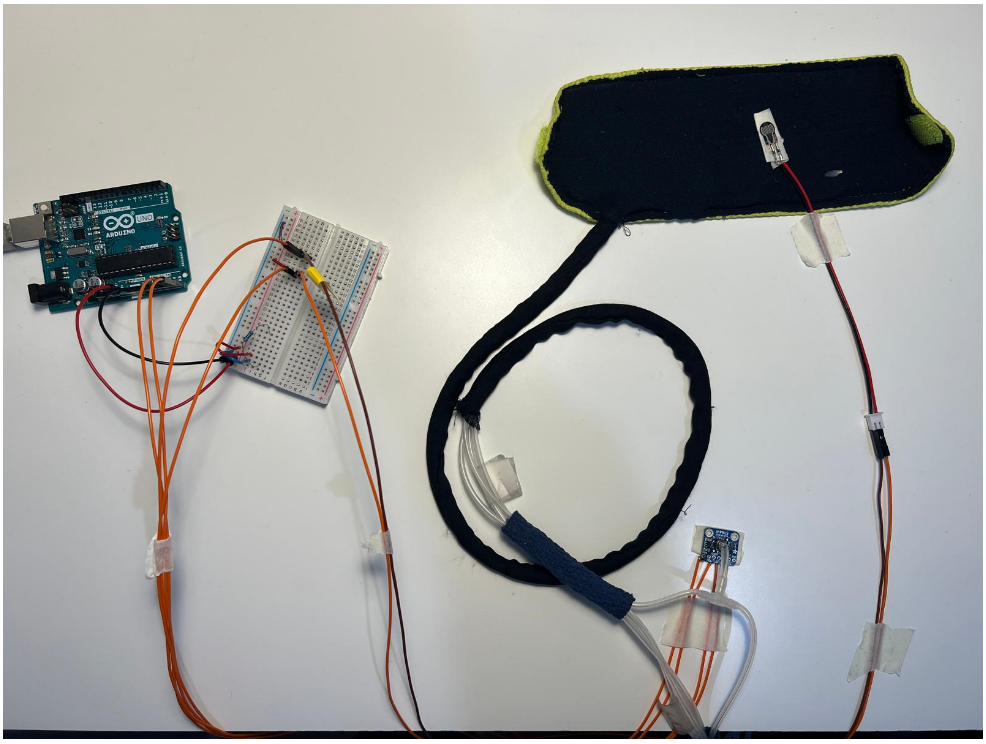

Figure 4.6: Final Prototype: Enhanced Inflatable Device with Additional Features

The development of the inflatable device highlights the value of simplicity and functionality in design. Its ability to satisfy key criteria without requiring extensive iterations demonstrates how a well-conceived initial concept can successfully balance user comfort with technical requirements.

4.2 Workshop Procedure

I employed a standardized protocol in the workshops to maintain consistent data collection and a positive participant experience. The protocol was meant to introduce the devices, gather data on comfort, relaxation, and pressure preferences, and permit participants to withdraw from the study. The three major components of each experiment were the introduction, the experiment, and the debriefing. All sessions were video recorded with a mobile phone.

- Introduction
First, all participants were thanked for their cooperation in this research. They were then asked to read and sign the "consent form." After they signed the form, I briefly read it to remind participants of their rights, including the right to withdraw from the study at any time. This procedure underscored the voluntary aspect of their participation and responded to any initial questions or issues.

- Device Introduction and Demonstration
Upon completing the consent process, I presented both devices, the mode of operation, how they are worn, and how pressure is delivered. The information was presented concisely to avoid inundating participants. Demonstration of each device being worn was done, and participants were allowed to ask questions before the test sessions began.

- Experiment Procedure
The test sessions were conducted one device at a time, beginning with the servo motor device and proceeding to the inflatable device. For each device, the steps were as follows:

- I began by introducing the range of pressure the device could offer. I communicated the level of intensity that the device could reach in pressure.

- Together, we identified an enjoyable pressure level for the participant. I controlled the pressure, increasing or decreasing it based on their feedback. This step was repeated 3 times, ensuring the person enjoyed a certain pressure level and that the FSR sensor registered almost the same number. This repetition ensured consistency in the data collection process.

- Once the enjoyable pressure level was found, three different pressure patterns (Constant, pulsating, and wave-like) were applied. After experiencing each, participants indicated which pressure pattern they enjoyed most and were asked to explain their preferred device features.
- Each participant was asked to rate the device's comfort on a scale from 1 to 10, where 1 indicated not comfortable, and 10 indicated very comfortable.

- Debriefing
At the end of the session, I thanked the participants for their participation. Then, I reviewed the following points:

- I asked if they enjoyed the session.
- I asked if they would want to participate in such studies in the future.
- I inquired which device they liked the most and asked them to share the reasons for that choice.
- I reiterated their right to withdraw from the study at any time and ensured they had no further questions.

4.3 Participatory Evaluation

Testing and evaluation were conducted exclusively in a controlled, quiet room at the Södertälje Library to ensure consistency and eliminate external influences. This environment was chosen to provide a focused space where participants could fully engage with the devices without distractions. As I documented, "The quiet environment allowed participants to concentrate solely on their experience with the prototypes, ensuring more reliable feedback."

The servo motor device underwent four iterations of design refinement, each informed by my first-person feedback during the initial stages of development. These iterations addressed usability challenges and enhanced the device's comfort and functionality. The final prototype was evaluated by participants, whose feedback indicated that it aligned with their needs and expectations. Overall, participants were satisfied with the fabric used, enjoying its softness and comfort. Three participants mentioned the temperature changes of the device as an unexpected but pleasant feature for relaxation. One participant remarked, "I really like the temperature changes; I prefer hotter over colder." Several participants also rated the balance between functionality (applied pressure) and comfort as highly favorable, emphasizing the effectiveness of the design refinements.

The inflatable device received comments about its simplicity and was described as providing even and adjustable pressure around the wrist with every use: "I feel like the pressure is evenly distributed over my wrist." One subject with smaller hands enjoyed its adaptability, adding, "The ability to adjust to fit hand size is a great feature of this design." Unlike the servo motor device, the inflatable required no further iterations after the prototype, which speaks highly to the success of the design of its original concept.

Overall, these evaluations highlighted the importance of iteration and refinement for the servo motor device and the robustness of a well-designed prototype for the inflatable device. This stage of the project reinforced the central role of user feedback and iterative development in creating functional and user-centered wearable technologies.

4.4 Design Decisions Guided by Iterative Refinement

The iterative refinement process, driven by my first-person feedback, was pivotal in shaping several critical design decisions for the wearable haptic devices. Testing and documenting each prototype informed key choices regarding the application site, material selection, and pressure mechanisms, ensuring the devices met functional and user-centered goals.

1. **Focus on the Forearm**: The forearm was selected as the main point of applying pressure because of a significant gap in prior research. Most studies have targeted pressure stimulation on areas such as the torso or legs, but few have covered the forearm area. Therefore, this project aims to focus on this area for novel insights into the potential of forearm-based wearable devices for relaxation.

   My self-testing revealed that the forearm offered practicality and comfort, aligning with the project's aim to explore underutilized areas in wearable haptic devices. Unlike more common sites such as the torso or legs, the forearm was a convenient and practical location for delivering haptic feedback in daily settings.

2. **Material Selection**: Initial iterations highlighted the importance of material choice for comfort and usability. Early prototypes with stiff, non-elastic fabrics were uncomfortable and impractical for extended wear. Through iterative testing, I transitioned to elastic, skin-friendly materials that conformed better to the forearm, significantly enhancing the device's wearability. For the inflatable device, air-retentive materials were chosen to ensure consistent pressure application and adaptability to varying wrist sizes.

3. **Pressure Mechanisms**: Hands-on testing and iterative adjustments guided the refinement of pressure mechanisms. The precise positioning of dual servo motors was optimized for the servo motor device to deliver consistent and balanced pressure. In the inflatable device, adjustable inflation patterns through hidden balloons allowed users to customize the pressure, ensuring uniform distribution for a comfortable and practical relaxation experience.

