Designing Pneumatic Wearables

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ABSTRACT

This thesis explores pneumatic wearables as soft, bodily extensions that are designed to enrich everyday life experiences. While Human–Computer Interaction (HCI) has largely focused on sensing, often in serious or efficiency-driven contexts, recent work highlights the potential of actuation, particularly shape change, to support more embodied and playful interactions. However, most materials used are rigid and limit wearability. In response, this thesis investigates pneumatics as a soft and flexible alternative for creating shape-changing wearables. Five pneumatic bodily extensions were designed to promote embodied experiences: prompting goodbye waves; elongating the ear to encourage becoming a better listener; moving the hand away from the keyboard after prolonged typing; extending the nose when lying; and inflating the bicep as a result of exercise. Studies in participants' homes suggested that these bodily extensions supported interpersonal engagement, sparked social interaction, fostered wellbeing, encouraged self-reflection, and promoted physical activity. Synthesising the studies' findings, this thesis presents a framework for designing future bodily extensions that enrich embodied experiences. Ultimately, this work broadens the scope of bodily extension research, advancing the design of technologies that are expressive, personal, and enrich our embodied connection to the world.

DECLARATION

This thesis is an original work of my research and contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, or any use of generative artificial intelligence technologies, except where due reference is made in the text of the thesis.

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Date: February 2nd, 2026

PUBLICATIONS

Some of the research detailed in this thesis has been published at peer-reviewed venues in the field of Human-Computer Interaction. Furthermore, I have also contributed to publications in this field by collaborating with my peers across different institutions. A list of these publications is available below.

1. Florian 'Floyd' Mueller, Oğuz 'Oz' Buruk, Louise Petersen Matjeka, Aryan Saini. Towards understanding the design of playful bodily extensions via body schema and body image. International Journal of Human-Computer Studies. Volume 197, 2025.103457, ISSN 1071-5819,https://doi.org/10.1016/j.ijhcs.2025.103457.

2. Maria F. Montoya, Aryan Saini, Sarah Jane Pell, Phoebe O. Toups Dugas, and Florian 'Floyd' Mueller. 2025. Exploring the Role of Interactive Technology to Enrich Surfing. In Proceedings of the 2025 ACM Designing Interactive Systems Conference (DIS '25). Association for Computing Machinery, New York, NY, USA, 3581–3599. https://doi.org/10.1145/3715336.3735791

3. Rakesh Patibanda, Aryan Saini, Xiang Li, Yuzheng Chen, Elise van den Hoven, and Florian 'Floyd' Mueller. 2025. Playing with Yourself: How Electrical Muscle Stimulation Can Turn Your Body Into A Playful Interface. In Proceedings of the Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA '25). Association for Computing Machinery, New York, NY, USA, Article 919, 1–3. https://doi.org/10.1145/3706599.3721338

4. Nihar Sabnis, Dennis Wittchen, Ata Otaran, Fatima Badmos, Siyi Liu, Aryan Saini, Georg Regal, Vincent van Rheden, Florian 'Floyd' Mueller, Suranga Nanayakkara, Denys J.C. Matthies, Troy Nachtigall, Paul Strohmeier, Laia Turmo Vidal, and Don Samitha Elvitigala. 2025. Walking the Future: Bridging Foot Augmentation into Next Steps of Human Augmentation. In Proceedings of the Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA '25). Association for Computing Machinery, New York, NY, USA, Article 805, 1–7. https://doi.org/10.1145/3706599.3706742

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7. Maria F. Montoya, Aryan Saini, Nathalie Overdevest, Benjamin Randall, Sarah Jane Pell, and Florian Floyd Mueller. 2024. Exploring the Design of Playful Devices for Surfing. In Companion Proceedings of the 2024 Annual Symposium on Computer-Human Interaction in Play (CHI PLAY Companion '24). Association for Computing Machinery, New York, NY, USA, 200–207. https://doi.org/10.1145/3665463.3678786

8. Aryan Saini, Elise van den Hoven, and Florian ‘Floyd’ Mueller. 2024. PneuExtensio: Designing Pneumatic-based Bodily Extensions to Facilitate Embodiment across Everyday Life Experiences. In Companion Publication of the 2024 ACM Designing Interactive Systems Conference (DIS '24 Companion). Association for Computing Machinery, New York, NY, USA, 19–23. https://doi.org/10.1145/3656156.3665136

9. Rakesh Patibanda, Nathalie Overdevest, Shreyas Nisal, Aryan Saini, Don Samitha Elvitigala, Jarrod Knibbe, Elise van den Hoven, and Florian 'Floyd' Mueller. 2024. Shared Bodily Fusion: Leveraging Inter-Body Electrical Muscle Stimulation for Social Play. In Proceedings of the 2024 ACM Designing Interactive Systems Conference (DIS '24). Association for Computing Machinery, New York, NY, USA, 2088–2106. https://doi.org/10.1145/3643834.3660723

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11. Aryan Saini, Rakesh Patibanda, Nathalie Overdevest, Elise van den Hoven, and Florian ‘Floyd’ Mueller. 2024. PneuMa: Designing Pneumatic Bodily Extensions for Supporting Movement in Everyday Life. In Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA '24). Association for Computing Machinery, New York, NY, USA, Article 645, 1–4. https://doi.org/10.1145/3613905.3649125

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21. Aryan Saini, Haotian Huang, Rakesh Patibanda, Nathalie Overdevest, Elise van den Hoven, and Florian Floyd Mueller. 2022. SomaFlatables: Supporting Embodied Cognition through Pneumatic Bladders. In Adjunct Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology (UIST '22 Adjunct). Association for Computing Machinery, New York, NY, USA, Article 19, 1–4. https://doi.org/10.1145/3526114.3558705

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THESIS INCLUDING DECLARATION OF PUBLISHED WORKS

This thesis includes nine original papers, either published or submitted to peer-reviewed conferences and journals. These publications focused on designing pneumatic bodily extensions, which is the core theme of this thesis. The ideas, development, and writing of all the publications in this thesis were my responsibility under the supervision of Prof. Florian 'Floyd' Mueller and Prof. Elise van den Hoven during the 0190 Doctor of Philosophy program.

In the following table, I present and acknowledge the contributions of all my collaborators to the publications involved in this thesis.

Thesis Chapter	Publication Title	Publication Status (published, in press, accepted, or returned for revision, submitted)	Aryan Saini % Contribution	Co-author Name(s) % of Co-author's Contribution* and Support	Co-author(s), Monash Student Y/N*
Chapter 3: Approaches and Methods	PneuExtensio: Designing Pneumatic-based Bodily Extensions to Facilitate Embodiment across Everyday Life Experiences.	Published at DIS 2024	90%	Elise van den Hoven, Florian 'Floyd' Mueller 10%. Supported with feedback on writing.	N
Chapter 4: Case Study 1 - PneuMa	SomaFlatables: Supporting Embodied Cognition through Pneumatic Bladders.	Published at UIST 2022	90%	Haotian Huang, Rakesh Patibanda, Nathalie Overdevest, Elise van den Hoven, Florian 'Floyd' Mueller 10%.	Y

Thesis Chapter	Publication Title	Publication Status (published, in press, accepted, or returned for revision, submitted)	Aryan Saini % Contribution	Co-author Name(s) % of Co-author's Contribution* and Support	Co-author(s), Monash Student Y/N*
				Supported with feedback on the design of prototypes and writing.	
Chapter 4: Case Study 1 - PneuMa	PneuMa: Designing Pneumatic Bodily Extensions for Supporting Movement in Everyday Life.	Published at TEI 2024	80%	Rakesh Patibanda, Nathalie Overdevest, Elise van den Hoven, Florian 'Floyd' Mueller 20%. Supported with technology design, data collection, and feedback on writing.	Y
Chapter 5: Case Study 2 - Pneunocchio	Pneunocchio: A Playful Nose Augmentation for Facilitating Embodied Representation.	Published at UIST 2023	90%	Srihari Sridhar, Aarushi Raheja, Rakesh Patibanda, Nathalie Overdevest, Po-Yao (Cosmos) Wang, Elise van den Hoven, Florian 'Floyd' Mueller 10%. Supported with feedback on the design of prototypes and writing.	Y
Chapter 5: Case Study 2 - Pneunocchio	Pneunocchio: Understanding the Design of a Nose-based	Submitted	80%	Srihari Sridhar, Maria F. Montoya, Rakesh Patibanda, Nathalie	Y

Thesis Chapter	Publication Title	Publication Status (published, in press, accepted, or returned for revision, submitted)	Aryan Saini % Contribution	Co-author Name(s) % of Co-author's Contribution* and Support	Co-author(s), Monash Student Y/N*
	Bodily Extension that Suggests Lying.			Overdevest, Elise van den Hoven, Florian 'Floyd' Mueller 20%. Supported with technology design, data collection, and feedback on writing.	
Chapter 6: Case Study 3 - Pneumusculus	Inflated Exertion: Designing a Bodily Extension that Embodies Physical Activity.	Published at TEI 2025	90%	Sabari Vs, Maria Fernanda Montoya, Nathalie Overdevest, Rakesh Patibanda, Don Samitha Elvitigala, Elise van den Hoven, Florian 'Floyd' Mueller 10%. Supported with feedback on the design of prototypes and writing.	Y
Chapter 6: Case Study 3 - Pneumusculus	Pneumusculus: Understanding the Design of Bodily Extensions Through a Pneumatic Bicep that Embodies Physical Activity.	Submitted	80%	Elise van den Hoven, Florian 'Floyd' Mueller 20%. Supported with technology design, data collection, and feedback on writing.	Y

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I hereby certify that the above declaration correctly reflects the nature and extent of the student's and co-authors' contributions to this work. In instances where I am not the responsible author I have consulted with the responsible author to agree on the respective contributions of the authors.

Main Supervisor name: Prof. Florian 'Floyd' Mueller

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 Overview

This chapter provides an overview of the research conducted, including motivation (1.2), research gap (1.3), research question and objectives (1.4), followed by three case studies (1.5). The bodily extensions framework, synthesised with the help of the findings across the case studies, is then described in 1.6. This chapter concludes by presenting the key contributions and benefits of this thesis (1.7), acknowledging the use of generative AI (1.8), and outlining the thesis structure (1.9).

1.2 Motivation

Wearables, defined as devices worn on the body with computational capabilities, have been a significant area of interest in HCI (Jacobs et al., 2019; Weiser, 2002). Within this area, bodily extensions, defined as body-worn technologies that enhance the human ability to perform actions and perceive their environment through explicit control, often in the form of systems that are attached to the human body in a way that extends the human body (but could also push inward), have recently garnered interest (Bhatia et al., 2023; Buruk et al., 2023; Zhang et al., 2019). However, much of the existing research on bodily extensions adopts a predominantly utilitarian approach (Buruk et al., 2023; Lopes et al., 2018; Patibanda et al., 2023), prioritising efficiency and task performance. As a result, these explorations often underemphasise perspectives grounded in the "lived bodily experience" (Mueller et al., 2018), which foreground how such technologies are felt, interpreted, and integrated into everyday embodied life. Emerging works on bodily extensions have begun to adopt this lens of the "lived body experience" by embracing the experiential aspects (Buruk et al., 2023; Hartman et al., 2020; Peng, 2021; Svanaes & Solheim, 2016). However, most of these existing works remain confined to controlled lab or art and performance contexts, limiting their potential to engage with the experiences of everyday life (Hartman et al., 2020; Mehta et al., 2018; Walmink et al., 2014). While these prior explorations have facilitated novel user experiences in specific use cases, examining bodily extensions in everyday contexts is necessary to understand how such experiences unfold over time, are shaped by social and situational factors, and become meaningfully integrated into users' embodied lives (Rogers et al., 2007), especially considering that, with the technological advances, they might become commonplace. Furthermore, situating bodily extensions in everyday contexts provides a means to move beyond instrumental perspectives and investigate how bodies and technologies may co-shape lived experience over time.

This thesis explores the design of pneumatic bodily extensions in everyday life. Pneumatic systems, which rely on air pressure, afford lightweight and body-conforming constructions (Endow et al., 2021), resulting in soft, shape-changing forms. These qualities differentiate them from much prior HCI work on bodily extensions, which has often relied on rigid structures such as 3D-printed components (Hartman et al., 2020; Svanaes & Solheim, 2016). The softness, gradual actuation, and body conformity (Steimle, 2016) afforded by pneumatics make them particularly suitable for exploring how bodily extensions are experienced as a part of the body in everyday life (Karpashevich et al., 2022).

1.3 Research Gap

Foundational philosophical accounts of embodiment establish the body as central to human experience and perception. From a phenomenological lens, Merleau-Ponty (1962) conceptualised the body not as an object to be controlled, but as the lived medium through which the world is encountered. In this view, embodiment is an ontological condition of human existence: experience, meaning, and perception arise through the lived body rather than being mediated by it. Within HCI, these philosophical ideas have been translated into the framework of embodied interaction. Dourish (2001) reframed embodiment in interactional terms, arguing that meaning emerges through bodily engagement with the world rather than through abstract manipulation of symbols. Extending this perspective, Kirsh (2013) emphasised bodily movement as a form of cognition, proposing that gestures, postures, and physical actions are integral to thinking itself rather than ancillary to it. More recent design-oriented approaches, such as somaesthetic design (Höök, 2018) and work on embracing the lived body (Svanæs, 2013), have further foregrounded bodily awareness and sensation as central concerns for interaction design.

While embodied interaction has provided a productive and influential interpretation of embodiment theory within HCI, it does not fully account for embodiment as a lived, subjective, and phenomenological condition, especially with regard to bodily extensions. In practice, many embodiment-inspired systems focus on representing bodily data or facilitating interaction with the body through sensing and feedback mechanisms (Kim et al., 2022; van Erve et al., 2011). In such approaches, the body is often treated as an instrument or interface through which information is accessed or controlled (Kim et al., 2022; van Erve et al., 2011), rather than as the primary locus of experience itself (Rotter, 1966; Tholander, 2025). As a result, there remains a limited understanding of how body-centric technologies should be designed to support experiencing through the body. This limited understanding is particularly evident when it comes to the design of bodily extensions. Unlike systems that engage the body during interaction, bodily extensions physically extend and transform the conditions through which bodily experience is constituted (Buruk et al., 2023). Prior research has demonstrated their potential not only for instrumental, but also experiential aspects, including playfulness (Buruk et al., 2023; Hartman et al., 2020; Svanaes & Solheim, 2016). However, much of this work has relied on rigid structures and has not yet examined the lived experience (for example, Bhatia et al., 2023; Fontana et al., 2009a; Nishida et al., 2020).

In response, this thesis adopts an exploratory, design-led approach to investigate pneumatic bodily extensions as research artefacts. Rather than aiming to produce finalised systems, this research treats bodily extensions as conceptual and experiential probes through which the research question (detailed below) can be examined. Through this research, this thesis extends embodied interaction design knowledge.

1.4 Research Question and Objectives

In response to the identified gap in understanding of how bodily extensions are designed, this thesis investigates bodily extensions through an exploratory, design-led inquiry. Rather than assuming that bodily extensions inherently promote embodiment, this inquiry examines how embodiment may emerge from interactions with bodily extensions.

Accordingly, this thesis is guided by the following overarching research question:

"How do we design pneumatic bodily extensions to promote embodied experiences in everyday life?"

This overarching research question is explored through three case studies, each examining the design of bodily extensions from different perspectives. Across these case studies, the research is structured around three research objectives:

1. Objective 1: "To understand how materials and actuation approaches for bodily extensions can be designed for exploration within everyday life contexts."
2. Objective 2: "To understand how users experience, interpret, and negotiate bodily extensions."
3. Objective 3: "To understand how experiential insights and design knowledge derived from these investigations can inform future design of bodily extensions."