This iterative process exemplified the value of first-person documentation in wearable haptic device design. Each prototype iteration offered new insights, informing continuous improvements in material selection, mechanical design, and pressure mechanisms. Reflecting on this phase, I noted: "Each prototype taught me something new—what worked, what did not, and where I could push the design further." These design decisions highlight the importance of iterative refinement in achieving a balance between functionality, comfort, and usability in wearable technologies.

4.5 Sustainability Considerations

Recognizing the significance of sustainable development, the planning and creation of wearable haptic devices should take into account various environmental factors. Moving forward, a comprehensive Life Cycle Assessment (LCA) is essential to accurately measure the environmental impact and ensure compliance with regulations aimed at reducing harmful substances. Additionally, prioritizing recycling and managing end-of-life procedures, including disposal strategies, will be crucial in minimizing environmental pollution.

Chapter 5

Results and Analysis

This chapter presents the results of the design and evaluation process for wearable haptic devices aimed at promoting relaxation. The findings are drawn from two primary sources: the First-Person Research-through-Design (RtD) process, which documents iterative prototype development, and the User Evaluation Study, which collects quantitative data on comfort and relaxation ratings alongside qualitative insights into user preferences and feedback.

The chapter is organized as follows: First, the Data and Findings section reports outcomes from the RtD process and user evaluation. Next, the Statistical Analysis and Interpretation section examines the relationships between comfort, relaxation, and user preferences through statistical methods. Finally, the Synthesis of Results and Alignment with Project Goals section reflects on how the findings address the project objectives and identify future research and development opportunities.

This integrated approach provides a comprehensive understanding of the prototypes' performance, highlighting key strengths, areas for improvement, and insights for advancing wearable haptic technologies.

5.1 Data and Findings

5.1.1 First-Person RtD Process

The First-Person Research-through-Design (RtD) process formed the foundation of the iterative development of wearable haptic devices. This process focused on refining the design through hands-on experimentation, self-documentation, and systematic testing. This section outlines the key iterations, challenges, and solutions implemented during the development of the servo motor and inflatable device.

Iterative Prototyping

The RtD process began with exploring materials, mechanical structures, and user interaction mechanisms. The servo motor device underwent four distinct iterations:

1. **Iteration 1**: The initial prototype, built with non-elastic fabric, was functional but uncomfortable, failing to conform to the arm's shape. Gaps in fit and rigidity highlighted the need for improved material flexibility.

2. **Iteration 2**: Elastic materials were introduced, improving fit but creating excessive pressure in some areas. Adjustments to material elasticity and fit design addressed this issue.

3. **Iteration 3**: Skin-friendly fabrics enhanced user comfort, and structural modifications ensured uniform pressure distribution. However, the pressure was not sufficiently noticeable for relaxation.

4. **Iteration 4**: The final iteration added dual servo motors for balanced and noticeable pressure, complemented by a rotary potentiometer for user control and an integrated Force-Sensitive Resistor (FSR) to measure applied pressure.

The inflatable device, in contrast, followed a more linear development process due to its early success in meeting functional and ergonomic goals. Hidden balloons within an adjustable band ensured even pressure distribution, and skin-friendly, air-retentive materials provided comfort. While this device required fewer iterations than the servo motor device, additional features, such as pressure sensors (FSR and MPRLS), were added to enhance functionality and data collection.

Challenges and Solutions

- **Material Selection**: Early prototypes revealed the critical role of material choice in user comfort and device performance. Iterative testing led to the adoption of elastic, skin-friendly fabrics for both devices.

- **Pressure Mechanisms**: The servo motor device's precise pressure application required careful placement of motors and refinement of their operation to avoid uneven pressure. The inflatable device succeeded with even, adjustable pressure but faced challenges in achieving variability in intensity.
- **Wearability**: Addressing bulkiness and ergonomics, especially for the servo motor device, required iterative adjustments to balance functionality with extended wear comfort.

Insights and Contributions

The RtD process demonstrated the value of iterative refinement in wearable device design. Each iteration provided actionable insights into material selection, mechanical design, and user interaction, directly informing the final prototypes. These developments laid the groundwork for the user evaluation study, ensuring the devices were functional, comfortable, and aligned with user-centered design principles.

5.1.2 User Evaluation Study

5.1.2.1 Quantitative Results

- Comfort Ratings
Participants rated the comfort of the two devices on a scale of 1 to 10. The mean and median comfort ratings for each device are summarized as follows:

- **Servo Motor Device**: Mean = 8.0, median = 8.5, 95% Confidence Interval = (6.57, 9.43).
- **Inflatable Device**: Mean = 7.9, median = 9.0, 95% Confidence Interval = (6.17, 9.63).

The Wilcoxon Signed-Rank test did not reveal statistically significant differences in comfort scores between the two devices ($Z = 0.3$, $p = 0.763$, $r = 0.1$). Both devices performed similarly in terms of comfort, although the inflatable device had a marginally higher median rating.

- Relaxation Ratings
Relaxation ratings were also recorded on a scale of 1 to 10 for both devices:

- **Servo Motor Device**: Mean = 6.4, median = 7.0, 95% Confidence Interval = (5.13, 7.67).
- **Inflatable Device**: Mean = 7.1, median = 8.0, 95% Confidence Interval = (5.54, 8.66).

Although the Wilcoxon Signed Rank test indicated no statistically significant difference (Z = 1.3, p = 0.200, r = 0.5), the inflatable device exhibited slightly higher relaxation ratings than the servo motor device. This trend suggests potential differences in user experience that warrant further investigation.

- Pressure Pattern Preferences

Participants expressed their preferences for the three pressure patterns of both devices: constant, pulsating, and wave-like. The distribution of preferences is summarized below:

- **Servo Motor Device**: Constant (10%), Pulsating (30%), Wave-like (60%).
- **Inflatable Device**: Constant (10%), Pulsating (50%), Wave-like (40%).

A Chi-Square Test revealed no significant association between device type and pressure pattern preference ($X^2 = 0.2338$, p = 0.890). This finding suggests that user preferences for pressure patterns depend on the device type.

- Analysis of Overall Pressure Pattern Preferences

A Chi-Square Goodness-of-Fit test addressed whether the preference for time-dependent pressure patterns occurred by chance. The data from both devices were combined, and the following distribution of preferences was obtained:

Pressure Pattern	Count
Constant	2
Pulsating	8
Wave-like	10
Total	20

Table 5.1: Distribution of Overall Pressure Pattern Preferences Across All Participants

The null hypothesis stated no preference for any pressure pattern (i.e., all patterns are equally preferred). The Chi-Square test yielded a statistic of $X^2 \approx 5.2$, with $df = 2$ and $p = 0.074$. Since $p > 0.05$, we fail to reject the null hypothesis.

This shows that no statistically significant preference exists for any given pressure pattern when the data from both devices are combined. The observed differences in preferences could have occurred by chance.

- Visual Representations

Charts were developed to provide a clear overview of the data, which included:

- **Box Plots**: Both devices' range, median, and variability of ratings for comfort and relaxation were portrayed. These plots showed that the inflatable device had an edge in relaxation ratings, whereas the comfort ratings were more similar for the two devices.

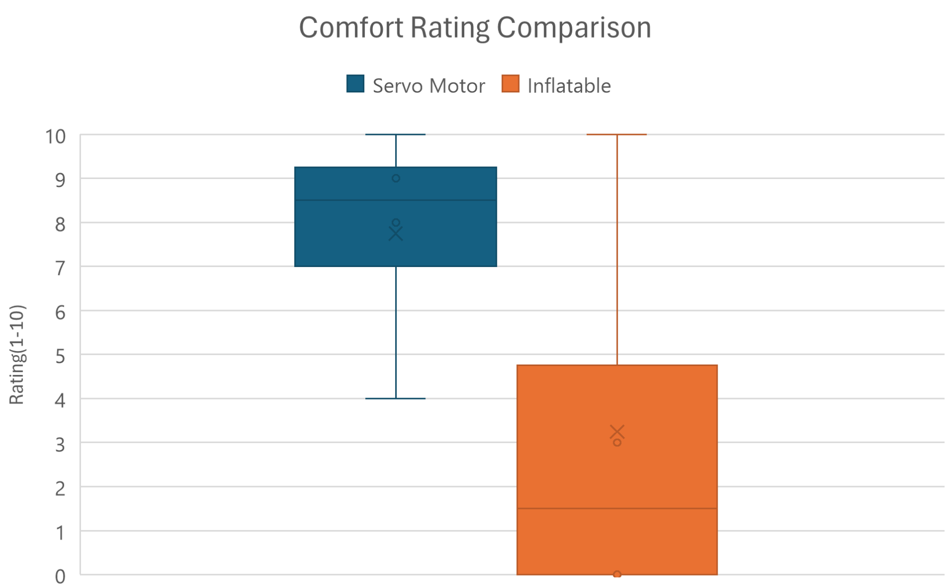

Figure 5.1: Comparison of comfort ratings for the servo motor and inflatable devices

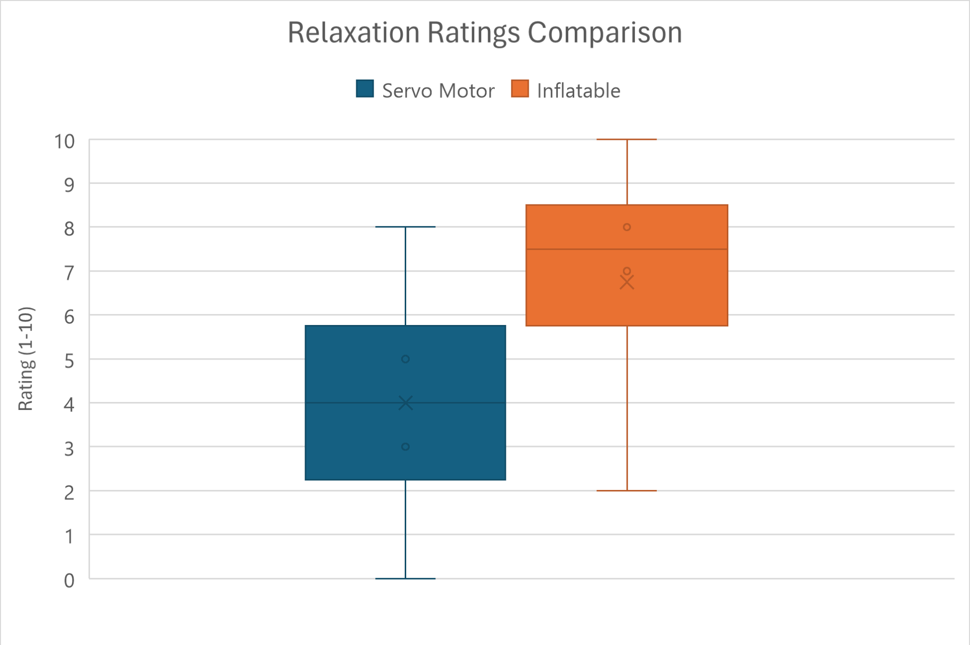

Figure 5.2: Comparison of relaxation ratings for the servo motor and inflatable devices

- **Bar Chart**: Depicted the distribution of pressure pattern preferences across the two devices. This chart highlighted the diversity in user preferences, where wave-like patterns were generally favored.

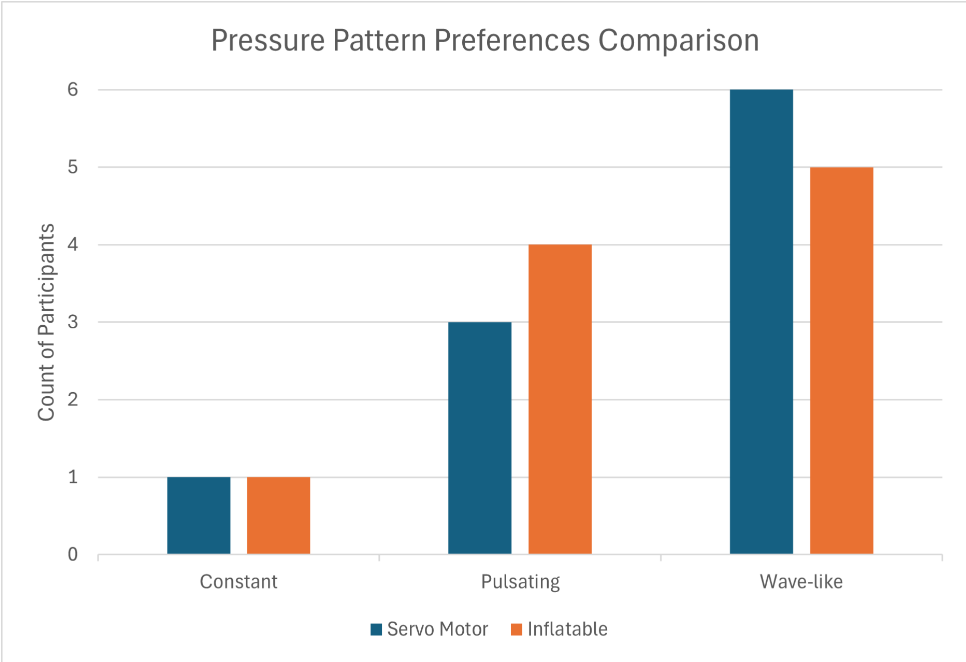

Figure 5.3: Distribution of participants' pressure pattern preferences (constant, pulsating, wave-like) for the servo motor and inflatable devices

- Comfortable Pressure Levels

Force Sensitive Resistors (FSRs) were used to measure the applied pressure in real-time during each session to analyze the range and intensity of pressure participants found most comfortable. The raw ADC values recorded by the FSRs were converted into forces in Newtons (N) using the following calibration equation:

$$F(N) = 0.0997 * (ADCValue) - 0.0124$$

To further contextualize these forces, they were converted into equivalent weights in grams (g) using the relationship:

$$F(g) = F(N) * 101.97$$

This conversion helped relate the applied pressures to familiar objects and tactile experiences. To provide additional context, real-world examples of forces were calculated based on Newton's Second Law:

- **2 N**: The weight of a medium-sized apple (∼200 g).
- **5 N**: Lifting a half-liter water bottle (∼500 g).

- **10 N**: The force required to grip a moderately heavy object like a large mug (∼1 kg).
- **15 N**: The force exerted when lifting a small dumbbell (∼1.5 kg).

Result for the Servo Motor Device: Most forces fell within the pressure range below 4 N, with only two measurements reaching pressure (4-8 N) and one exceeding 8 N. This indicates that the servo motor device predominantly delivered gentle pressures suitable for soft stimulation.

Result for the Inflatable Device: Most forces fell within the pressure range of 4–8 N, with three measurements exceeding 8 N. This broader range suggests that the inflatable device can deliver firmer pressures compared to the servo motor device.

These findings highlight distinct differences between the two devices: while the servo motor device primarily delivers gentle stimulation, the inflatable device provides more significant variability in pressure levels, potentially accounting for differences in user preferences.

The tables below present detailed datasets obtained from the Force-Sensitive Resistor (FSR) sensor for both devices, including raw ADC values, calculated forces in Newtons (N), and their equivalent weights in grams (g).