Together, the research question and the objectives frame bodily extensions as research artefacts through which embodied experience can be examined in everyday life. The objectives of this thesis are therefore not to validate embodiment as an outcome, but to contribute conceptual and experiential design knowledge.

1.5 Case Studies

To address the research questions outlined above, this thesis presents three case studies that investigate bodily extensions from different perspectives. Together, the case studies demonstrate how different forms of bodily extensions promote embodied experiences in complementary ways.

Across all three case studies, a research-through-design (Zimmerman et al., 2007) approach was employed, supported by iterative design, to create and refine the bodily extensions. To investigate the user experience associated with wearing such bodily extensions in everyday contexts, seven-day field studies were conducted for each case study (Oulasvirta, 2009; Rek et al., 2013). Semi-structured interviews (Dearnley, 2005; Longhurst & Johnston, 2023) were used to elicit participants' reflections on wearing and living with the extensions, and thematic analysis (V. Braun et al., 2019; V. Braun & Clarke, 2006) was employed to identify recurring experiential patterns. Insights derived from these analyses informed the development of the framework presented later in this thesis.

1.5.1 Case study 1: PneuMa

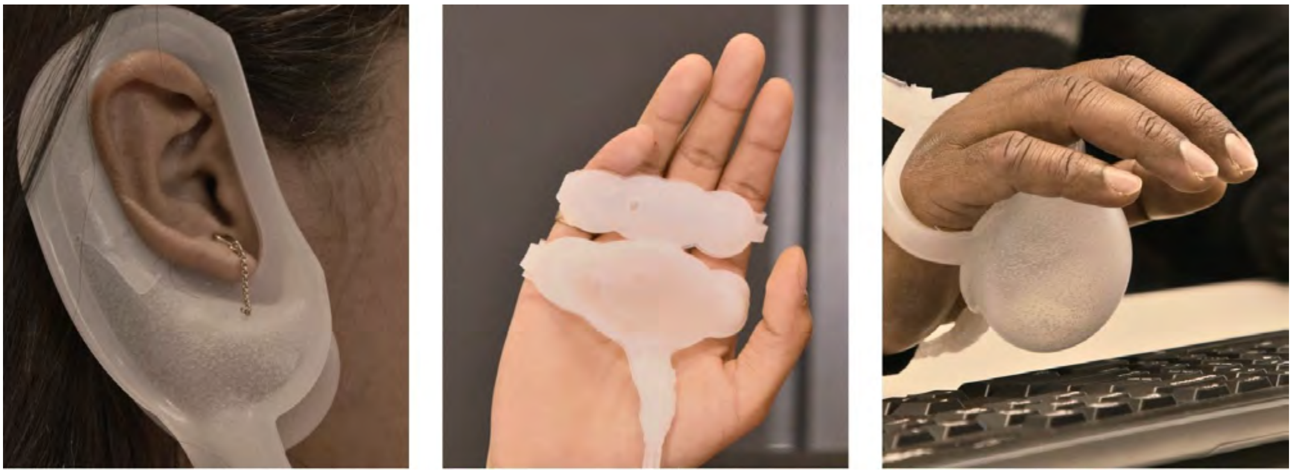

Figure 1: The inflated PneuMa bodily extensions (from left to right): "Pardon?", "Greetings", and "Take a break".

PneuMa presents three soft, silicone-based pneumatic bodily extensions designed to prompt subtle bodily movement during everyday activities (Figure 1). The extensions intervene in routine activities, such as desk work or gestural communication, by encouraging bodily action. This case study examined how soft, externally driven bodily prompts were experienced in everyday life contexts. A seven-day field study revealed three themes – bodily awareness, perception of the scenarios, and anticipating movement – that contributed to an initial understanding of the bodily extensions framework.

1.5.2 Case study 2: Pneunocchio

Figure 2: The inflated Pneunocchio bodily extension.

Pneunocchio presents a playful, nose-based pneumatic bodily extension (Figure 2) that inflates in response to bio signals, specifically heart rate and electrodermal activity, associated with physiological stress, such as when lying, drawing inspiration from the tale of Pinocchio (Collodi, 1916). This case study explored how internal bodily states can be externalised and made socially visible through a bodily extension. A seven-day field study with 12 participants revealed three key themes: Pneunocchio as a social organ; dichotomy of perceived control; and heightened self-awareness of the participants' bodies. These findings helped further refine the bodily extensions framework.

1.5.3 Case study 3: Pneumusculus

Figure 3: The inflated Pneumusculus bodily extensions.

The Pneumusculus case study presents a pneumatic sleeve worn on the bicep that inflates gradually throughout the day in response to a user's physical activity, offering an embodied representation of exertion inspired by muscle growth (Figure 3). This case study investigated how slow, cumulative actuation shapes users' perception of physical activity beyond screen-based metrics. A seven-day field study with 12 participants identified four themes: appreciation of the physicality of the representation; motivation through in-body-built tracking; appreciation of delayed inflation; and heightened awareness of activity through physical sensation. These insights helped to complete the bodily extensions framework.

Taken together, the three case studies collectively probed different ways that bodily extensions may shape embodied experience, and their results informed the design framework developed later in this thesis.

1.6 Design Framework

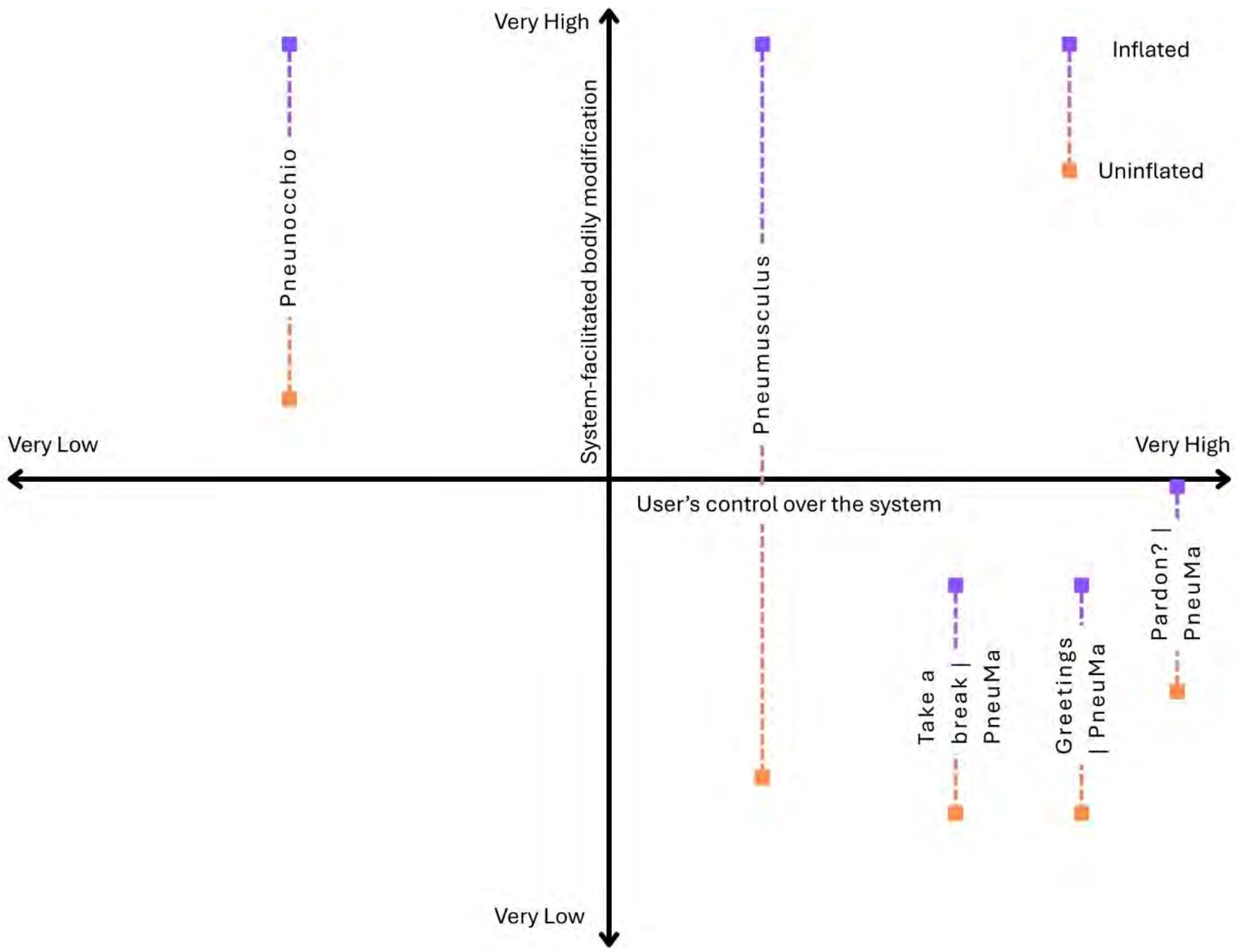

Figure 4: Bodily extensions framework (explained in chapter 7).

Building on insights generated through the research-through-design process and the converging experiential themes identified across the three case studies, this thesis proposes an initial bodily extensions framework (Figure 4). This framework is intended to support conceptual reasoning about how bodily extensions may shape embodied experience in everyday life, rather than to prescribe optimal designs or guarantee particular experiential outcomes.

The framework comprises two complementary layers. First, the framework articulates a descriptive design space derived from reflection on the case studies, thereby offering a structured way to situate and compare bodily extension designs in terms of how they influence the users and how the users influence them. Second, the framework presents a set of strategies for designers wanting to design future bodily extensions that enrich embodied experiences in everyday life.

As mentioned above, central to the framework is an understanding of bodily extensions as participating in a bidirectional relationship between the user and the system. Bodily extensions are not treated as passive outputs of sensing and actuation, nor is the body treated as a static recipient of technological intervention. Instead, the framework foregrounds how users and bodily extensions mutually shape one another through ongoing interaction over time. In doing so, the framework explicitly foregrounds temporality, recognizing that bodily extension experiences often evolve as users adapt, reinterpret, or accommodate bodily actuation across everyday life contexts.

As such, the bodily extensions framework serves as a conceptual and generative tool. The framework's dimensions and design strategies are elaborated in detail in Chapter 7.

1.7 Contributions and Benefits

This thesis makes the following contributions to HCI research, as categorised by Wobbrock (2012):

1. System Contribution

This thesis presents five speculative pneumatic bodily extensions (three in PneuMa, one in Pneunocchio, and one in Pneumusculus) that explore different ways that bodily extensions may shape embodied experience in everyday life. Rather than presenting finalised systems, these artefacts serve as research probes that present design possibilities and consider how soft, shape-changing actuation can mediate bodily awareness, agency, and social experience. These insights can be useful for developers seeking inspiration when aiming to create systems that promote embodied experiences in everyday life.

2. Empirical Contribution

Through seven-day field studies involving 36 participants (12 per case study), this thesis provides empirical insights into the experience of wearing pneumatic bodily extensions in everyday life. The analysis identified 14 user experience themes that capture how users perceived, negotiated, and adapted to bodily extensions, including tensions around control, bodily awareness, social visibility, and temporality. These findings can be useful for user experience researchers aiming to understand how people experience bodily extensions in the field, outside lab-based controlled environments.

3. Conceptual Contribution

This thesis contributes an initial bodily extensions framework, which articulates a design space defined by user influence (control) and bodily influence (modification). The framework introduces user experience regions within the design space and presents trajectories that unfold over time. Accompanied by design strategies grounded in design practice and empirical findings, the framework serves as a conceptual and generative tool to inform future research and the design of bodily extensions. This framework can be helpful for HCI researchers aiming to understand and design future bodily extensions.

1.8 Generative AI Statement

This thesis is based on original research, analysis, design, and interpretation conducted by the author, in collaboration with members of the Exertion Games Lab and the Materialising Memories Programme. All contributions, including the conception of the research, design of the bodily extensions, data collection, analysis, and development of arguments, are my own.

Generative AI tools (including ChatGPT and Gemini) were used in a limited capacity to support editing for clarity, structure, and expression during the writing process. These tools were not used to generate research ideas, design artefacts, or analyse data.

1.9 Thesis structure

This thesis consists of nine chapters:

Chapter 2 situates this thesis within prior research in HCI, reviewing work on embodiment and embodied interaction, bodily extensions, pneumatic and shape-changing wearables, and everyday embodied experiences. This chapter establishes the theoretical and empirical foundations for identifying the research gap.

Chapter 3 describes the research approach and methods employed in this thesis. It details the research-through-design approach, iterative design processes, and qualitative methods used to design, deploy, and study the pneumatic bodily extensions.

Chapters 4 to 6 present three case studies (PneuMa, Pneunocchio, and Pneumusculus). Each chapter includes one to three pneumatic bodily extensions designed to explore embodied experience in everyday life from a different perspective. These case studies contribute empirical and experiential insights that form the foundation for the development of the framework.

Chapter 7 introduces the bodily extensions framework by synthesizing insights from the case studies. This chapter presents a descriptive design space along with a set of design strategies, demonstrating how bodily extension experiences can be understood as dynamic trajectories rather than static configurations. This chapter serves as the point of conceptual integration in this thesis.

Chapter 8 presents the design, technical, methodological, and conceptual limitations of the thesis, and outlines opportunities for future research.

Chapter 9 concludes this thesis by revisiting the research question and objectives while reflecting on the contributions to offer an understanding of how bodily extensions can be designed to promote embodied experience in everyday life.

CHAPTER 2: LITERATURE REVIEW

2.1 Overview

This chapter reviews prior research that informed the research underpinning this thesis. It situates this research within the fields of HCI research on embodied interaction, experiential dimensions of bodily extensions, and pneumatic wearables, and examines how these bodies of work have addressed bodily experience in everyday contexts. This chapter focuses on prior work that is relevant to understanding how bodily extensions are designed and experienced.

This literature review builds upon theoretical foundations to articulate the material and experiential concerns that motivate the case studies presented in later chapters. Section 2.2 examines how embodied interaction has been articulated within HCI and how bodily movement, engagement, and materiality have been treated as resources for interaction design. While this prior work establishes important conceptual foundations, it also reveals limitations when applied to technologies that extend the body itself. Section 2.3 builds on this discussion by reviewing experiential dimensions that recur across bodily extension research, including ownership, agency, bodily awareness, and social legibility. This section highlights how these dimensions complicate assumptions about everyday wearability and use. Section 2.4 reviews prior work on pneumatic and shape-changing wearables, and Section 2.5 reframes relevant work through the conceptual lens of reflection through bodily change. Finally, Section 2.6 synthesises gaps and opportunities across these bodies of work and articulates the research question and objectives addressed in the remainder of this thesis.

2.2 Embodied Interaction in HCI

Foundational accounts of embodied cognition challenge the view that cognition is primarily abstract and internal, and emphasise instead that understanding and action emerge through sensorimotor engagement with the world (Benford et al., 2020; Dourish, 2001; Kirsh, 2013;

Rekimoto & Nagao, 1995; Shapiro & Spaulding, 2021; van Dijk et al., 2014). Within HCI, these ideas have been taken up through the framework of embodied interaction, which reframes interaction as situated, physical, and bodily grounded (Kirsh, 2013). From this perspective, the body is treated not merely as a channel for input and output, but as an active site of perception and experience (Kirsh, 2013; van Dijk et al., 2014). This framing has been influential in motivating the development of interactive systems that deliberately engage bodily movement and sensation as integral components of interaction.