Raw Value (ADC)	Force (N)	Force (g)
44	4.38	446.47
37	3.68	375.64
38	3.78	385.83
36	3.58	365.45
18	1.78	181.52
54	5.37	547.56
88	8.76	892.80
33	3.29	335.00
56	5.57	568.94
110	10.96	1,118.82

Table 5.2: Summary of FSR Sensor Data Showing Raw ADC Outputs and Calibrated Force Values for the **Servo Motor Device**

Raw Value (ADC)	Force (N)	Force (g)
171	17.05	1,739.64
94	9.38	955.67
70	6.97	710.51
68	6.77	690.00
46	4.58	467.09
113	11.28	1,149.57
44	4.38	446.47
57	5.65	575.88
106	10.56	1,076.47
69	6.87	700.26

Table 5.3: Summary of FSR Sensor Data Showing Raw ADC Outputs and Calibrated Force Values for the **Inflatable Device**

5.1.3 Qualitative Results

Qualitative data were obtained from workshops with 10 participants, 5 of whom were males and 5 of whom were females. These workshops examined the usability and effectiveness of two wearable haptic devices: the servo motor and inflatable models. Participants provided detailed feedback on various aspects, including comfort, relaxation, and design preferences.

5.1.3.1 Key Themes and Insights

Feedback from 10 participants highlighted the following themes:

- Design Features and Relaxation Efficacy
The servo motor device impressed them due to its precise application of pressure, whereas the inflatable device did the same by applying pressure evenly. Most participants were fascinated by the therapeutic value of both devices. One claimed, "The servo motor provides noticeable pressure, while the inflatable one is more even in distribution and soothing.

Both devices could induce relaxation, as most subjects continuously commented on their different operation mechanisms. For example, the servo motor mechanical feedback was characterized by some "dynamic but slightly inconsistent," whereas the inflatable device had been mentioned to perform "reliable and gentle compression."

- Pressure Mechanisms and Customization
Wave-like patterns emerged as the most popular for both devices. For many, the fact that they could change between different patterns added to their feelings of control over their relaxation experience. One participant said, "Having patterns one can customize will make this device feel more tailored to my needs."

Moreover, feedback showed the importance of device adjustability. Participants pointed out the importance of different pressure levels as a pre-programmed option. One participant explained, "Sometimes I need to have a firmer pressure, while other times a gentler setting feels more relaxing. Both options should be available."

- Wearability, Comfort, and Immediate Feedback
Participants constantly reflected on wearability and comfort in feedback provided during testing sessions that ranged between 10 and 15 minutes for each device. Though a servo motor device's soft fabric drew applause from participants, some noted how such bulk could affect comfort upon prolonged wearing. However, several participants had nothing but praise regarding the weight of the inflatable device. One participant shared, "The inflatable device feels natural on my wrist—it is almost unnoticeable during the short session."

Participants emphasized the importance of the material quality used in the inflatable device's balloons, highlighting that skin-friendly materials enhance comfort during brief testing periods. However, some noted that further refinements could be made to reduce potential discomfort if these devices are used for longer durations.

5.1.3.2 Participant-Driven Design Suggestions

The participants also gave insightful views on the development and functionality of the two devices to enhance their use and efficiency. Key recommendations included:

- **Consistency in Pressure Delivery**: Participants noted that while the servo motor device worked well, its application of pressure should be more consistent across different uses. One participant emphasized this discovery: "The pressure is effective but feels uneven at times, which could distract from the relaxation experience."
- **Automatic Operation**: The respondents suggested that the inflatable

device should have an automatic mode to be used hands-free. Such a feature would further enhance the seamless and effortless nature of relaxation.

- **Material Improvements**: Participants emphasized the importance of advanced materials to improve comfort and durability. They suggested using softer, more breathable fabrics for extended wear and materials that are better at resisting wear and tear. Additionally, they considered allergies some people may have to certain materials.

One participant suggested an exciting feature: the inclusion of temperature control within the inflatable device. They explained, "Adding warmth to the pressure application would make it even more relaxing, especially in colder environments or for stress relief during the winter."

Qualitative feedback underlines the need to balance functionality, comfort, and adaptability in wearable haptic devices. While both devices successfully met the goals of relaxation, user preferences highlighted areas for improvement, especially in customization and long-term wearability. These insights provide a foundation for future design iterations, ensuring that the devices continue to address user needs effectively.

5.2 Statistical Analysis and Interpretation

This section presents the statistical analysis of the data collected during the study. Non-parametric and parametric methods were used in carrying out the analysis; the results were interpreted at both the theoretical and practical levels to meet the study's purpose of evaluating wearable haptic devices.

5.2.1 Shapiro-Wilk Test for Normality

Shapiro-Wilk test was performed to determine the normality of distribution for relaxation and comfort rating datasets. This test is the most appropriate for a small sample size, which applies to the current study involving 10 participants. The results are as follows:
Interpretation: The servo motor dataset for relaxation ratings was approximately normal, while the inflatable device dataset was not. For comfort ratings, both datasets were not approximately normal. Given these results, non-parametric methods such as the Wilcoxon Signed-Rank test were deemed appropriate for comparing medians.

Rating Type	Device	p-value	Interpretation
Relaxation Rating	Servo Motor	0.1012	Approximately normal ($p > 0.05$)
	Inflatable	0.02621	Not approximately normal ($p \leq 0.05$)
Comfort Rating	Servo Motor	0.03705	Not approximately normal ($p \leq 0.05$)
	Inflatable	0.04106	Not approximately normal ($p \leq 0.05$)

Table 5.4: Summary of Shapiro-Wilk Test Results for Comfort and Relaxation Ratings

5.2.2 Wilcoxon Signed-Rank Test

The Wilcoxon Signed-Rank test, a non-parametric alternative to the paired t-test, was used to compare the medians of relaxation and comfort ratings between the two devices.

- **Relaxation Ratings**:
  - **Devices**: Servo Motor (Mdn = 7) vs. Inflatable (Mdn = 8)
  - **Results**: Z = 1.3, p = 0.200, r = 0.5
  - **Interpretation**: No statistically significant difference was found. The medium effect size (r = 0.5) suggests a trend favoring the inflatable device for relaxation but without statistical confirmation.
- **Comfort Ratings**:
  - **Devices**: Servo Motor (Mdn = 8.5) vs. Inflatable (Mdn = 9)
  - **Results**: Z = 0.3, p = 0.763, r = 0.1
  - **Interpretation**: No statistically significant difference was found. The small effect size (r = 0.1) indicates minimal practical difference in device comfort ratings.

5.2.3 Pearson Correlation Analysis

The Pearson correlation coefficient was used to evaluate the relationship between comfort and relaxation ratings for each device.

Device	Correlation Coefficient (r)	p-value	Interpretation
Servo Motor	0.657	0.039	Significant large positive relationship
Inflatable	0.611	0.061	Non-significant large positive relationship

Table 5.5: Pearson Correlation Analysis for Comfort and Relaxation Ratings

Interpretation: A significant strong positive correlation was observed for the servo motor device, indicating that higher comfort scores are associated with higher relaxation scores. Similarly, a strong positive correlation was observed for the inflatable device; however, this relationship did not reach statistical significance.

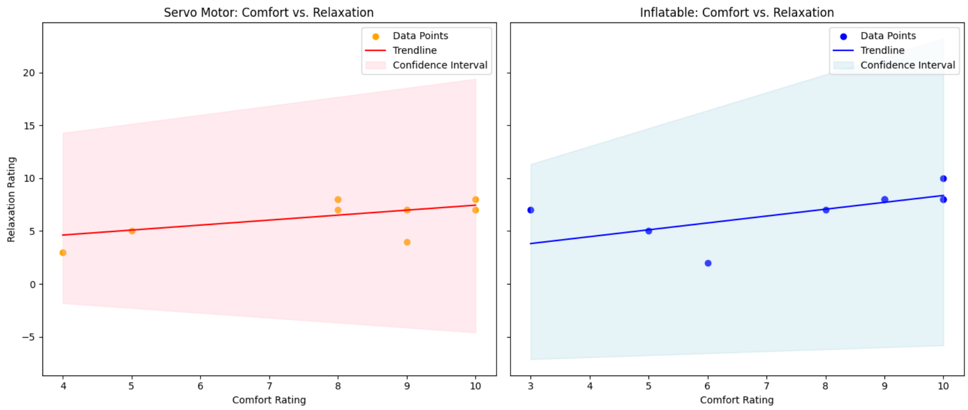

Figure 5.4: Scatterplots of comfort vs. relaxation ratings for the servo motor device (left) and inflatable device (right), with trendlines and confidence intervals

scatterplots in Figure 5.4 illustrate the relationship between comfort and relaxation ratings for both devices. For the servo motor device, a significant positive correlation was observed ($r = 0.657$, $p = 0.039$), indicating that higher comfort scores are strongly associated with higher relaxation scores. In contrast, the inflatable device showed a positive correlation ($r = 0.611$, $p = 0.061$) that did not reach statistical significance, suggesting variability in participants' experiences with comfort and relaxation. The trendlines represent the general relationship between these variables, while the shaded areas indicate confidence intervals to account for variability.

Servo Motor Device: The correlation analysis shows a significant positive relationship between comfort and relaxation ratings ($r = 0.657$, $p = 0.039$). This result indicates that higher comfort ratings are strongly associated with higher relaxation ratings for the servo motor device.

Inflatable Device: The inflatable device demonstrates a positive correlation between comfort and relaxation ratings ($r = 0.611$, $p = 0.061$). However, the relationship is not statistically significant, suggesting variability in how participants experienced comfort and relaxation with this device.

5.2.4 Combined Interpretation

The statistical findings align with the study objectives, providing valuable insight:

1. Both devices were similarly effective for comfort and relaxation, with slight trends favoring the inflatable device.
2. The strong positive correlation between comfort and relaxation for the servo motor device underscores the importance of prioritizing comfort in design.
3. The popularity of wave-like patterns highlights user preferences that should guide future iterations.

5.3 Synthesis of Results and Alignment with Project Goals

This section reflects on how the findings align with the project's goals and highlights the study's contributions to developing, evaluating, and refining wearable haptic devices for relaxation. The key goals and their alignment with the results are as follows:

Goal 1: Develop Functional Wearable Haptic Devices for Relaxation
Two functional prototypes were developed and refined: a servo motor device and an inflatable device. Iterative prototyping improved the servo motor device to balance comfort and functionality, while the inflatable device achieved its goals with minimal iterations, demonstrating its simplicity and effectiveness.

Goal 2: Evaluate Comfort and Relaxation Efficacy
Quantitative and qualitative analyses validated the devices' efficacy in providing comfort and relaxation. Both devices received high comfort and relaxation ratings, with the inflatable device slightly outperforming the servo motor device in comfort. The Pearson correlation analysis further supported the connection between comfort and relaxation.

Goal 3: Understand User Preferences for Pressure Patterns
User feedback highlighted the popularity of wave-like pressure patterns, emphasizing the importance of dynamic stimulation in promoting relaxation.

These findings underscore the need for customizable pressure patterns to enhance user satisfaction in future designs.

Goal 4: Investigate Correlations Between Comfort and Relaxation Ratings

The significant positive correlation between comfort and relaxation for the servo motor device highlights the importance of comfort in enhancing relaxation efficacy. While a strong positive correlation was observed for the inflatable device, it did not reach statistical significance, indicating potential variability in user experiences.

The results demonstrate strong alignment with the project goals and provide valuable insights into wearable haptic technologies for relaxation. These findings establish a foundation for further research and development.

Chapter 6

Discussion

The Discussion chapter discusses the findings of the study and the project's objectives based on the implications of quantitative and qualitative outcomes. The discussion will include ratings of comfort and relaxation, user feedback, and statistical test results of servo motor and inflatable devices to measure the success, shortcomings, and further improvements.
This chapter synthesizes these findings into their practical, theoretical, and design implications within the greater context of wearable haptic technology. It emphasizes that this study contributes to advancing user-centred design principles and lays the foundation for future research into existing gaps in the field. Furthermore, this chapter points out the study's limitations and, based on this, provides recommendations for actionable future research and development.
This discussion even situates the study in wearable haptic devices relevant to relaxation, shedding light on pathways to innovation and applications.

6.1 Key Findings

6.1.1 Quantitative Results Discussion

The quantitative results provide rich insights into the performance and usability of wearable haptic devices. Both devices received a high rating for comfort: the servo motor device had a mean rating of 8.0 and a median of 8.5, while the inflatable device followed closely with a mean rating of 7.9 and a median of 9.0. Even though the Wilcoxon Signed-Rank test on comfort ratings was insignificant ($Z = 0.3$, $p = 0.763$, $r = 0.1$), the high, consistent scores support that the devices meet user comfort expectations.

The ratings for relaxation revealed a slight trend in favor of the inflatable device, which scored an average rating of 7.1 and a median of 8.0 against the servo motor device, with an average of 6.4 and a median of 7.0. Although this trend was not statistically significant (Z = 1.3, p = 0.200, r = 0.5), it reflects participants' perception of the inflatable device as a more effective tool for relaxation. This observation, together with qualitative feedback, indicates possible design features, such as pressure distribution and lightweight construction, that contributed to the inflatable device's perceived efficacy.

Pressure pattern preference showed that 60% of the participants using the servo motor device and 40% using the inflatable device favored wave-like patterns. A Chi-Square Test was conducted to determine whether a statistically significant association existed between device type (servo motor vs. inflatable) and pressure pattern preference (constant, pulsating, wave-like). The results showed that there was no strong correlation ($X^2 = 0.02338, p = 0.0890$), suggesting that user preference for pressure patterns was independent of the device.
This lack of statistical significance does indicate that all participants' preferred wave-like patterns were consistent in both devices, regardless of mechanisms for pressure distribution. While the finding suggests an absence of significance in the correlation of device type to pattern preference, it establishes a general consensus for dynamic versus constant or pulsed stimulation patterns.
Physiologically, wave-like patterns can replicate natural breathing rhythms or calming movements of massage, which are known to be relaxing in nature. Psychologically, these patterns would naturally create a sense of flow and continuity, making the relaxation process more pleasant. Qualitative feedback supports this reading, with subjects explaining wave-like patterns as "natural" and "comforting."
The finding emphasizes the resilience of dynamic pressure mechanisms for future haptic systems. Integrating wave-like patterns in wearable haptic technology must be designers' top priority, along with other features that can be customized to cater to personal tendencies. This universal preference for devices means that wave-like pattern mechanisms may also be a global feature in haptic technologies specifically developed for relaxation.

Interpretation of Pressure Pattern Preferences: Statistical analysis of overall pattern preference for pressure patterns uncovered some intriguing results.

While the raw data suggested an overall pattern trend towards time-dependent patterns (pulsating and wave-like), the Chi-Square Goodness-of-Fit test $X^2 \approx 5.2, df = 2, p = 0.074$ failed to confirm this perceived preference as statistically significant at the standard $\alpha = 0.05$ level. This outcome differs from our early observation and qualitative feedback, which favor dynamic stimulation. There are several explanations for this disparity:

1. **Sample Size**: With only 20 total observations in the sample, the study might lack the statistical power necessary to identify a proper preference if one exists.

2. **Individual Variations**: The results' inability to be statistically significant may be due to true individual variability in preference, suggesting that personalization may be the priority in future device design.

3. **Device Differences**: Though we combined data from both devices for this analysis, device-related effects on preference may not be apparent in the combined data.

These results demonstrate the richness of haptic preference and justify further study using more extensive sample populations and advanced experimental designs. While we cannot claim to find a large preference for time-dependent patterns, the data trend and qualitative remarks still provide useful guidance for the future design of wearable haptic devices for relaxation.

6.1.2 Qualitative Results Discussion

The qualitative findings from this study provide rich, nuanced insights into the usability and perceived effectiveness of wearable haptic devices. By capturing participants' feedback, this research has illuminated the juncture of user experience and device design, thus carving key directions for future development.

Among the most recurring themes in participant feedback was the value of customization in achieving a tailored relaxation experience. The preference for wave-like and pulsating patterns underlines the need for dynamic stimulation rather than static pressure. One participant said, "Having patterns one can customize will make this device feel more tailored to my needs." This discovery affirms the importance of personalization and suggests that user preferences are central to the success of wearable haptic technologies.