A substantial body of work demonstrates that bodily movement plays a critical role in how people perceive, communicate, and act (Benford et al., 2020; Fdili Alaoui et al., 2015; Kimble, 2022). Research in embodied cognition suggests that bodily action is used to structure tasks, anticipate outcomes, and make sense of the environment (Kirsh, 2013). In parallel, studies of gesture and movement link bodily action to conversational articulation and social coordination, thereby motivating interaction designs that explicitly facilitate bodily engagement (Cicone et al., 1979; Cook et al., 2010; La Delfa et al., 2020; Mueller et al., 2018; Mueller et al., 2020). These insights have informed design frameworks that encourage body-centric perspectives and position bodily experience as a design material rather than a constraint (Fdili Alaoui et al., 2015; Höök, 2018; Hornecker, 2005; F. “Floyd” Mueller et al., 2011; Patibanda, 2024).

Embodied interaction has been leveraged into practice through a wide range of systems (Benford et al., 2020; Svanæs, 2013; Ullmer et al., 2022; van Erve et al., 2011). Tangible and embodied interfaces leverage familiar physical actions to support engagement (Anderson et al., 2013; van Dijk et al., 2014; Yamagami et al., 2020). Here, bodily movement is not treated solely as an instrumental means to achieve interaction goals, but as an experiential resource that shapes how users attend to their bodies and surroundings.

At the same time, many systems that actively facilitate or guide movement rely on actuation technologies, such as electrical muscle stimulation (EMS) or exoskeletons (Chiri et al., 2012; Nishida et al., 2020; Patibanda et al., 2023). EMS has enabled proprioceptive interaction, playful experiences, and force feedback in a range of contexts (Chen et al., 2021; Lopes, 2016; Lopes et al., 2018; Patibanda et al., 2023), while exoskeletons have primarily been used for assistance and movement facilitation in expert, industrial, or rehabilitation-oriented settings (Fontana et al., 2009b; Secco & Tadesse, 2020; Virk et al., 2020). However, prior work has consistently identified limitations related to comfort, intrusiveness, and suitability for everyday use. For example, EMS has been described as uncomfortable or even painful (Knibbe et al., 2018), and exoskeletons have often been characterised as heavy or impractical outside specialised contexts (Heo et al., 2012; Mueller et al., 2020; Nishida et al., 2020).

Together, these prior works established embodied interaction as a foundational lens for understanding bodily engagement in HCI, while simultaneously revealing a tension between actuation capability and everyday wearability. This tension becomes particularly evident when considering technologies that extend the body itself, rather than merely mediating the body's interaction with external systems. Consequently, interest has grown in alternative actuation approaches that are more compliant, body-conforming, and suitable for prolonged wear in everyday life (Mueller et al., 2020). This recent interest motivates the exploration of pneumatic bodily extensions to examine how bodily engagement and experience unfold beyond task-oriented or efficiency-driven interaction.

2.3 Experiential Dimensions of Bodily Extensions

Within HCI, a large body of work has explored bodily extensions through a technical lens, focusing on their sensing, processing, and actuation (Bhatia et al., 2023; Feng & Stockman, 2019; Zhang et al., 2019). However, prior research consistently demonstrates that the significance of bodily extensions depends not only on functional operation but on how they are experienced, interpreted, and negotiated by users (Hartman et al., 2020; Mehta et al., 2018; Rapp, 2023). As bodily extensions intervene directly in bodily form, movement, or sensation, their effects extend beyond task performance to shape users' perceptions, agency, and social interaction. This section foregrounds four experiential dimensions that recur across bodily extension research and are central to this thesis: ownership, agency, bodily awareness, and social legibility (Svanæs, 2013; Svanæs & Barkhuus, 2020; Svanaes & Solheim, 2016; Umezawa et al., 2022). Together, these dimensions provide lenses through which we can examine how a bodily extension is lived with in everyday contexts, not just whether that bodily extension functions as intended.

2.3.1 Ownership and Incorporation

Ownership refers to the extent to which users experience a bodily extension as belonging to their body and sense of self (Danry et al., 2021; Svanæs, 2013; Umezawa et al., 2022). Phenomenological accounts conceptualise the body as the lived medium through which the world is encountered, which suggests that technologies become meaningful when they are incorporated into bodily experience rather than remaining external objects (Kirsh, 2013; Loke & Robertson, 2011; Merleau-Ponty, 1962; Svanæs, 2013). Within bodily extension research, ownership is therefore understood as an experiential outcome that emerges through interaction rather than as a property that can be designed directly.

Empirical studies demonstrate that ownership can develop even for novel or artificial bodily structures, if users are afforded sufficient time and coherent sensorimotor coupling to integrate those structures into their bodies (Feng & Stockman, 2019; Umezawa et al., 2022; van Dijk et al., 2014). At the same time, ownership is neither immediate nor guaranteed. Studies involving bodily extensions, such as tails and ears, show that attachment alone is insufficient; ownership develops through repeated use, movement, and attention, and can be disrupted when there is misalignment between user intention and system behaviour (Svanaes & Solheim, 2016). These findings highlight the importance of longer engagement when studying bodily extensions because short-term or in-laboratory evaluations may overlook how incorporation evolves or breaks down over time.

2.3.2 Agency and Control

Agency and control are concerned with a user's sense of initiating, influencing, and controlling actions involving a bodily extension (Benford et al., 2020). In the context of bodily extensions, agency is shaped not only by whether control is explicit or implicit, but also by how predictable, interpretable, and temporally aligned the extension's behaviour is with the user's actions and expectations. Prior research indicates that many bodily extensions emphasise explicit control mechanisms, while implicit coupling via physiological signals or contextual factors remains comparatively underexplored in everyday settings (Hartman et al., 2020; Morris et al., 2023; Peng, 2021).

Where implicit coupling is employed, studies highlight the importance of timing and pacing in shaping agency (D'Angelo et al., 2018; Limerick et al., 2014; Morris et al., 2023). Gradual or delayed actuation can help prevent bodily change from becoming overwhelming or disruptive, thereby supporting a sense of influence and ownership even when direct control is limited (Kasahara et al., 2019). These findings suggest that agency in bodily extensions is not a binary condition but a negotiated experience that emerges through the interaction between system behaviour, bodily response, and context of use.

2.3.3 Bodily Awareness and Somaesthetic Attention

Bodily extensions can influence what users notice about their bodies, directing their attention toward, for example, movement, posture, breathing, or internal physiological states (Fdili Alaoui et al., 2015; Höök, 2018; Karpashevich et al., 2022; Morris et al., 2023). Prior work demonstrates that wearable systems can support bodily awareness by externalizing subtle processes through touch, pressure, or form change, thereby making bodily activity perceptible in ways that are felt rather than explicitly represented (Karpashevich et al., 2022; N. A. Semertzidis et al., 2023; Turmo Vidal et al., 2024). In parallel, somaesthetic and body-centric design approaches emphasise the importance of attending to bodily perception and sensation as central aspects of interaction (Gallagher, 2005; Höök, 2018; Mueller et al., 2020).

These perspectives challenge evaluation approaches that treat awareness as a secondary effect or proxy for performance. Instead, they motivate design and analysis that foreground how technologies shape felt experience and attentional orientation toward the body. In the context of bodily extensions, bodily awareness is therefore not simply an outcome but a key site through which meaning and reflection can emerge.

2.3.4 Social Legibility and Expressive Meaning

Because bodily extensions alter visible body form, they inevitably participate in social interpretation. Prior work shows that bodily extensions can function as expressive artifacts, communicating aspects of emotional state, intention, or identity to others through bodily change (Buruk et al., 2023; Hartman et al., 2020; Mehta et al., 2018; Peng, 2021; Walmink et al., 2014). At the same time, increased visibility can introduce vulnerability, self-consciousness, or discomfort, particularly when bodily change is not fully under the wearer's control (Buruk et al., 2023; Peng, 2021; Walmink et al., 2014).

These dynamics highlight that bodily extensions operate simultaneously at personal and interpersonal levels. Social context, including the presence of others and cultural norms around bodily display, plays a significant role in how bodily extensions are interpreted and experienced (Buruk et al., 2023). As a result, social legibility must be considered alongside ownership, agency, and bodily awareness when designing and evaluating bodily extensions intended for everyday life.

These experiential dimensions indicate that bodily extensions cannot be adequately understood through technical performance metrics alone. Instead, they must be examined as technologies that reshape bodily experience, agency, and social interaction. This perspective provides the basis for examining how material choices and actuation strategies, such as those afforded by pneumatic systems, can influence everyday experiences of bodily extension, which is explored in the following section.

2.4 Pneumatic Wearables

Pneumatic wearables offer a distinct technological and material approach to bodily extension. Pneumatic systems rely on air pressure to create deformation, compression, or volumetric change, resulting in actuation that is soft, compliant, and often body-conforming. Within HCI, pneumatics have been explored in a range of applications, including haptic feedback, virtual reality, accessibility, rehabilitation, and skill support (Goto et al., 2020; Kilic Afsar et al., 2021; Naik et al., 2019; Teng et al., 2018; Zhang et al., 2019). The relevance of pneumatics to this thesis lies not only in their capacity for actuation but in the experiential qualities afforded by soft bodily change, such as gradual transformation and material compliance.

In contrast to rigid mechanical actuation, pneumatic systems allow for gradual bodily change, which aligns with calls for wearable technologies that adapt to bodily morphology and support prolonged wear (Mueller et al., 2020; Steimle, 2016). As a result, pneumatics have been positioned as a promising alternative (Allen d'Ávila Silveira et al., 2022; Belforte et al., 2014) to actuation approaches that are frequently associated with discomfort, bulk, or restricted movement, such as electrical muscle stimulation or rigid exoskeletons (Heo et al., 2012; Knibbe et al., 2018). Rather than emphasizing force or precision, pneumatic actuation supports bodily engagement through qualities that are particularly relevant for everyday contexts, including softness, resistance, and temporal variation.

A substantial portion of prior work on pneumatic interfaces has focused on prototyping and fabrication (Endow et al., 2021; Ghosal et al., 2019; Moradi & Torres, 2020; Yao et al., 2013). Toolkits and rapid fabrication methods have lowered barriers to creating inflatable and compressive interfaces, thereby enabling designers to experiment with expansion, contraction, and shape change (Ghosal et al., 2019; Yao et al., 2013). Systems such as Compressables demonstrate how pneumatic actuation can be embedded into wearable forms and provide a foundation for exploring compression-based sensations (Endow et al., 2021). While these contributions are valuable for expanding the design space, they often foreground technical feasibility and fabrication efficiency, with limited attention to how pneumatic bodily extensions are experienced in everyday life.

Other work demonstrates pneumatic wearables in applied or domain-specific settings. Pneumatic actuation has been used to provide force feedback in immersive environments (Delazio et al., 2018, 2018; Teng et al., 2018), to guide movement in expert practices such as dance (Allen d'Ávila Silveira et al., 2022), and to create sensory illusions through subtle tactile stimulation (Gohlke et al., 2022; Wu & Culbertson, 2019). While these studies illustrate the expressive and perceptual potential of pneumatic systems, they typically evaluated the pneumatic systems in bounded contexts, leaving open questions about how such systems are experienced in everyday life.

More recent research has begun to attend to experiential considerations in pneumatic wearables, particularly in relation to physiological coupling. Morris et al. highlight the role of pacing and timing strategies in preserving agency and ownership when bodily change is driven by physiological signals (Karpashevich et al., 2022; Morris et al., 2023). Related work suggests that shape change can support reflection and movement facilitation when designed with attention to temporality and bodily sensation (Søndergaard et al., 2020). Despite these advances, design knowledge remains limited regarding pneumatic bodily extensions intended for diverse everyday contexts and for experiential concerns. This gap motivates further investigation into pneumatic bodily extensions as experiential technologies, rather than solely as technical or functional systems.

2.5 Reflection through Bodily Change

The reviewed literature exhibits a recurring concern with how interactive systems support reflection on bodily states, actions, and experiences. Within HCI, reflection has often been facilitated through visualizations, dashboards, and other screen-based representations that externalise experience for inspection and interpretation (Bahng et al., 2020; Isaacs et al., 2013; Mols et al., 2016). While such approaches can support monitoring and goal-oriented behaviour, they frequently frame reflection as a predominantly cognitive activity mediated through abstract representations. In contrast, research on embodied interaction suggests that reflection may also emerge through bodily sensation and form change, without relying on explicit numerical or visual representations (Kirsh, 2013; Valentini & Guarnacci, 2021; van Dijk et al., 2014).

Work on tangible and wearable artifacts demonstrates that physical form can support interpretation and meaning-making over time (Cochrane et al., 2022; Flechtner et al., 2020; Karpashevich et al., 2022). Rather than emphasizing precision, these systems often leverage ambiguity, presence, and material engagement to invite users to develop personal interpretations. Prior research on activity and health tracking has shown that screen-centric tools can limit engagement and contribute to abandonment, and these insights have motivated alternative representational approaches that integrate more directly into lived experience

(Lazar et al., 2015; Rapp & Tirabeni, 2020). For example, Edipulse materialises activity metrics through edible artifacts, thereby illustrating how playful and tangible forms can foster engagement and motivation without relying on conventional displays (Khot et al., 2017). Similarly, Jones et al. (2023) explore long-term attachment to bodily signals through wearable textile representations and show how a wearable artifact can mediate ongoing relationships with bodily states over time.

Bodily extensions extend this line of work by making the body itself the site of change. Rather than requiring users to consult an external artifact, reflection may unfold through changes that are seen and felt on the body. Importantly, this approach does not imply that all bodily change represents "data" or is interpreted in a uniform way. Instead, bodily change can function as a prompt for interpretation and draw attention to recent actions, internal states, or social situations without prescribing specific meanings. For instance, wearable systems that promote awareness of breathing through touch demonstrate how physiological processes can be rendered perceptible through bodily sensation, thereby supporting attentiveness and reflection (Karpashevich et al., 2022; Morris et al., 2023; Peng, 2021). Similarly, physiologically driven and expressive bodily extensions show how bodily change can invite interpretation in everyday social contexts, where meaning emerges through interaction with others as well as through personal experience (Buruk et al., 2023; Hartman et al., 2020; Peng, 2021).

Temporality plays a critical role in this process. While immediate and precise feedback often encourages correction or optimization, delayed, periodic, or gradual bodily change can create space for interpretation, narrative sense-making, and reflection (Cheng et al., 2011; Odom, 2015; Odom et al., 2019). Pneumatic actuation is particularly relevant in this regard because its temporal properties allow bodily change to unfold gradually and to be negotiated through the body, rather than demanding constant attention (Morris et al., 2023). In this thesis, reflection through bodily change is therefore treated as a unifying experiential concern across the case studies, despite differences in the specific bodily signals or actions that drive actuation in those case studies.

2.6 Gaps

Synthesizing the literature reviewed in this chapter reveals several gaps that motivate the investigation undertaken in this thesis. First, there remains a limited understanding of how bodily extensions are lived with and experienced. Many prior studies evaluate bodily extensions in controlled, task-focused settings, despite evidence that experiences of ownership, agency, and social meaning develop, stabilise, or break down through use and repeated social encounters (Bermúdez, 2015; N. Braun et al., 2018; Tsakiris et al., 2007; Umezawa et al., 2022).

Second, although pneumatics are widely used in haptics, prototyping, and specialised application domains, there is limited design knowledge concerning pneumatic bodily extensions as everyday experiential technologies (Delazio et al., 2018; Ghosal et al., 2019; Hu & Hou, 2019; Yao et al., 2013; Zhang et al., 2019). Existing contributions frequently emphasise toolkits, fabrication techniques, and feasibility, while paying comparatively less attention to wearability, interpretation, and social meaning (Endow et al., 2021; Ghosal et al., 2019; Moradi & Torres, 2020). As a result, how pneumatic bodily extensions are designed and experienced remains underexplored.