Future designs could include adaptive algorithms that adjust pressure patterns based on user inputs or biometric feedback in real-time, offering real-time personalization.

Participants also emphasized the importance of device adjustability, particularly in pressure intensity. For instance, one participant noted, "Sometimes I need to have a firmer pressure, while other times a gentler setting feels more relaxing. Both options should be available." This feedback suggests that future iterations of the devices could benefit from pre-programmed pressure levels, allowing users to toggle between settings depending on their relaxation needs or environmental context.

Wearability emerged as a critical factor in determining the overall user experience. The lightweight design of the inflatable device and its seamless fit were often pointed out as strong positives. One participant said, "The inflatable device feels natural on my wrist-it's almost unnoticeable during the short session." This finding emphasizes that proper ergonomic design and the choice of materials are particularly relevant in wearable technologies. On the other hand, participants pointed out some drawbacks, such as the bulkiness of the servo motor device and possible discomfort after prolonged wear. These insights suggest that future designs should use materials that combine durability with comfort and pursue compact form factors to improve wearability over extended periods.

Other points raised in the feedback that were of interest included how extra features, such as temperature control, would add to the relaxation effect. One participant suggested, "Adding warmth to the pressure application would make it even more relaxing, especially in colder environments or for stress relief during the winter." This result again stresses the multimodal nature of wearable haptics; adding features such as heat or vibration could extend the devices' appeal and functionality.

In summary, the qualitative findings underscore the importance of user-centred design in wearable haptic technologies. Customization, adjustability, and ergonomic considerations came to the fore as decisive factors in shaping user satisfaction. Incorporating these insights into future designs could lead to devices that meet and exceed user expectations, fostering a more immersive and personalized relaxation experience. These findings provide a guideline to enhance the adaptability and usability of wearable haptic devices, ensuring their relevance in diverse contexts and applications.

6.1.3 Synthesis of Findings

Findings integration consolidates quantitative results with qualitative insights into one coherent understanding of the performance, usability, and potential of wearable haptic devices developed in this study. During the first-person design process, I observed that material selection played a crucial role in achieving both comfort and functionality. This insight aligned with user feedback emphasizing wearability and skin-friendly materials, validating the iterative approach used. The section explores how these findings converge and diverge, pointing out their implications for future design and application.

Complementarity Between Quantitative and Qualitative Insights
The quantitative results showed that both devices were rated highly in comfort and relaxation, though the inflatable device had a slight perceived advantage in relaxation. This trend is consistent with the qualitative feedback, in which many participants commented on the inflatable device's lightweight and even pressure distribution. However, the lack of statistical significance in rating differences indicates large variability in user preference and experience, highlighting the need for customization and user-specific design considerations.
This preference for wave-like pressure patterns quantitatively observed at 60% in the case of a servo motor device, and 40% in the case of an inflatable device is further supported by qualitative insights: Participants consistently commented on the dynamic and soothing nature of wave-like patterns, suggesting that these evoke a natural rhythm, such as breathing or massage movements. These findings underline that haptic devices should provide dynamic and adjustable stimulation patterns for different user preferences.

Intersection of First-Person RtD and Participant Feedback
The first-person RtD process was crucial during the prototyping phase, giving the necessary insights into making the devices comfortable and functional to wear while providing effective haptic feedback. The iterative process highlighted the most important aspects concerning material selection, wearability, and pressure mechanisms that were later validated by participant feedback.
For instance, the servo motor device was a balancing act for precision in the application of pressure and the overall comfort of the subjects. The

iteration refinement was significant, with users pointing out the effectiveness of applying pressure with focal points. Equally, its initial success, informed through first-person documentation, was further validated by the participants' positive experiences, who felt that it had an ergonomic design and was easy to use.

Comparing First-Person Reflections with User Feedback
First-person reflections complement user feedback with overlying and differing priorities concerning both design and evaluation. First-person RtD emphasized choice of material, control over pressure, and manageability in a prototype. At the same time, users expressed additional long-term needs about wearability over a longer time, adaptability, and increased possibilities for customization.

For the servo motor device, first-person insights focused on refining pressure application and ergonomics. While users appreciated such refinements, they indicated they are bulky for extended wear. In the inflatable device, simplicity and even pressure were key strengths from the designer's perspective. At the same time, users suggested adding features, like variable intensity and temperature control, that would enhance functionality.

Key themes included the shared focus on comfortable materials; user feedback regarding long-term wear and personalization added a lot. Such a comparison underlines the importance of combining focused, first-person testing with a broader set of user perspectives in refining wearable haptic devices that balance technical precision with user satisfaction.

Bridging User Preferences with Design Improvements
Qualitative data revealed user preferences beyond quantitative measures, including adjustable pressure intensity, temperature control, and compact form factors. These indicate opportunities to extend the current design by incorporating multimodal features and pre-programmed settings that meet individual needs.
While the quantitative analysis quantified comfort and relaxation, the qualitative feedback provided context and depth, illustrating how specific design elements—like pressure mechanisms and material choices—impacted user experience. Combining these methods offers a comprehensive evaluation, guiding future iterations toward user-centric innovation.

Overarching Conclusions
These findings show that comfort and relaxation are related, while users' satisfaction depends both on the technical functionality of the devices and how well they match a person's individual preferences. This synthesis of the results underlines that iteration in design, user feedback, and a multimodal approach can add substantial value to designing wearable haptic technologies for promoting relaxation.
Future works should embed such insights into scalable and adaptable solutions by filling the gap between laboratory testing and real-world application.

6.2 Interpretation of Statistical Results

6.2.1 Implications of the Shapiro-Wilk Test

The Shapiro-Wilk test indicated that most datasets were not normally distributed, so non-parametric statistics had to be used. This determination is especially true for small sample sizes, where normality assumptions are rarely met. The choice of the Wilcoxon Signed-Rank test guaranteed the validity of the statistical comparisons, which further speaks to the importance of choosing appropriate methods of analysis in research.

6.2.2 Implications of Wilcoxon Signed-Rank Test Results

Wilcoxon Signed-Rank test results indicated no statistically significant differences in comfort or relaxation ratings between devices. However, the medium effect size for the relaxation ratings ($r = 0.5$) indicates there may be a trend to favor the inflatable device. This finding is consistent with the qualitative responses, which indicated that the even distribution of pressure and light weight of the inflatable device were major contributors to its perceived efficacy.

This finding underscores the importance of design features that enhance user comfort and relaxation, even when statistical significance is not achieved. The medium effect size indicates that, while the quantitative difference in ratings may not be statistically significant, the observed trend is meaningful in the context of user experience. This outcome suggests that user perceptions, as captured in qualitative responses, provide valuable insights that complement statistical analyses.

By integrating statistical and qualitative findings, the study highlights the potential for iterative design to address subtle user preferences and needs, ultimately shaping the development of wearable haptic devices for relaxation.

6.2.3 Pearson Correlation Analysis

Pearson's correlation analysis indicated that the servo motor device had a significant positive relation with comfort and relaxation ratings, $r = 0.657$, $p = 0.039$. That is, with increasing comfort, the ratings for relaxation also significantly improved. In contrast, the strong positive correlation in the case of the inflatable device was insignificant, $r = 0.611$, $p = 0.061$. This outcome is intriguing because it begs more questions regarding what factors drive this relationship and would be worth further investigation.

For the servo motor device, this significant correlation may be due to the precision and directed nature of the applied pressure. The mechanical design probably let the participants perceive and appreciate the direct impact of the pressure on their relaxation, as user feedback highlighted the device's effectiveness in delivering "noticeable pressure." The documented positive relationship between physical comfort and psychological relaxation could explain why participants who rated the device as comfortable were likelier to report higher relaxation levels.

On the other hand, the non-significant correlation for the inflatable device may reflect variability in user experiences with its design. While many participants praised its lightweight and even pressure distribution, others suggested room for material quality and long-term wearability improvement. This variability could have diluted the relationship between comfort and relaxation. Furthermore, the inflatable device's softer and more diffuse pressure application might have been less noticed by some participants, which would eventually make it more difficult to associate their comfort experience with relaxation.

Another important factor involves the user preferences of individuals that could have affected the relationship outcomes. In these subjects, the preference for dynamic patterns of pressure, such as wave-like or pulsating, may have led them to perceive a more significant difference between the two devices in their potential to provide such patterns, which in turn could mean the servo motor device better aligned with their preferences and therefore enhanced the comfort-relaxation relationship. On the contrary, the evenly distributed pressure of the inflatable device, while soothing for some, may have been too nondynamic for others and thus elicited more significant variability in user responses.

Testing conditions may also have contributed to the observed differences. While the controlled environment for testing effectively minimizes external variables, it may not fully represent real-world scenarios where relaxation and comfort interact differently. For example, the inflatable device's lightweight and ergonomic design may provide more significant advantages in dynamic or outdoor settings, where wearability and adaptability become more critical than other features.

The significant correlation underlines the importance of focused and noticeable pressure application for relaxation in the servo motor device. At the same time, design variability and user preference play a more significant role in shaping user experiences in the inflatable device. These results indicate that future designs would benefit from the servo motor device's precision and the inflatable device's ergonomic advantages, thus improving comfort and relaxation outcomes. Testing in diverse real-world environments may provide deeper insight into how these relationships evolve under different conditions.

6.3 Practical Implications

The results of this study hold several practical implications for the design and applications of wearable haptic devices:

1. **Ergonomic Design and Material Innovation**: Ergonomics became an important user experience factor. The servo motor and inflatable devices both showed that wearability is important, with test participants mentioning the need for light, comfortable materials that do not affect functionality. The success of the inflatable device in being "natural on the wrist" underlines the value of using skin-friendly, breathable fabrics that allow for extended wear. Fasteners could be further refined in future designs for security with adjustability in wearing, especially when different users have wrists of varying sizes.

   Another area for improvement is in device bulk reduction, especially in the servo motor device. While its application of targeted pressure was much appreciated, several participants commented on how this could become uncomfortable during extended use because of its mechanical nature. This outcome infers that compact and integrated designs would be necessary, which can also maintain functionality without adding weight or rigidity. Development in material science, including lightweight composites or flexible electronics, may significantly enhance both devices' ergonomic appeal.

2. **Dynamic Pressure Mechanisms and Customization**: The strong preference of the participants for wave-like and pulsating pressure patterns emphasizes that dynamic stimulation is quite effective in promoting relaxation. That means that in the future, devices should be designed to strongly emphasize personalized mechanisms for adjusting pressure. Such customization features could include pre-programmed settings or user-controlled pressure adjustments. The ability to switch seamlessly between patterns, such as wave-like motions for calming effects and pulsating motions for energizing stimulation, could significantly improve user satisfaction and extend the devices' appeal.

   Additionally, user feedback suggested advanced features such as temperature modulation. Incorporating warmth into the pressure application, especially for the inflatable device, could add other layers of sensory stimulation, making the devices even more effective for relaxation, especially in cold environments.

3. **Applications in Stress-Inducing and Therapeutic Contexts**: Applications for wearable haptic devices range from stress management in high-pressure workplaces to therapeutic interventions for individuals with anxiety or sensory processing disorders. For instance, in fast-paced office environments, these devices can be used as subtle tools for mid-day relaxation that help users manage stress without interrupting their workflow. Such a device could also provide a gentle and variable pressure that might be very calming as sensory input in therapeutic settings, such as in patients undergoing rehabilitation or those with autism spectrum disorder.

   The inflatable device's simplicity and portability especially make it suitable for dynamic or outdoor settings, such as during the rush of commuting or relaxation outdoors. On the other hand, with its precision in applied pressure, the servo motor device may be better suited for controlled environments when focused therapeutic effects are desired, as in a clinical setting.

4. **Future Design Directions**: Results of this study give a pointer for future developments in wearable haptic technology. By merging further ergonomic improvements, dynamic pressure mechanisms, and sophisticated sensory features, such devices should evolve to meet heterogeneous user needs. Testing in ecological conditions, combined with iterative user feedback, will play a crucial role in these devices' functional capability and adaptability to various contexts.

This study makes several practical recommendations on ergonomic design, user customization, and real-world applicability. These results confirm the wearables' potential as devices for relaxation and allow us to draw some heuristic recommendations relevant to their further development and integration into everyday life.

6.4 Contributions to Project Goals

6.4.1 Alignment with Goals

This project has made several key contributions towards understanding and developing wearable haptic devices for relaxation:

1. **Develop Functional Wearable Haptic Devices for Relaxation**: During development, two prototypes that can be worn and functional—a servo motor and an inflatable device—were designed, built, and refined. The number of iterations that the servo motor device went through was 4, and the iterations were balanced between comfortability, usability, and practical pressure application. Contrary to this, the inflatable device exemplified the importance of simplicity and effectiveness by fulfilling the functional criteria with minor modifications. The findings of this research show that the design process, which has been done iteratively, is a way of creating functional and user-friendly devices.

2. **Evaluate Comfort and Relaxation Efficacy**: Quantitative evaluation methods included the efficacy of the devices in providing comfort and relaxation by ratings on a standardized scale. Both were good, but the inflatable device performed better than the servo motor device regarding

relaxation ratings. These findings underpin evidence-based insights into the effectiveness of devices by underlining the evaluation of user experiences in wearable haptic technology.

3. **Understand User Preferences for Pressure Patterns**: This work applied RtD and participatory design to study user preferences related to the usage of various haptic pressure patterns. Wave-like patterns emerged as the most preferred, indicating dynamic stimulation in developing captivating and relaxing experiences. These results give some actionable insights for possible designs, focusing on the need for modifiable pressure patterns given different users' needs.

4. **Investigate Correlations Between Comfort and Relaxation Ratings**: The quantitative analysis yielded a highly positive correlation between the comfort and relaxation ratings for the servo motor device, which is very much in agreement with the hypothesis that comfort enhances the perceived effectiveness of haptic stimuli during relaxation. At the same time, even though the correlation for the inflatable device did not attain statistical significance, its strong positive trend suggests further research about design features that optimize comfort and relaxation.

These contributions highlight the importance of iterative design, user-centred methodologies, and rigorous evaluation in developing effective and practical wearable haptic technologies for relaxation and well-being. This project lays the groundwork for future innovation in this domain by addressing key literature gaps and leveraging participatory methods.

6.4.2 Broader Contributions

Bridging Literature Gaps: The novelty of the present research involves key gaps in the existing literature on the forearm as a novel application site for pressure-based haptic feedback and the integration of user preferences in device design. These contributions help directly expand the knowledge in the area of effectiveness in relaxation by wearable devices based on the forearm and investigate user preferences about pressure patterns.

Methodological Contributions The study used a mixed-methods methodology, combining RtD, participatory design, and quantitative analysis to evaluate these devices comprehensively. This combination has provided a practical methodology to validate comfort and relaxation efficacy; it has provided a model for future research balanced between technical innovation and user experience and aligned to use robust methodologies for investigating the effectiveness of haptic stimuli.

Foundation for Future Innovation This study forms a baseline for a solid start on this intensive progress by showing that by identifying user choices or wave-like pressure patterns and adjusting the pressure stress levels, the link between comfort and relaxation is established. This knowledge can provide us with important information regarding satisfaction and adaptation in the future.

6.5 Limitations of the Study

This study faced several limitations, which should be considered when interpreting the findings and planning future research:

1. **Sample Size and Diversity**: The sample size was small and homogeneous, with 10 participants, of which half were males and half females. While this sample size allowed for rich qualitative feedback and preliminary quantitative analysis, it limits the generalizability of the findings. A more extensive and diverse participant pool would allow for broader conclusions and may reveal trends that apply to specific demographics, such as age groups, cultural contexts, or occupational settings. Future studies will increase the sample size to ensure high statistical power and that the findings are generalizable to a larger population.