Finally, reflection is often treated as a secondary outcome or as a function of explicit representation, despite evidence that bodily change itself can function as a medium for reflection in a range of contexts. However, how bodily extensions might be designed to invite such reflective engagement, particularly through soft, actuated bodily change, remains insufficiently articulated. Prior work demonstrates that reflection can emerge through physicalised and bodily forms without relying on precise or numerical feedback (Jones et al., 2023; Karpashevich et al., 2022; Khot, 2014; Khot et al., 2017).

These gaps point to an opportunity for an investigation that examines bodily extensions not as finished solutions, but as research artefacts through which experiential questions of agency, bodily awareness, social interpretation, and reflection can be explored. This perspective motivates the research question and objectives introduced in the following section and the research-through-design approach described in Chapter 3.

2.7 Research Questions

Responding to the gaps identified in the preceding sections, this thesis is guided by the following overarching research question:

"How do we design pneumatic bodily extensions to promote embodied experiences in everyday life?"

This research question is examined through three objectives, which are explored across the case studies presented in Chapters 4 to 6:

1. Objective 1: "To understand how materials and actuation approaches for bodily extensions can be designed for exploration within everyday life contexts."
2. Objective 2: "To understand how users experience, interpret, and negotiate bodily extensions."
3. Objective 3: "To understand how experiential insights and design knowledge derived from these investigations can inform future design of bodily extensions."

This research question, along with the objectives, frames an investigation into bodily extensions that foregrounds everyday life and lived experience, motivating the Research-through-Design approach outlined in Chapter 3.

CHAPTER 3: APPROACHES AND METHODS

3.1 Overview

This chapter describes the approach employed to investigate how pneumatic bodily extensions can be designed to foster embodied experiences in everyday life. The research is situated within the Human–Computer Interaction (HCI) tradition of Research-through-Design (RtD), in which knowledge is generated through the iterative design, deployment, and interpretation of artifacts as research instruments (Zimmerman et al., 2007). Rather than treating bodily extensions as finalised products, each design iteration functions as a site of inquiry into how pneumatic actuation, materiality, and bodily placement shape lived experience over time.

Parts of the methodological approach described in this chapter build upon prior published work:

Aryan Saini, Elise Van Den Hoven, and Florian 'Floyd' Mueller. 2024. PneuExtensio: Designing Pneumatic-based Bodily Extensions to Facilitate Embodiment across Everyday Life Experiences. In Companion Publication of the 2024 ACM Designing Interactive Systems Conference (DIS '24 Companion). Association for Computing Machinery, New York, NY, USA, 19–23. https://doi.org/10.1145/3656156.3665136

This chapter contains five sections after this one. Section 3.2 outlines RtD as the overarching methodological orientation and describes how staged design cycles were employed across the thesis. Section 3.3 introduces bodystorming as an embodied ideation method used during early design explorations. Section 3.4 describes the longitudinal field studies conducted to examine participants' lived experiences with the bodily extensions. Sections 3.5 and 3.6 then detail the quantitative and qualitative data collection and analysis methods used to interpret this data and support synthesis across case studies.

3.2 Research-through-Design

This thesis adopts RtD as its central methodological orientation (Zimmerman et al., 2007). RtD positions design practice as both the method and the outcome of inquiry and emphasises the production of knowledge through the iterative processes of making, deploying, and reflecting on artifacts. Within this approach, artifacts are treated as epistemic objects that materialise research questions and enable situated understanding to emerge through use, rather than as neutral instruments to be evaluated after design decisions have been finalised.

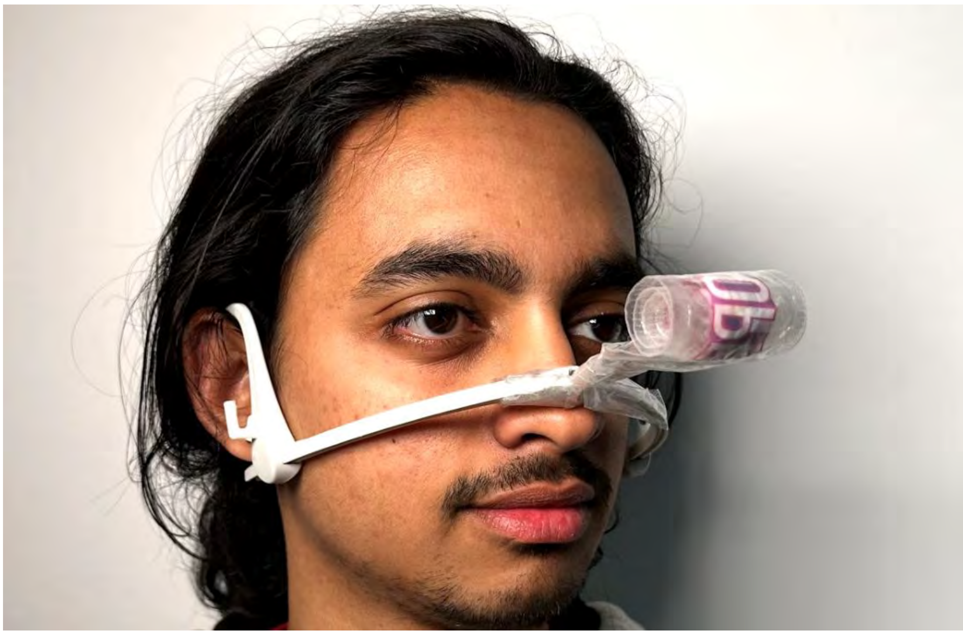

Figure 5: An early version of the Pneunocchio bodily extension.

Within HCI, RtD has been employed to investigate experiential, embodied, and affective phenomena that resist complete understanding when studied using analytical or purely empirical methods (Baur et al., 2025; Epp et al., 2024; Mariani & Hansen, 2023). Bodily extensions, particularly those that alter perception, movement, or bodily awareness, could exemplify such phenomena. The effects of such bodily extensions unfold through lived bodily experience, social interpretation, and temporal adaptation, making them difficult to study solely through controlled laboratory experiments. Therefore, RtD provides an appropriate methodological lens for exploring how pneumatic actuation, materiality, and bodily placement shape experiences of embodiment.

In this thesis, RtD was operationalised through a sequence of iterative design cycles (Figure 5, Figure 6, Figure 7, and Figure 8) encompassing concept development, prototyping, deployment, and reflection. Each bodily extension was designed as a research probe (Paulos & Jenkins, 2005) to explore particular experiential dimensions of embodiment, such as bodily awareness, social visibility, agency, or temporality. The case studies were not treated as isolated experiments, but as cumulative explorations, with insights from earlier designs informing subsequent ones. This progressive structure enabled the refinement of conceptual understandings across case studies and ultimately supported the development of a design framework for pneumatic bodily extensions.

Figure 6: Exploring materials of fabrication for the Pneumusculus case study.

3.3 Case Study Approach

This thesis is structured around three design case studies, each situated within a different everyday-life context. Within HCI and design research, case studies are a well-established methodological strategy for examining complex, situated phenomena that cannot be meaningfully isolated from their context of use (Boronowsky et al., 2001; Carros et al., 2020;

Croes & van Dartel, 2020). In RtD, case studies serve not primarily as instances of hypothesis testing, but as sites for generating and articulating design knowledge through concrete artifacts and their use (Deng, 2025; Moros Ortiz, 2024; Patibanda, 2024).

The choice to conduct three case studies reflects a balance between breadth and depth. A single case study would limit a researcher's ability to explore variation across bodily locations, interaction modalities, and experiential outcomes, and a larger number of cases would risk superficial engagement with each design. Three case studies allow for sustained, in-depth exploration while still supporting comparative reflection across designs.

Each case study investigated a distinct interpretation of "everyday life," spanning environmental context, bodily action, and physiological response. Together, they enabled the examination of how pneumatic bodily extensions are experienced across diverse situations while maintaining a coherent methodological structure. Concluding the thesis with a design framework follows established RtD practice, whereby insights from multiple case studies are synthesised into transferable design knowledge that can guide future work (Benford et al., 2005; Mueller et al., 2011; Patibanda, 2024).

This case-study-driven structure has been adopted in several prior doctoral theses within HCI and interaction design, particularly those addressing embodied, somaesthetic, or experiential phenomena (Li, 2021; Patibanda, 2024; Paulos & Jenkins, 2005; Semertzidis, 2022). In such work, the contribution lies not in generalizable claims derived from statistical inference, but in the articulation of design spaces and design strategies grounded in rich empirical engagement.

3.4 Bodystorming

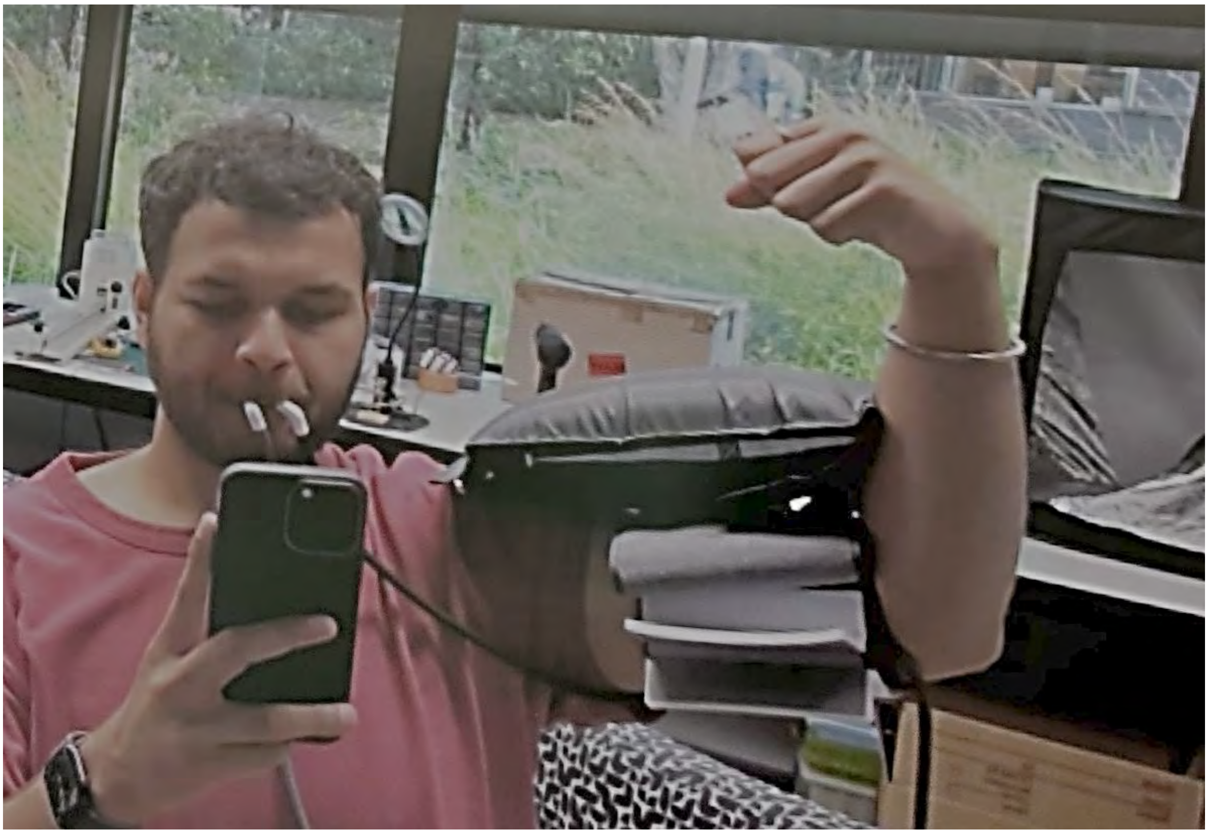

Figure 7: Exploring sensations at the bicep for the Pneumusculus case study.

Early explorations of the bodily extension design space were conducted through bodystorming: an embodied ideation technique that situates design thinking within physical and sensory experience (Oulasvirta et al., 2003; Segura et al., 2016). Bodystorming was used to speculate on how pneumatic actuation might be felt on the body, how it could influence bodily perception, and how different body locations might afford distinct experiential qualities.

Figure 8: An early version of the "Pardon?" bodily extension in the PneuMa case study.

During bodystorming sessions, bodily movements were enacted, and imagined extensions that could inflate, contract, or shift shape in response to bodily or contextual inputs were explored (Figure 7, Figure 8, ,Figure 9 and Figure 10). Everyday materials, such as balloons, tubing, and fabrics, were attached to different parts of the body to simulate sensations of expansion, resistance, and constraint. These embodied rehearsals enabled early reflection on comfort, playfulness, visibility, restriction of movement, and social interpretation.

Figure 9: Bodystorming with off-the-shelf inflatables to understand bodily sensations and movements.

Figure 10: Exploring inflatables at different body locations; here, beneath the sole.

Insights from bodystorming informed key design decisions, including the selection of bodily locations (e.g., ear, hand, nose, and arm) and the choice of materials and mechanical configurations that could support pneumatic actuation while remaining wearable in everyday contexts. While bodystorming did not generate evaluative data directly, it played a critical role in shaping the design directions explored in each case study. This approach was consistent with prior work that positions bodystorming as a generative rather than evaluative method.

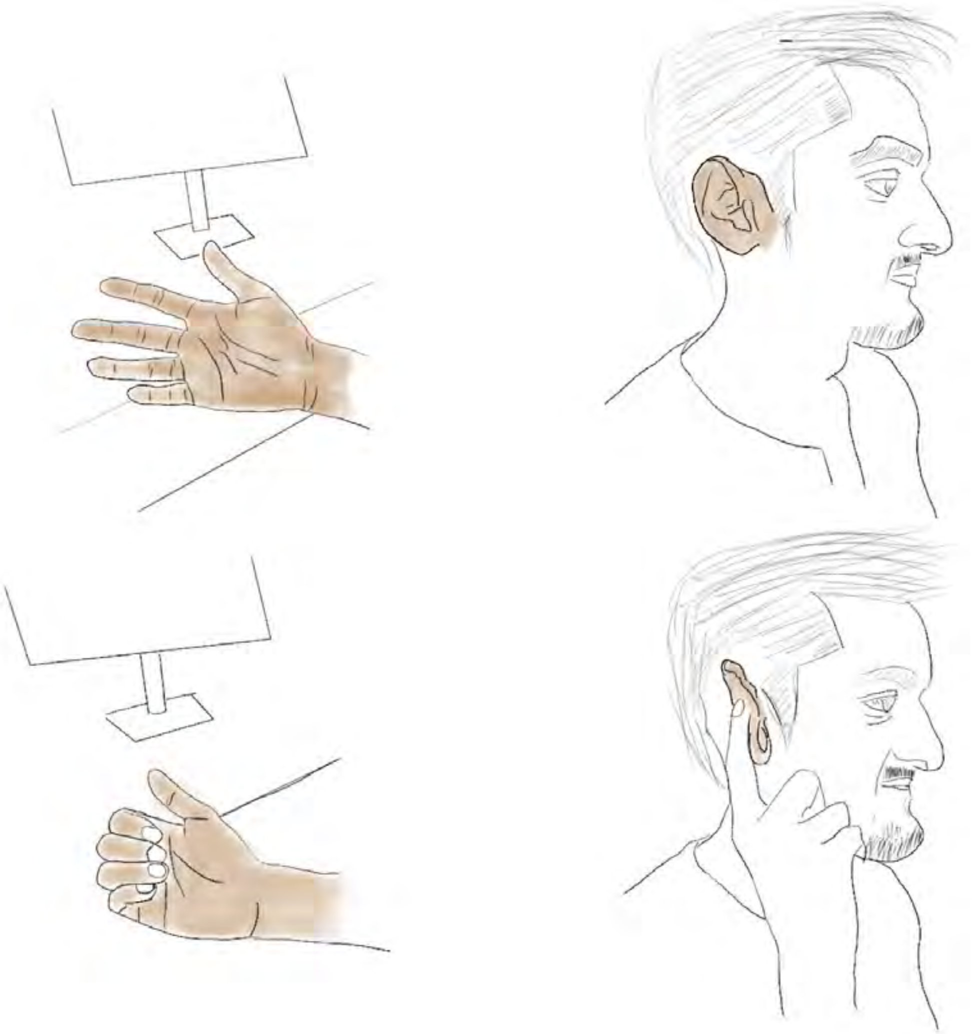

Figure 11: Sketches from movement exploration during the PneuMa case study.

3.5 Field Studies

While the design of bodily extensions formed the generative core of the RtD process, understanding how embodiment unfolds in everyday life required empirical engagement with participants. Field studies were therefore employed to investigate how bodily extensions were experienced, interpreted, and appropriated within participants' everyday routines.

Within HCI, field studies are well established as a method for examining interaction as it unfolds over time and across contexts, rather than under controlled laboratory conditions (Grzyb & Dolinski, 2021; Oulasvirta, 2009; Rek et al., 2013; Wong & Blandford, 2003). The researcher felt that this approach could be important for bodily extensions, where habituation, social encounters, and shifts in bodily awareness may only emerge through prolonged use. Allowing participants to engage with the bodily extensions in unsupervised settings also enables unanticipated practices and personal meaning-making to surface (Koch et al., 2018; Shin et al., 2019).

Each case study involved 12 participants who wore a bodily extension for seven consecutive days. These participants were recruited by sending out flyers on the Exertion Games Lab's mailing lists, social media, and snowballing within Monash University and Melbourne, Australia. Participants were onboarded through in-person sessions (with the researcher) that introduced the study aims, demonstrated system functionality, and allowed participants to familiarise themselves with the setup. During the field study period, participants were encouraged to use the bodily extensions opportunistically within their everyday activities rather than follow scripted tasks. At the conclusion of each study, semi-structured interviews were conducted to elicit reflections on bodily sensations, emotional responses, social interactions, and experiences of embodiment (Dearnley, 2005; Longhurst & Johnston, 2023). The length of these interviews (60 – 90 minutes), the field study duration (seven days), and the number of participants (12) were maintained across all case studies to ensure methodological consistency.

3.6 Quantitative Data Collection and Analysis

Quantitative data were collected to complement qualitative insights and to contextualise participants' experiences through measurable indicators of system behaviour and use. Data streams included system logs capturing sensor input, duration, and timing of pneumatic actuation across all case studies. In Pneunocchio, physiological signals such as heart rate and electrodermal activity were recorded using wearable sensors. In Pneumusculus, physical activity metrics, including energy expenditure and active calories, were obtained through smartwatch integration.

These datasets were analysed descriptively to identify patterns of engagement, frequency of actuation, and relationships between system input and bodily response. Quantitative data were not used to support inferential statistical claims. Instead, they provided an empirical grounding that supported the interpretation of qualitative findings and enabled system behaviour to be examined in relation to participants' reported experiences.

3.7 Qualitative Data Collection and Analysis

As the primary source of insight for this thesis, qualitative data enabled the in-depth examination of participants' lived experiences with the bodily extensions. Semi-structured interviews were conducted with all participants at the conclusion of each field study, with prompts encouraging reflection on physical sensations, emotional responses, social encounters, perceived agency, and personal meaning.

All interviews were audio-recorded, transcribed verbatim, and analysed using inductive thematic analysis (V. Braun et al., 2019; V. Braun & Clarke, 2006). Qualitative analysis software (NVivo, 2025) was used to support systematic organization and coding of the data. Initial coding was conducted to identify patterns within each case study, followed by iterative refinement of codes into higher-level themes through discussion and comparison.

Thematic analysis enabled the identification of experiential patterns both within and across case studies. These themes informed reflection in the individual case study chapters and provided the empirical foundation for the synthesis presented in the framework chapter. Through this process, qualitative analysis functioned not only as a method of interpretation but also as a bridge between design practice and conceptual contribution.

3.8 Implementing Methods and Approaches

Building on the methodological approach outlined in Chapter 3, chapters 4, 5, and 6 present three design case studies that utilised RtD through the creation, deployment, and evaluation of pneumatic bodily extensions. Each case study examines a distinct everyday-life context and explores how pneumatic actuation, bodily placement, and interaction modality shape lived bodily experience over time. Together, the case studies serve as empirical and experiential probes that ground the investigation of embodiment in concrete design practice.

Chapter 4 introduces the first case study, PneuMa, which explores pneumatic bodily extensions that respond to everyday environmental cues and bodily actions. This case study establishes an initial design space for pneumatic bodily extensions by focusing on explicit interaction and subtle bodily influence, and it provides a foundation for the subsequent case studies, which progressively introduce greater ambiguity, implicit coupling, and bodily transformation. Insights from PneuMa inform the design rationale of Chapters 5 and 6, ultimately contributing to the synthesis presented in the bodily extensions framework in Chapter 7.

CHAPTER 4: CASE STUDY 1 - PNEUMA

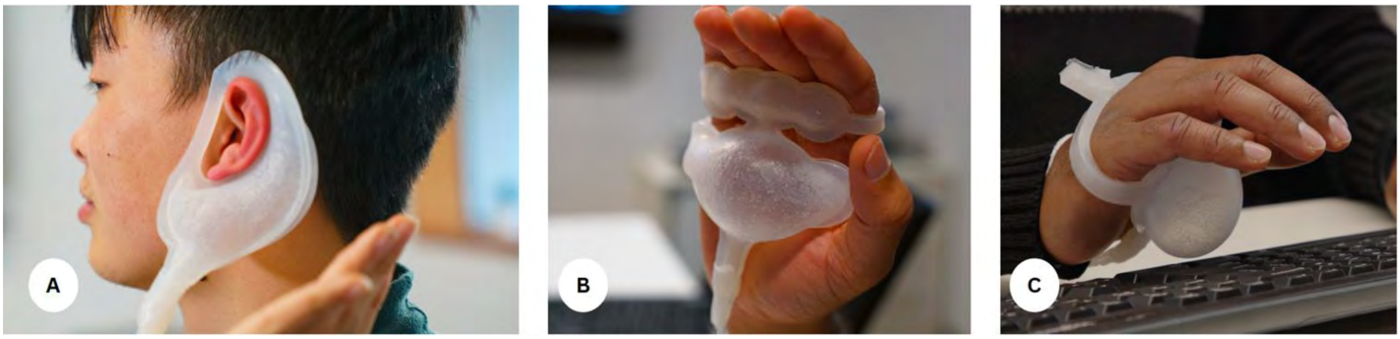

Figure 12: PneuMa Bodily Extensions: A) “Pardon”, B) “Greetings”, and C) "Take a break".

4.1 Overview

This chapter presents the first case study, PneuMa, which explores pneumatic bodily extensions (Figure 12) designed to support movement in everyday life contexts. As the initial case study in this thesis, PneuMa investigates how pneumatic actuation can be embedded into everyday life while maintaining explicit user control. This positioning enables the case study to serve as an entry into the broader design space of bodily extensions explored throughout this thesis.

The chapter contains seven more sections. Section 4.2 introduces the PneuMa case study. Section 4.3 describes the design rationale, material choices, and fabrication of three bodily extensions. Section 4.4 details the seven-day field study conducted to examine how participants experienced these extensions in their everyday lives. Section 4.5 presents the findings from post-study interviews, organised into three themes, and Section 4.6 offers a discussion of these findings. Section 4.7 reflects on the limitations of the case study and outlines directions for future work. Finally, Section 4.8 articulates how insights from PneuMa contributed to the bodily extensions framework presented in Chapter 7 of this thesis, and how this case study informed the progression toward more implicitly controlled and experiential designs in subsequent chapters. Parts of the design and evaluation presented in this chapter informed two peer-reviewed publications:

- Aryan Saini, Haotian Huang, Rakesh Patibanda, Nathalie Overdevest, Elise van den Hoven, and Florian Floyd Mueller. 2022. SomaFlatables: Supporting Embodied Cognition through Pneumatic Bladders. In Adjunct Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology (UIST '22 Adjunct). Association for Computing Machinery, New York, NY, USA, Article 19, 1–4. https://doi.org/10.1145/3526114.3558705
- Aryan Saini, Rakesh Patibanda, Nathalie Overdevest, Elise van den Hoven, and Florian 'Floyd' Mueller. 2024. PneuMa: Designing Pneumatic Bodily Extensions for Supporting Movement in Everyday Life. In Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '24). Association for Computing Machinery, New York, NY, USA, Article 1, 1–16. https://doi.org/10.1145/3623509.3633349

4.2 Case Study Motivation and Positioning

This case study introduces PneuMa, a pneumatic bodily extension system designed to investigate how bodily extensions can be situated within everyday life. In relation to the overarching research question, "how do we design pneumatic bodily extensions to promote embodied experiences in everyday life?", PneuMa serves as an initial investigation of how bodily extensions can be lived with during routine activities.

A key challenge in designing bodily extensions for everyday contexts is that embodiment cannot be assumed to emerge simply from adding actuation to the body (Kimble, 2022). Instead, bodily extensions must first be wearable over time, understood in their behaviour, and compatible with existing social practices (Hapuarachchi & Kitazaki, 2022; Kirsh, 2013). PneuMa aims to address these challenges by deliberately constraining bodily transformation and maintaining explicit user control. This design decision allowed the case study to examine how subtle, body-conforming actuation is encountered when it accompanies familiar actions rather than disrupts them. The PneuMa case study responds to the research question by providing an understanding of whether and how the bodily extensions were experienced as acceptable, interpretable, and negotiable in everyday life.

Pneumatic actuation was selected to afford softness, compliance, and conformity to the body, enabling bodily extensions that can be worn for extended periods without rigid constraint. PneuMa focuses on gentle bodily interventions that foreground explicit interaction. This positioning allows investigation of how bodily extensions can support bodily engagement without requiring users to relinquish control or adapt to unfamiliar bodily mappings.

The PneuMa system enables three bodily extensions, each designed around a commonly occurring everyday scenario:

“Greetings”: The system moves the user’s hand toward a goodbye gesture when the word “goodbye” is spoken, detected via a smartphone microphone.

“Pardon?”: The system moves the user’s ear forward and enlarges it when phrases such as “Beg your pardon?” are spoken, drawing attention to listening as a bodily act.

“Take a Break”: The system moves the user’s hands away from the keyboard after a predefined timer expires, encouraging a pause from prolonged typing.

These scenarios were selected because they are common to everyday social and work practices. By grounding the bodily extensions in recognizable situations, the study avoided artificial task framing and enabled observation of how participants encountered, negotiated, and sometimes resisted bodily actuation during everyday activities. This approach directly supported the research question by revealing how embodiment-related experiences, such as bodily awareness, anticipation of movement, and interpretation of bodily cues, emerge under everyday conditions rather than experimental ones.

This chapter presents the design and implementation of the PneuMa bodily extensions (Figure 13), followed by a seven-day field study with 12 participants. Post-study interviews were analysed using thematic analysis, resulting in three experiential themes: bodily awareness, perception of the scenarios, and anticipating movement. These findings provide an empirical insight into how explicit and subtle bodily extensions contribute to embodied experience in everyday life, and they establish points of comparison for subsequent case studies that introduce implicit coupling and different forms of bodily modification. A video demonstrating PneuMa can be found here: https://youtu.be/NMbNGdyC99c.

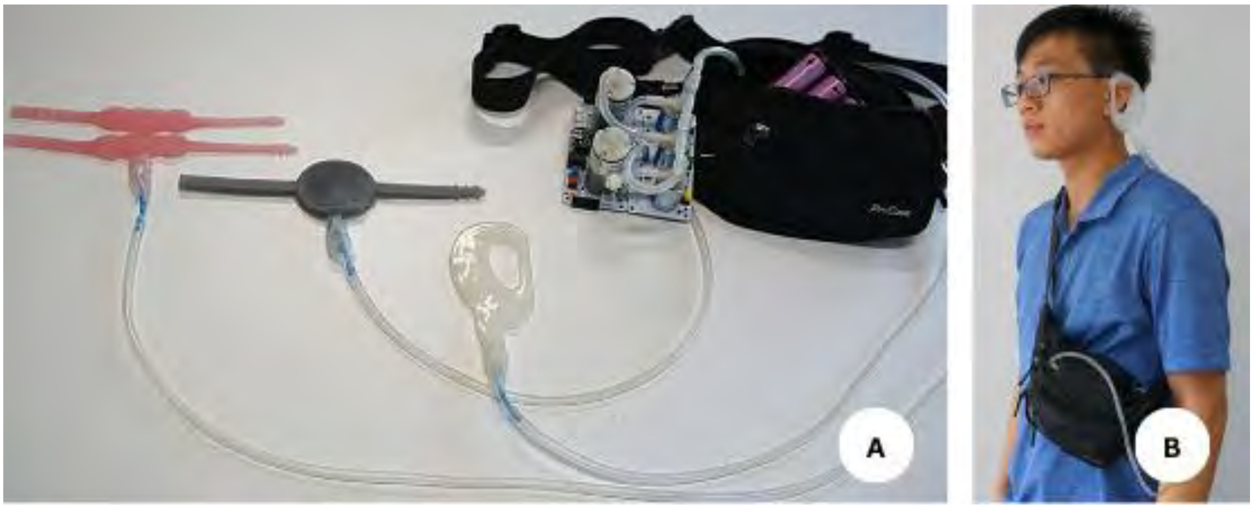

Figure 13: A) The pneumatic controller in a waist bag along with the three bodily extensions (from left to right: "Greetings", "Take a break", and "Pardon?"); and B) A person wearing the "Pardon?" bodily extensions.

4.2.1 Contributions to the Design Framework

This case study contributed to the development of the bodily extensions framework by establishing foundational insights into how pneumatic bodily extensions can be designed, experienced, and interpreted in everyday life when interaction remains explicit and bodily influence is constrained.

First, the PneuMa case study contributed design exemplars in the form of three pneumatic bodily extensions situated within familiar everyday scenarios. These exemplars populate the design space at a point characterised by high user influence and limited bodily modification, helping to anchor the framework in system implementations. The design and implementation knowledge generated through these exemplars supports the articulation of how different inputs, bodily locations, and actuation strategies can be combined while maintaining wearability.

Second, the seven-day field study contributed empirical grounding to the framework through three experiential themes: bodily awareness, perception of the scenarios, and anticipating movement. These themes provided early evidence of how users make sense of bodily extensions that operate through explicit control and subtle actuation, and they informed the framework's treatment of user control, bodily influence, and their relationship to everyday practices. As such, the PneuMa findings helped highlight the higher control regions of the design space and clarify experiential boundaries that distinguish PneuMa from later case studies.

Third, this case study contributed initial design strategies that informed the prescriptive component of the framework. These strategies articulate how designers might begin exploring bodily extensions for everyday life by prioritizing explicit control. Within the framework, these strategies function as entry points for designers seeking to navigate the design space and to consider how different configurations may shape embodied experience.

Together, these contributions position PneuMa as a foundational case study that grounded the bodily extensions framework in everyday contexts and provided a foundation on which subsequent chapters examine further designs.

4.3 Designing Pneuma

The design of the PneuMa bodily extensions was informed by prior wearable and embodied interaction design, as well as by existing literature on pneumatic actuation, which is predominantly situated within engineering and robotics disciplines (Delazio et al., 2018; Naik et al., 2019; Oguntosin & Abdulkareem, 2020). While this body of work provides technical insight into pneumatic systems, it offers limited guidance on how such systems are experienced when worn on the body in everyday contexts. PneuMa therefore adopted an interaction design–led approach that complemented engineering knowledge with experiential investigation.