2. **Controlled Testing Environment**: All testing sessions were conducted indoors under controlled conditions in a quiet room at the Södertälje Library. These conditions were perfect to exclude disturbance factors and provide a base that was as uniform as possible but may not perfectly reproduce real-life use. For example, participants did not test the devices in environments that mimic typical stress-inducing settings, such as workplaces or public spaces. Testing in diverse environments should be included in future studies to evaluate the usability and effectiveness of the devices in real-life contexts. Field tests in outdoor or dynamic settings could provide additional insights into the robustness and adaptability of the devices.

3. **Duration of Testing**: Testing sessions were limited to 10–15 minutes per device. The above duration was adequate to acquire initial

impressions of comfort and relaxation but did not enable the evaluation of long-term effects. More extended periods of wear could provide further information regarding wearability, durability, and effectiveness in maintaining a relaxed state. For example, more extended studies might measure discomfort from more extended usage or fluctuating levels of relaxation. Longitudinal studies that follow participants over weeks or months would provide a complete understanding of how the devices affect stress management and well-being.

4. **Focus on Subjective Measures**: While comfort and relaxation ratings gave meaningful subjective insights, no objective physiological measurements existed. Such measures as heart rate variability, cortisol levels, or skin conductance can confirm the self-reported data and, therefore, give a holistic evaluation of the effectiveness of the devices. Objective measures would also possibly be able to outline the variations in physiological responses concerning different pressure patterns and intensities, thus giving valuable suggestions for optimizing device functionality

5. **Limited Iterations for Inflatable Device**: Whereas the servo motor device had been iterated on after initial success, the inflatable device was not refined beyond that point. The device's functionality generally justified this, but further iterations may have produced areas for improvement; this could be the development of alternative designs, including improved materials or additional features such as temperature control, which could improve the device's appeal and functionality even further.

By acknowledging these limitations, this study provides a foundation for iterative improvement and targeted research, ultimately contributing to advancing wearable haptic technology for relaxation.

6.6 Recommendations for Future Work

Based on the limitations identified in this study, future research should:

- Address the limited sample size and homogeneity by recruiting a larger, more diverse participant pool, including individuals from different age groups and cultural backgrounds.

- Conduct testing in more realistic environments, such as workplaces or homes, to assess how external factors influence device performance and user experience.
- Research advanced features such as temperature control, customizable profiles, and automatic pressure adjustment that would increase user experience.
- Extend the duration of testing sessions to evaluate the long-term wearability and sustained effectiveness of haptic devices over days or weeks.
- Emphasize cost-effectiveness and sustainability to make wearable haptic devices accessible to a broader audience.

This chapter has shown how the results reflect the project's objectives by providing valuable insights into the design, usability, and effectiveness of wearable haptic devices for relaxation. In light of the discussion in interpreting the results and the statistical analysis, user feedback shows the devices' strengths and areas that need improvement. The contributions of this study on wearable haptic technology will lay a foundation for further research that secures these devices into continued evolution to meet users' needs effectively.

Chapter 7

Conclusions and Future Work

This chapter summarizes the findings and contributions of this study by reflecting on how they address the project goals. It further assesses the research's outcomes, discussing limitations and making recommendations for future work. Besides that, it contemplates the wider implications of wearable haptic devices from an economic, social, environmental, and ethical perspective. The insights gained in this research add to the growing field of wearable haptic technologies and form a starting point for future innovation and application.

7.1 Conclusions

7.1.1 Alignment with Project Goals

This study successfully addressed its objectives by designing, evaluating, and analyzing wearable haptic devices for relaxation. Key accomplishments include:

1. **Device Development and Evaluation**: Two functional wearable haptic devices, a servo motor device and an inflatable device, were successfully developed and tested.

2. **User Preferences and Experience**: User preferences for dynamic pressure patterns, especially wave-like patterns, were identified.

3. **Correlation Between Comfort and Relaxation**: A significant positive correlation between comfort and relaxation was found for the servo motor device, highlighting the importance of comfort in haptic device design.

7.1.2 Key Insights and Achievements

This study contributes to the field of wearable haptic technology in several ways:

- **Dynamic Stimulation**: Wave-like patterns were preferred, showing their contribution to making the experience more engaging and relaxing.
- **Ergonomic Design**: The lightweight and comfortable design of the inflatable device represents a step toward user-centered design in wearable technologies.
- **Customization**: The desire for adjustable pressure patterns and levels further supports the customization of haptic devices.

7.1.3 Challenges and Drawbacks

While the study achieved its objectives, it encountered several challenges:

- **Sample Siz**: A small and homogeneous sample limited the generalizability of the findings.
- **Controlled Testing Environment**: The absence of real-world testing conditions limited the scope of the review.
- **Limited Iterations for the Inflatable Device**: Although initially successful, more refinements would have made it more valuable and attractive.

7.2 Evaluation of the Degree Project

Accomplishments
The project served to fill the gap within the research on wearable haptic devices for relaxation. Because of the iterative design process and integration of user feedback, the prototypes were much in line with the project's aims. They gave valuable insights into user preferences and design features.

Reflections on Methodology
The mixed-methods approach, which combined quantitative and qualitative data, proved effective in capturing user experiences and evaluating device efficacy. However, the reliance on subjective measures highlighted the need for integrating objective metrics in future research.

7.3 Limitations

1. **Sample Size and Diversity**: The small, homogeneous sample reduces the representativeness of the findings. Increasing the pool of participants with diverse demographics would enrich the validity and applicability of the results.

2. **Controlled Environment**: Testing in a quiet indoor environment controlled for variables that exist in natural environments, which may affect device performance and user experience.

3. **Testing Duration**: Short testing sessions limited the ability to evaluate long-term wearability and effectiveness.

4. **Subjective Measures**: Lack of physiological measures further limited the scope of analysis, leaving room for more comprehensive device efficacy.

5. **Limited Iterations for the Inflatable Device**: More iterations could have introduced features such as temperature control that would have greatly enhanced functionality.

7.4 Future Work

Future research should focus on expanding the understanding and application of wearable haptic devices for relaxation by:

- Investigating how individual differences (e.g., age, culture, preferences) influence the effectiveness of haptic devices and tailoring designs to specific user profiles.

- Exploring advanced features such as temperature control, personalized pressure profiles, and adaptive algorithms to enhance haptic device user experience and efficacy.

- Conducting long-term studies to evaluate the sustained effects of haptic devices on stress reduction and overall well-being.

- Developing objective methods for measuring relaxation responses and physiological data to validate subjective results and improve device efficacy.

- Prioritizing sustainable design practices and accessible materials to promote the widespread adoption of haptic devices.

7.5 Reflections

Social and Economic Implications
Wearable haptic devices could democratize stress management by making accessible, affordable, and portable solutions for various populations representing versatility and value to society, from applications within workplaces and therapeutic settings to personal use.

Environmental Considerations
To reduce the potential environmental impact, sustainable design methods must be considered, including the use of recyclable materials and energy-efficient mechanisms. Further research in biodegradable materials should be undertaken to develop such devices.

Ethical Considerations
In wearable technology, inclusivity and privacy protection are of the essence. Devices should be made to accommodate various users and sensitivities, and any integration with biometric data should maintain high ethical standards to bring transparency and user trust to a product.

Personal Reflections
The project has been an enlightening and multi-faceted experience. Being able to consider the work of both the engineer in developing the prototypes and the user in testing them has indeed been enlightening. Initially, I had concerns that my reflections might be biased due to the personal effort invested in creating the prototypes. However, seeing that many participants' preferences aligned with my observations was reassuring. Additionally, documenting first-person experiences offered valuable insights into the importance of structured self-reflection in research. Overall, this journey underscored the significance of user-centered design, iterative development, and interdisciplinary collaboration, providing a solid foundation for advancing wearable haptic technologies.

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