An iterative prototyping process was employed to explore, evaluate, and refine the bodily extensions over successive design iterations (Hartman et al., 2020; Ishii et al., 1994; Nielsen, 1993). Iterations focused not only on technical feasibility, but also on how bodily movement, comfort, visibility, and social interpretation emerged through use. Given that PneuMa actuates the wearer's body through physical manipulation (as opposed to invasive technologies, such as EMS (Lopes, 2016; Patibanda et al., 2021)), particular attention was paid to how the bodily extensions were perceived both by wearers and by onlookers. During early prototyping stages, design iterations were worn by a collaborator and myself and observed in situ to reflect on bodily sensation, movement quality, and social acceptability. These embodied and observational reflections informed subsequent refinements prior to the field study.

The following subsections describe the key design decisions underlying PneuMa, with a focus on choice of material, bodily placement, and input modalities.

4.3.1 Choice of Material

Material selection was guided by the need to support soft, body-conforming actuation suitable for extended wear. Silicone was selected as the primary material for the inflatable bodily extensions due to its combination of softness, elasticity, and structural resilience. Silicone affords a compliant tactile quality when in contact with skin, while maintaining sufficient mechanical integrity to withstand repeated inflation and deflation cycles (Endow et al., 2021; Moradi & Torres, 2020).

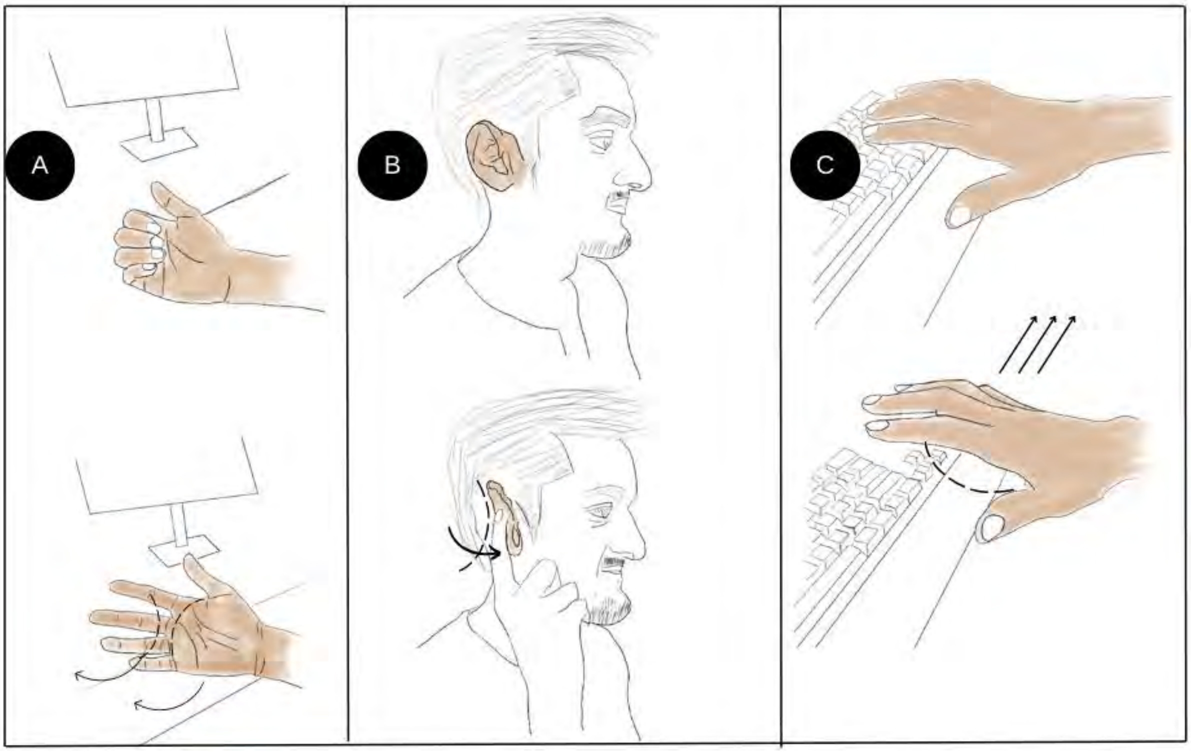

Figure 14: Sketches during the ideation process of possible movements around different body parts: A) movement of the hand in an open and closed position; B) movement of the ear cartilage; and C) wrist movement when pushing things away.

In addition to safety considerations, silicone enables controlled deformation, supporting both gross and fine-motor movements. Silicone's support for fine-motor movements was important for PneuMa because the case study aimed to explore subtle, everyday bodily interventions rather than large or forceful movements. The material choice, therefore, supported the broader research aim of examining bodily extensions that can coexist with everyday life activities without introducing discomfort or risk.

4.3.2 Locations Across the Body

Identifying appropriate bodily locations was a critical part of the design process because the effectiveness of pneumatic actuation depends on how inflatable elements interact with surrounding bodily structures. For a bodily extension to support movement, the inflatable element must be insertable or attachable in a deflated state, while having sufficient space to expand and exert force when inflated. These design parameters require the bodily location to be bounded by at least two surfaces against which the extension can react to produce motion.

In addition to spatial constraints, bodily locations were selected based on their capacity for movement. Only areas of the body with at least one degree of freedom were considered viable, as the goal of PneuMa was to facilitate movement rather than static deformation. The scale of each inflatable element was also calibrated relative to the size of the targeted body part and the intended extent of movement, ensuring that actuation remained perceptible yet restrained.

These considerations led to the selection of locations such as the hand, ear, and forearm, which afford subtle movement, are socially legible, and can accommodate pneumatic actuation without obstructing everyday activities (Figure 14). The resulting placements enabled explorations of how fine bodily movements can be supported through soft actuation while remaining compatible with everyday routines.

4.3.3 Input Modalities

The interaction design of PneuMa prioritised input modalities that minimised explicit physical effort while remaining understandable and predictable. Rather than relying on touch-based or manual input, the bodily extensions were designed to respond to contextual cues present in everyday life. Speech-based input was therefore employed as a primary trigger for actuation, with a smartphone microphone used to detect it and an accompanying application to process it.

Speech was selected because it is a natural and socially embedded form of interaction that does not often require users to divert attention away from ongoing activities. By coupling bodily movement to spoken keywords and contextual timing (e.g., phrases commonly used in conversation or prolonged periods of work), PneuMa explored how environmental and situational cues can initiate bodily actuation without introducing complex control mechanisms.

Importantly, while input was implicit, in the sense that it did not require deliberate physical manipulation, system behaviour remained explicit and predictable. This design choice allowed the case study to examine how bodily extensions can respond to everyday context while preserving user understanding and a sense of control. This emphasis distinguished PneuMa from later case studies that introduced greater ambiguity and implicit coupling.

Figure 15: Fabrication kit for creating silicone-based bodily extensions. A) Liquid silicone; B) Weighing scale and a beaker for mixing silicone; C) Silicone tape for sealing the bodily extensions post fabrication; D) Silicone tube to connect the bodily extension to the pneumatic controller; E) Silicone dye; F) Piston for injecting water during fabrication; G) A 3D printed mould and PVA-based separator for the "Greetings" bodily extension; H) Tweezers to add the separator to the silicone layer; I) Safety gloves.

4.3.4 Fabrication Process

The fabrication process for the PneuMa bodily extensions was designed to support personaliszation, rapid iteration, and safe pneumatic actuation on the body. Given the diversity of bodily locations and the need for close bodily fit, the fabrication approach also prioritised adaptability in shape, size, and structural behaviour across different body parts.

Figure 16: Experimenting with colours for PneuMa bodily extensions.

To fabricate silicone-based inflatable bodily extensions, a PVA-less moulding technique inspired by Moradi and Torres (2020) was adopted (Figure 15). This approach enabled the creation of internal air pockets within silicone structures without relying on permanent sacrificial materials. The method involved sandwiching a thin layer of polyvinyl alcohol (PVA) between two layers of silicone during fabrication. After curing, warm water was injected through the air inlet to dissolve the PVA, leaving a sealed internal cavity connected to a pneumatic tube. This technique allowed for the fabrication of soft, airtight inflatables that could be safely actuated while remaining compliant against the body.

Figure 17: Iterative progression in design for "Greetings."

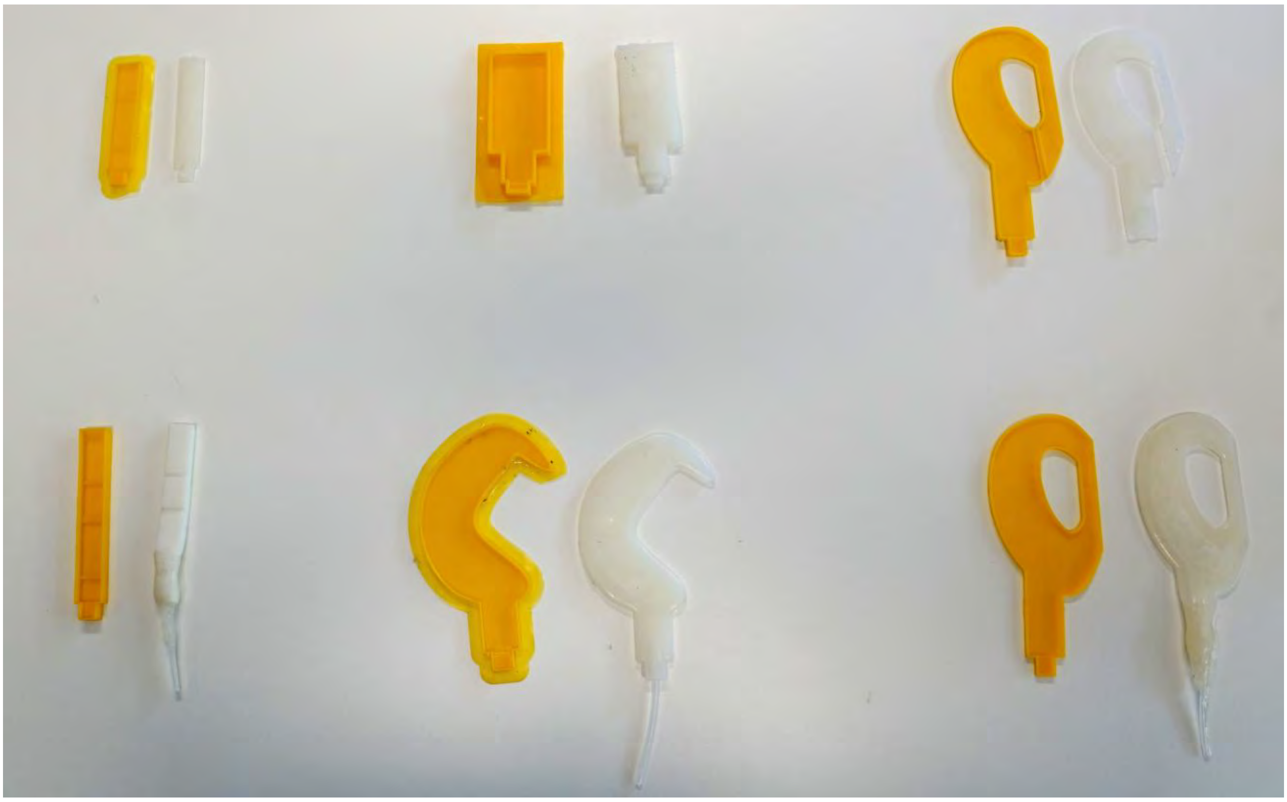

Figure 18: Iterative progression in design for "Pardon?"

The fabrication process consisted of three main steps.

As the first step, the target body part and intended movement were identified, and the relevant bodily dimensions were measured. These measurements informed the design of a custom mould using Onshape, a collaborative online 3D CAD platform (Onshape, 2026). The mould defined the outer geometry of the inflatable extension and was designed to ensure sufficient surface contact with the body while accommodating expansion during inflation. Although silicone is inherently stretchable, adjustable straps were incorporated into the design to accommodate variation in body size and to maintain consistent positioning, functionality, and comfort during wear.

Alongside the mould, a PVA separator layer was designed to define the size and shape of the internal air cavity. The separator played an important role in determining both the mechanical behaviour and durability of the inflatable. Multiple iterations of separator geometry were explored to balance structural integrity with the ability to generate perceptible movement. The separator was typically offset by approximately 2.25 mm from the inner boundaries of the mould to ensure sufficient bonding between the two silicone layers, reducing the risk of rupture when overinflated.

As the second step, the mould and separator were 3D printed (Figure 17, Figure 18 and Figure 19), and a silicone mixture was prepared. During early iterations, a faster-curing silicone was used to enable rapid prototyping, despite a higher likelihood of minor defects. The silicone was first poured halfway into the mould and allowed to partially cure. Once cured, the PVA separator was carefully placed onto the first silicone layer, after which additional silicone was poured to fill the mould. The assembled mould was then cured in an oven at 57 °C for approximately 15 minutes, ensuring full bonding between layers.

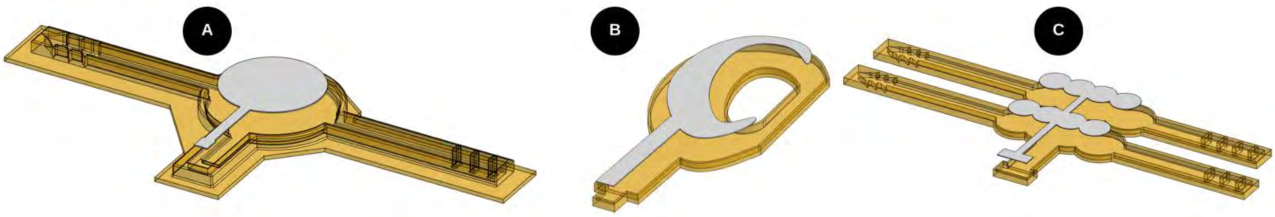

Figure 19: The 3D printed mould and separator during the fabrication process for the PneuMa case study.

As the final step, the cured inflatable was demoulded, and air was injected through the pneumatic inlet to verify airtightness. Warm water was then injected through the same inlet to dissolve the PVA separator. A binder clip was temporarily applied to the inlet to retain the water and facilitate complete dissolution of the PVA. Once the separator had fully dissolved, the clip was removed, and the remaining water was drained, leaving a sealed internal cavity ready for pneumatic actuation.

Figure 20: Fabrication steps in the PneuMa case study.

This fabrication approach supported rapid customization (Figure 16) and iteration across bodily locations while maintaining consistent material behaviour. Importantly, it enabled exploration of fine-grained bodily movements through soft actuation, which aligned with the broader goal of investigating wearable and suitable bodily extensions for everyday life. In these ways, the fabrication process functioned not only as a means of construction but as a critical enabler of experiential inquiry within the RtD methodology.

4.3.5 Three Scenarios

Three everyday scenarios were selected to ground the PneuMa bodily extensions in routine social and private interactions. Rather than treating scenarios as application-specific use cases, they were designed as comparative probes to examine how explicit, subtle pneumatic actuation is experienced across different everyday contexts. Collectively, the scenarios were chosen to vary in social visibility, temporal structure, and bodily placement, while remaining familiar and accessible to participants (Table 1).

The selection was guided by the following considerations, which together supported the study's aim of examining bodily extensions in everyday life:

- Temporal characteristics: The scenarios were intentionally brief and repeatable, thereby increasing the likelihood that participants would encounter them multiple times during their everyday routines. This feature enabled observation of habituation, anticipation, and evolving interpretation over the seven-day field study.
- Convenience and familiarity: Scenarios were embedded in activities that require little explanation or explicit prompting, allowing bodily actuation to be encountered organically rather than as part of an imposed task.
- Technical feasibility: Scenarios were constrained by the capabilities of soft pneumatic actuation. Activities involving large forces, rapid motion, or high physical exertion were deliberately excluded to ensure safety and reliability within the prototypical design.
- Cultural and demographic accessibility: Drawing on prior work conducted in similar participant populations (La Delfa et al., 2020; Overdevest et al., 2023; Patibanda et al.,

2023), scenarios were selected to be broadly recognizable across cultural backgrounds, ages, and occupations.

- Ambidexterity: All bodily extensions were designed to be wearable on either side of the body, allowing participants to choose placements that suited their preferences.

Limiting the case study to three scenarios balanced breadth and participant burdens, thereby enabling comparative insight while maintaining a manageable scope. Together, the scenarios demonstrated that pneumatic bodily extensions are not tied to a single activity but can be configured across multiple everyday situations. While not exhaustive, they provided a structured starting point for reasoning about how bodily extensions may be designed and experienced across contexts.

The three scenarios, “Greetings”, “Pardon?”, and “Take a Break” are described below.

Table 1: The list of scenarios considered in the design of the PneuMa case study, and evaluation of their feasibility against the selection considerations (first column).

	Greetings	Pardon	Take a break	Way finder	Alcohol Limiter
Situation	Social (remote)	Social (in-person)	Private	Private	Social (in-person)
Prompted movement	Fingers plus hand	Ear	Wrist plus hand	Feet plus legs	Arms
Temporal feasibility	✓	✓	✓	✗	✓
Convenience	✓	✓	✓	✗	✗
Technical feasibility	✓	✓	✓	✗	✓
Cultural consideration	✓	✓	✓	✓	✗
Demographic factor	✓	✓	✓	✗	✓
Ambidexterity	✓	✓	✓	✓	✓

Greetings

“Greetings” features a bodily extension worn inside the user’s palm. When the system detects the keywords “bye-bye” or “goodbye” via a mobile phone application, a wireless command triggers pneumatic inflation. The actuation opens the hand from a closed position into a straightened posture, initiating a goodbye gesture.

The bodily extension consists of two inflatable chambers that press against each other and against the user’s palm and fingers. This configuration enables a controlled opening motion without requiring active muscular effort from the user. As a socially visible and explicitly triggered interaction, "Greetings" explores how bodily extensions can accompany familiar gestures while preserving user agency and interpretability.

Pardon?

"Pardon?" features a bodily extension attached behind the user's ear. When the phrases "Pardon?", "Sorry?", or "Can you repeat?" are detected, the extension inflates to move the ear forward while simultaneously enlarging its apparent size.

This actuation serves multiple functions. The forward orientation may support auditory attention by directing the ear toward the sound source, while the enlargement may help channel sound waves (Mortensen, 2016). Beyond functional considerations, the visible transformation communicates attentiveness to conversation partners, signalling engagement even when hearing is incomplete. As such, "Pardon?" explores how bodily extensions can mediate social legibility and bodily awareness through subtle, yet noticeable, form change.

Take a Break

"Take a Break" features a bodily extension worn on the palms, similar in placement to "Greetings." The system encourages breaks from prolonged keyboard typing by actuating after a configurable time interval. Inspired by the Pomodoro technique, which promotes productivity through structured work–break cycles (Costales et al., 2022), the extension gently pushes the hands away from the keyboard.

Instead of visual or auditory notification, "Take a Break" employs bodily movement as a prompt, making the interruption felt rather than seen or heard. This scenario explored how pneumatic actuation can introduce temporal structure into everyday work practices through embodied cues, without relying on screens or alarms.

4.3.6 Technical Implementation

The PneuMa system is built around a programmable pneumatic controller that supplies compressed air to the bodily extensions (Programmable Air, 2026). The controller communicates wirelessly with a Unity-based smartphone application via Bluetooth. The pneumatic controller operates at a maximum pressure of 50 kPa and is powered by three 3.7 V lithium-ion batteries connected in series. The complete system, including the waist bag used to carry the controller, weighs approximately 1.5 kg.

At any given time, a single bodily extension can be connected to the controller via an air tube. Extensions can be easily detached and swapped, allowing participants to alternate between scenarios without modifying the underlying hardware. This modular setup supports comparative exploration across bodily locations and interaction contexts while maintaining a consistent technical baseline.

For the “Greetings” and “Pardon?” scenarios, the smartphone application (Figure 21: Screenshots from the smartphone application for the PneuMa system: the screenshots are A) the landing screen for the application, B) the "Greetings" tab for voice input containing the activation phrases, C) the "Pardon?" tab for voice input containing the activation phrases, and D) the "Take a break" tab for setting a custom timer.) uses the device’s microphone to detect predefined keywords associated with conversational cues. Upon detection, the application sends a command to the pneumatic controller to initiate inflation. In the Take a Break scenario, the application allows participants to set a timer duration, after which the bodily extension is actuated to prompt a pause from typing.

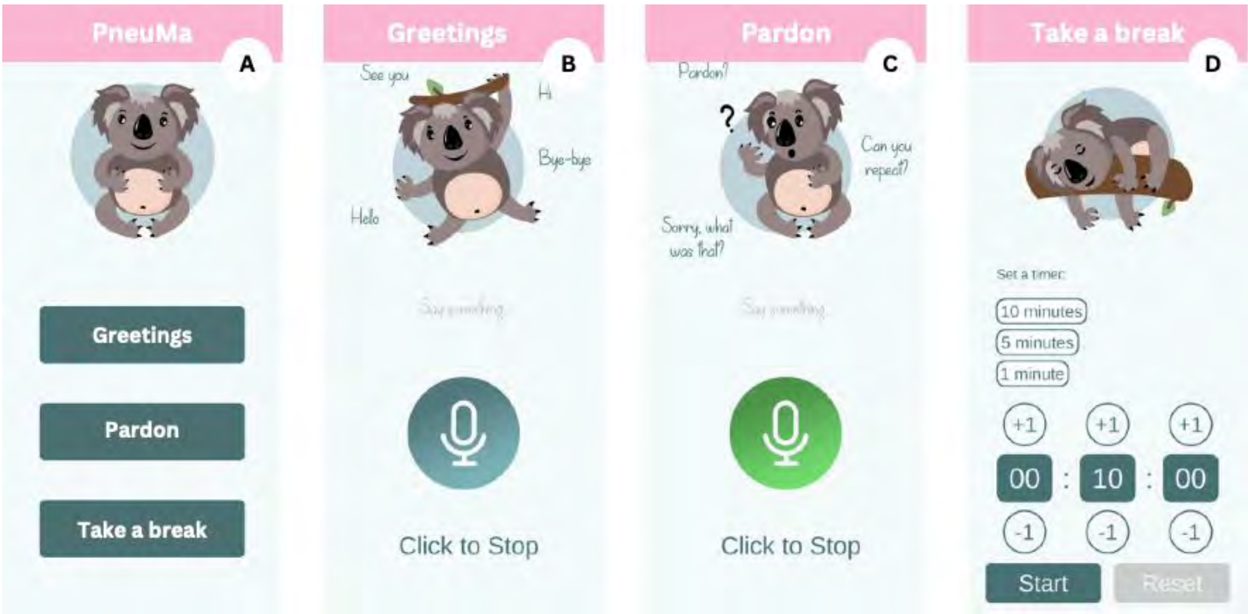

Figure 21: Screenshots from the smartphone application for the PneuMa system: the screenshots are A) the landing screen for the application, B) the "Greetings" tab for voice input containing the activation phrases, C) the "Pardon?" tab for voice input containing the activation phrases, and D) the "Take a break" tab for setting a custom timer.

4.4 PneuMa Study Design and Analysis

This case study employed a seven-day field deployment to examine how the PneuMa bodily extensions were experienced as part of participants' everyday lives. The study design focused on capturing situated experiences of wearing and interacting with pneumatic bodily extensions across diverse personal and social contexts, rather than evaluating task performance or system efficiency.

Participants were onboarded through an in-person session designed to establish familiarity with the PneuMa system and ensure safe and informed use during the field study. Participants were then introduced to the three PneuMa bodily extensions, their intended bodily locations, associated everyday scenarios, and the companion smartphone application.

Participants were guided through hands-on interaction with each bodily extension to gain functional familiarity. Each extension was tried on at least twice, and participants were encouraged to ask questions regarding operation, comfort, and usage. This onboarding session lasted 32 minutes on average (M = 32.3 minutes, SD = 4.2 minutes). Following onboarding, participants were provided with the full PneuMa kit and instructed to use the bodily extensions in their preferred order and at moments they considered appropriate during the study period.

Twelve participants took part in the study, aged between 18 and 35 years (M = 24, SD = 5.5). Five participants identified as female and seven as male; none identified as non-binary or self-described. Two participants reported prior experience with exoskeleton systems, probably due to the framing of the recruitment material, while none had previous experience with pneumatic-based wearable technologies.

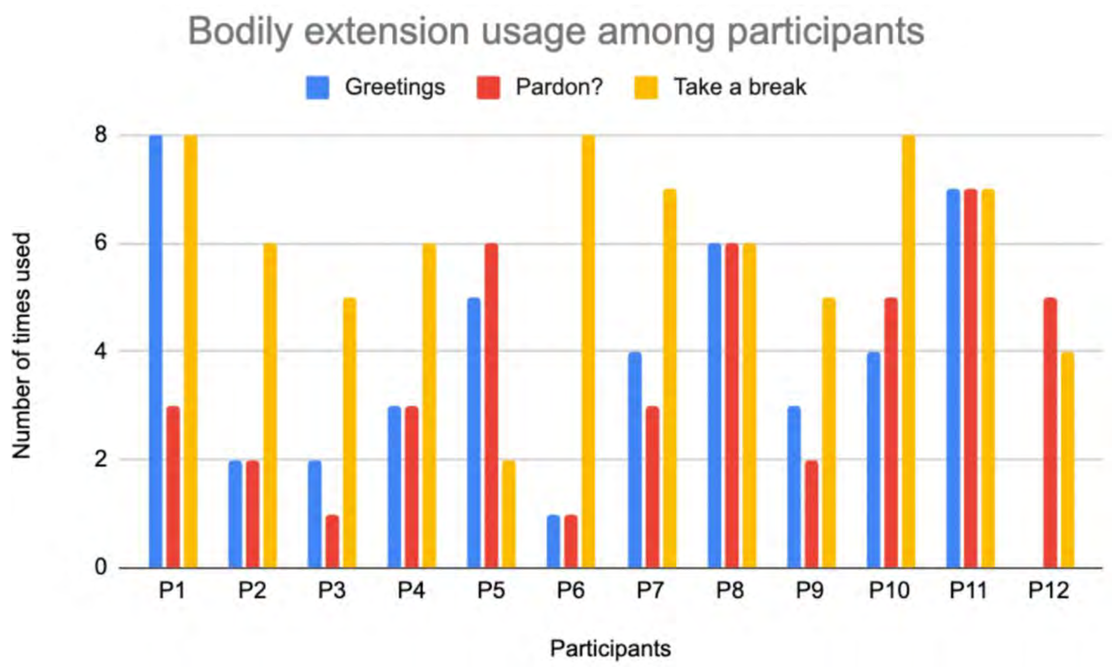

Figure 22: Usage patterns of the bodily extensions across the 12 participants from a field study with the PneuMa system.

Participants were asked to use the PneuMa bodily extensions over a period of seven consecutive days. Only one bodily extension could be connected to the pneumatic controller at a time, although participants could freely swap extensions by reconnecting the air tubing. Participants were encouraged to integrate the bodily extensions into their everyday routines without following scripted tasks or predefined usage schedules.

To support continued engagement and capture intermediate reflections, optional video-based check-ins were conducted approximately every two days when participant schedules permitted. These sessions lasted around 20 minutes on average (M = 19.2 minutes, SD = 2.38 minutes) and were audio- and video-recorded. During these check-ins, participants demonstrated their use of the bodily extensions and reflected on emerging experiences or challenges.

In addition, participants were asked to self-record short videos during everyday use outside the scheduled check-ins using an action camera provided as part of the study kit.

At the conclusion of the field deployment, participants took part in individual semi-structured interviews lasting 53 minutes on average (M = 52.68 minutes, SD = 6.24 minutes). The interviews focused on participants' lived experiences with the bodily extensions, including bodily sensations, perceived agency and control, social interactions, evolving interpretations over time, and reflections on wearing and moving with the extensions in everyday contexts.

Interviews were analysed using inductive thematic analysis, following the procedure outlined in Chapter 3. The resulting themes formed the basis of the findings presented in Section 4.5 and informed the broader synthesis toward the pneumatic bodily extensions framework.

4.5 Findings from the PneuMa Field Study

This section presents the findings from the PneuMa case study, combining descriptive quantitative results with three overarching experiential themes derived from qualitative analysis: bodily awareness, perception of the scenarios, and anticipating movement. Together, these findings provide insight into how explicitly controlled pneumatic bodily extensions are encountered and interpreted in everyday life, and how they contribute to embodied experience in non-trivial ways.

4.5.1 Quantitative Results: Usage Patterns

Quantitative data were analysed to provide contextual insight into how frequently participants engaged with each bodily extension during the study period (Figure 22 and Table 2). These data are not used to make claims about effectiveness or preference, but rather to situate the qualitative findings within patterns of everyday use.

Across participants, the "Take a Break" extension was used most frequently, with a mean usage of approximately six interactions per participant. In contrast, "Greetings" and "Pardon?" were used less often, with mean usage values of 3.75 and 3.67, respectively. Median usage followed a similar pattern, with values of 6 for "Take a Break", 3.5 for "Greetings", and 3 for "Pardon?". The alignment of mean, median, and mode for "Take a Break" suggests relatively consistent engagement across participants, whereas the greater spread observed for "Greetings" and "Pardon?" indicates more varied appropriation.

Measures of variability further support this interpretation. "Take a Break" exhibited the lowest standard deviation (1.81) and standard error (0.52), suggesting relatively stable usage across the participant group. In contrast, "Greetings" and "Pardon?" showed greater dispersion, reflecting differences in how participants perceived the relevance, timing, or social appropriateness of these scenarios.

Importantly, these usage patterns should be understood as reflective of situated opportunity and choice, rather than utility alone. The quantitative data indicated that different everyday scenarios afforded different levels of engagement, which, in turn, affect how participants experienced bodily actuation, anticipated movement, and reflected on their bodily experience. These patterns provided an initial understanding against which the qualitative themes were interpreted.

Table 2: Descriptive statistics of usage patterns from the PneuMa field study with 12 participants.

	Greetings	Pardon?	Take a break
Mode	2.000	3.000	6.000
Median	3.500	3.000	6.000
Mean	3.750	3.667	6.000
Std. Error of Mean	0.698	0.595	0.522
Std. Deviation	2.417	2.060	1.809
Variance	5.841	4.242	3.273
Minimum	0.000	1.000	2.000
Maximum	8.000	7.000	8.000

4.5.2 Qualitative Results

Theme 1: Bodily awareness

The theme of bodily awareness emerged from the analysis of 83 units of data, and it describes the participants' experiences in regard to the awareness of their bodies. In particular, this theme highlights how the participants' experiences evolved over time with the bodily extensions and their reflections regarding the perception of their own bodies.

Sub-theme 1: Appropriation of the system

Eight participants reported noticing the bodily extensions even when deflated mostly due to their weight and body location, as indicated by statements such as, *"I could definitely notice the (bodily) extensions as they were worn on a part which is usually empty"* (P5), and *"wearing these prototypes felt a bit unnatural as they were not something I would wear often"* (P9). These quotes indicate that the participants were aware of the placements of the bodily extensions across their bodies, primarily citing the weight of the bodily extensions as the reason. A participant compared the bodily extensions to a second skin, stating, *"it's similar to wearing a second skin, I think mostly because of how they feel to touch"* (P6).

Sub-theme 2: Perceived utility of the bodily extensions

Four participants perceived the extensions as an augmentation that would lend an extra ability: *"the extension felt as if it was there to help me somehow because I would not often wear anything around my hands or ears"* (P8). One participant commented that *"I did not really bother on how they feel to be worn as I just knew they were on my body, and would do something."*

Sub-theme 3: Change in perception of the bodily extensions over time, bringing the body to the foreground of attention.

P1 suggested that wearing the bodily extensions, initially, *"instilled curiosity"*. The participants described their experience with PneuMa as something that brought the different parts of their body and its physiology to their notice. Comments included, *"while using the system, I could notice how my hand actually moves, which is something I wouldn't usually do"* (P10) and *"although the interactions seemed unnatural at first, once I got used to them, my attention shifted towards how my body was pulled into a scenario"* (P12).

Sub-theme 4: Fusion between bodily extensions and participants' bodies

Participants noted that using the system became easier over time. Their comments included that *"wearing the extensions sort of seemed natural to me over time, it was similar to wearing an accessory around my body every day"* (P5) *and that, "at first seemed tricky to navigate, but by the end of the study, I felt way more comfortable with the extensions and was able to get around it quickly around my body"* (P10). This feedback suggests that, over time, the participants became familiar and comfortable with wearing the bodily extensions, as if they were wearable accessories.

Sub-theme 5: Changes in perception of self over time

Participants' perceptions of the bodily extension also changed over the period of the study. For example, a participant noted that *"I can feel I have two hands (talking about the "Greetings" bodily extension) because of the shape, and that made me feel I have two hands attached* *together like a part of my body"* (P6) and another that *" I could feel my ears bigger than usual which made me feel wise"* (P1, while talking about the "Pardon" extension). These results suggest that using bodily extensions altered how the participants perceived their own bodies navigating everyday life scenarios, which was augmented by the bodily extensions.

Participants also mentioned that they became more aware of the morphology of their bodies. Comments included that *"I had not observed my hands and the joints this closely before"* (P3) and *"when I reflected upon the design of the extensions, I could understand how my body is constructed"* (P8). These results suggest that, although the bodily extensions felt *"unnatural"* and *"weird"* at first, the participants' bodily awareness changed over the duration of the study.

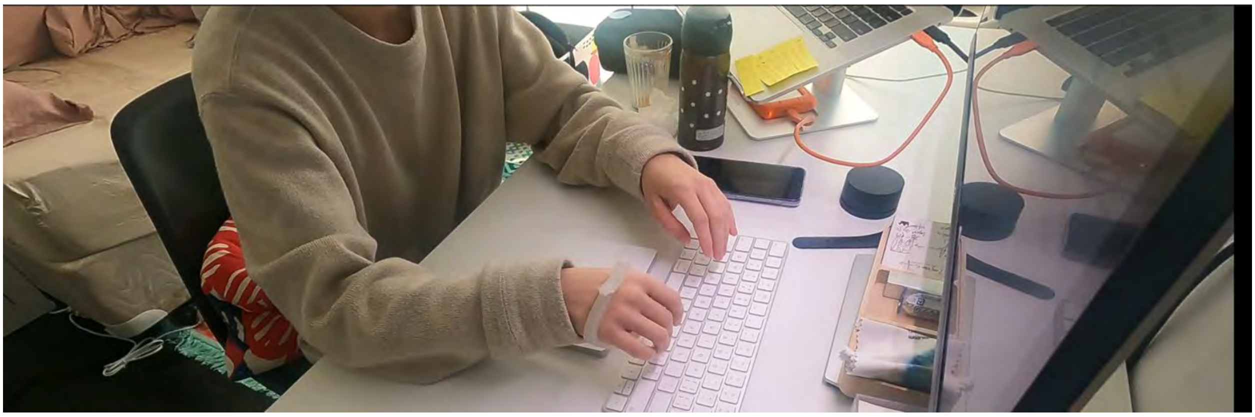

Figure 23: A person is using the "Take a break" extension.

Theme 2: Perception of the scenarios

This theme explores how participants understood and reflected on the scenarios supported by the system as they navigated everyday life. This theme comprises 67 data units and describes participants' experiences in relation to the scenarios supported by the bodily extensions and their intended functionality.

Sub-theme 1: Learning curve with the bodily extensions within context

Initially, participants reported experiences of curiosity, surprise, and confusion associated with the bodily extensions. Participants noted that *"even though I knew the extensions would help me navigate day-to-day situations by prompting me to move, I was surprised when the* *inflations occurred"* (P7) and *"I actually got distracted by the inflations and stopped what I was doing just to look at them"* (P2). Three participants also mentioned a feeling of apprehension towards the bodily extensions, with P8 commenting that *"I was concerned how the extensions looked on me while I was talking to other people,"* while P4 said, *"I was not really sure if they would work well; they felt a bit strange"*.

Sub-theme 2: Presence of the bodily extensions serving as a reminder

However, once they had become used to the bodily extensions, the participants' user experience was driven towards reflecting on the utility of bodily extensions. P3 expressed that *"even though the phone application was sometimes unable to catch my words, just wearing the extensions served as a reminder that I probably need to move"*, and P1 stated that *"it kind of seems obvious when the extensions prompt you towards those movements, for example for taking a break, you would usually lift up your hands to get away from wherever you are."*

Sub-theme 3: Utility of bodily extensions in the scenarios supported by PneuMa

Participants described the experience as *"wholesome"* and *"entertaining"*. They also explained how they perceived the bodily extensions in the specific scenarios, stating, *"I think [they] were really accurate, direct and helpful"* (P7) and *"it's something kind of magical in a way on how they keep your body in sync" (P11)*.

Sub-theme 4: Contextual movements facilitated by PneuMa

Participants described their experiences with each of the bodily extensions individually. For *"Greetings,"* P6 commented that *"although I am not used to waving to other people, more of a handshake or a hug person, the inflation served as feedback for me to go in for a hug."* P2 also stated that, *"I don't usually realise when my hands move while waving, the extension helped me kind of kickstart the motion."*

Figure 24: A person using the "Pardon?" extension.

Sub-theme 5: The bodily extensions as a social organ

For the "Pardon?" extension, P9, initially bemused by the scenario, commented that "*it felt strange at first as to why should I wear something that helps other people speak better; however, as the other person could see the extension inflate, it served as a reminder for the other person that I had some difficulty in either hearing or understanding them.*"

P12 articulated their experience with the "Pardon?" extension: *"I wasn't sure if I could feel my ear move from the inflation, but hearing the inflation, I improvised by turning my ear towards the speaker, hoping they could see the extension."*

These comments suggest that, although the bodily extensions were designed to prompt movement, the participants sometimes did not explicitly rely on or wait for the extension to facilitate the movement and improvised as they saw fit.

Additionally, four participants felt that wearing these bodily extensions served as a conversation starter, with P1 explaining that, "*when I was on a video call with my parents, this was the first thing they asked about, rather than their usual question of my whereabouts.*" These results suggest that participants' social experiences profited from the presence of the PneuMa system.

Sub-theme 6: PneuMa facilitated bodily feedback

While describing their experience with the *"Take a break"* extension, seven participants (who were familiar with the Pomodoro technique) made similar comments to P3: *"unlike the timer on my phone, this [bodily extension] did not feel distracting at all. I felt as if I had reached the limits of my body."* Participants also appreciated the explicit nature of the interaction facilitated by the "Take a break" extension. For example, P11 stated that *"I forgot about the extension when I started working, although it was in mind somewhere, I did not pay attention to the extension; however, when the inflation occurred, to my surprise, I felt I could not work anymore as my hands were giving me instructions."* These experiences suggest that while *"Take a break"* leveraged a different modality (prompting movement as opposed to auditory feedback) to alert the user about the time to take a break, the extension made it explicit to the participants due to the induced movement. Additionally, two participants commented on their altered perception of time when using the *"Take a break"* bodily extension. P8 stated that *"I never realised 10 minutes were so long",* while P9 added that *"I thought my time awareness was top notch, but I kept checking the clock as to when the timer would expire in anticipation of the movement."*

These experiences show how participants perceived the situation facilitated through the PneuMa system, along with their understanding of the bodily extensions' functionality to support movement in these situations.

Theme 3: Anticipating movement

This theme arose from the analysis of 79 data units, and it describes how the bodily extensions facilitated participants' anticipation and understanding of the movements being facilitated in everyday life.

Sub-theme 1: Movements facilitated situational awareness

Participants mentioned that the movements helped them understand the context of their situation as they experienced the movement both in an embodied and visual manner. P2 stated that *"I felt more aware of the situation I was in and knew what movements to make in case the* *system failed."* P10 added that *"I thought the extensions were sort of helping to relearn movements based on context."*

Sub-theme 2: The nature of movement supported by pneumatics was appreciated

While describing their experience in the moment of inflation, P3 commented that *"the inflations were really relaxing to look at because the air filled the bodily extensions slowly and gave it a soothing effect."* Additionally, P1 explained that *"I really enjoyed the prompted movements from the system as it was not too forceful but subtle enough."* Participants also stated how they felt touching the bodily extensions and that they appreciated the pneumatics' ability to support subtle movements. P2 commented that *"the extensions, when inflated, felt comforting to me as if they were inviting me to press on them."* These results suggest that the soft and body-conforming nature of the bodily extensions served as a favourable material to promote bodily movements.

Sub-theme 3: Building a relationship with the system owing to the facilitated movements

The participants talked about how they engaged with their bodies to support the system. P5 explained that *"I felt the need to relax and let my body loose so that it could be moved by the extension."* Additionally, P1 described how *"the movements prompted were really easy; I never felt that the system was overpowering."* These results indicate that the bodily extensions, while facilitating movement, preserved the participants' sense of control over the movement.

Sub-theme 4: Perceived control over the movements

Participants also pointed out the factors that might have resulted in a control-preserving experience. Five participants attributed the preservation of control to the choice of material, with P2 commenting that *"I think it was because of the non-restricting and soft material, I could just choose to press on the extension to deny the movement."* In comparison, P4 stated, *"I knew since the system was external, I could just reject the movements with just a little bit of force."* P9 similarly described their experience of control: *"as controls were dependent on me, I could just choose not to use the specific (key)words or use the same words in a different language."* These results suggest that, while the PneuMa system was successful in facilitating movement, participants sometimes chose to either ignore or override the movements whenever they did not feel those movements were appropriate.

Sub-theme 5: Ability to choose when to activate the movements helped with reliability

P6 articulated their experience in regard to choice and control: *"The choice to ignore or just not initiate the movement through the bodily extensions felt reassuring."* This feedback suggests that the design (especially the soft material and non-rigidity of the silicone-based bodily extension, along with the ability to regain control over the movement owing to pneumatics) supported participants' movement in a way that suited the variety of different everyday life contexts in which they found themselves.

4.6 Discussing PneuMa Study Results

This section discusses the findings of the PneuMa case study in relation to prior work, with the aim of extending design knowledge around bodily extensions that support movement and embodied experience in everyday life. This discussion focuses on how explicitly controlled, soft, pneumatic bodily extensions can shape bodily awareness, perceived control, and everyday action.

4.6.1 Designing for Embodied-being in Everyday Life

The experiential themes identified in this case study align with and extend prior work on embodiment in everyday interaction, particularly the Embodied Being-in-the-World framework proposed by van Dijk and Hummels (2017). Two of the themes, bodily awareness and perception of the scenarios, correspond closely to what van Dijk and Hummels describe as transforming the lifeworld, whereby design interventions alter how users perceive and act within everyday situations.

Participants' accounts indicated that wearing and interacting with the PneuMa bodily extensions altered their awareness of bodily movement during routine activities. Participants described attending more closely to specific parts of their bodies and becoming more conscious of how movements unfolded within familiar scenarios. This finding suggests that the bodily extensions functioned as interventions that reshaped perception–action coupling, rather than merely adding functional assistance.

In addition, participants reported reflecting on their movements during and after interaction, indicating moments of reflection both in action and on action. These observations resonate with van Dijk and Hummels' emphasis on embodiment as a reflective process grounded in lived experience. While van Dijk and Hummel's original framework was developed primarily in accessibility-related contexts, the PneuMa case study extends their findings by demonstrating how similar embodied transformations can occur through playful, non-assistive bodily extensions situated in everyday life.

4.6.2 Perceived Control Over Bodily Extensions

The findings of this case study also relate closely to prior work on playful bodily extensions, particularly the design implications proposed by Buruk et al. (2023), which emphasise the importance of perceived user control for bodily incorporation. In contrast to many bodily extensions driven by implicit physiological input, the PneuMa system relied on explicit triggers, such as speech-based cues and timers, which afforded users clear opportunities to decide when and whether actuation occurred.

Participants consistently described feeling in control of the bodily extensions, and they attributed this experience to two factors. First, explicit activation mechanisms allowed participants to determine the timing of movement, enabling them to accept, ignore, or delay actuation depending on context. Second, the use of soft, compliant materials allowed participants to physically resist or suppress inflation when the support felt inappropriate. This capacity to negotiate actuation through bodily resistance contributed to the participants' sense of confidence and trust in the system.

These findings extend prior design knowledge by suggesting that control in bodily extensions is not solely a matter of input modality, but also of materiality. Soft pneumatic bodily extensions can distribute agency between system and body by allowing users to override actuation through bodily interaction, rather than through digital commands alone. In this respect, the

PneuMa case study demonstrates how explicit input combined with soft materials can support a relatively high sense of control, offering a contrast to bodily extensions driven primarily by implicit physiological signals (explored in chapter 5).

4.6.3 Design Strategies Emerging from the PneuMa Case Study

This section presents a set of design strategies that emerged from the findings of this case study. Designers aiming to create bodily extensions that leverage explicit input to promote bodily movement could find these strategies useful when proposing future designs. These strategies need not be considered as an exhaustive set or in a particular order. Rather, they aim to serve as a starting point for future explorations in the area of bodily extensions.

Strategy 1 - Use soft materials for designing bodily extensions

Participants reported that silicone-based pneumatic bodily extensions were comfortable, body-conforming, and tolerant of everyday movement. The stretchable and shape-changing properties of silicone enabled subtle bodily actuation while allowing users to resist or modulate movement when necessary. Designers may therefore consider soft pneumatic materials when aiming to support bodily movement in everyday contexts, particularly where comfort, wearability, and negotiation of control are important.

Strategy 2 - Leverage explicit movements for increased awareness

The bodily movements prompted by the PneuMa extensions were explicit and easily interpretable in relation to the affected body part. Participants reported that this clarity supported awareness of bodily movement without requiring cognitive effort to interpret complex actuation. Designers seeking to foster embodied experience may therefore benefit from designing movements that are legible and familiar, thereby reducing interpretive load and allowing users' attention to remain on bodily sensation and action.

Strategy 3 - Design with explicit input for higher bodily control

Unlike bodily extensions driven by physiological signals, which can be difficult to influence directly, the explicit input mechanisms used in PneuMa afforded users clear agency over when movement occurred. Speech-based triggers and configurable timers allowed users to adapt the system to personal and contextual preferences. Designers may therefore consider explicit, user-accessible input mechanisms when aiming to support a strong sense of bodily control in everyday use.

Taken together, these strategies highlight how designing for explicit control, movements, and soft materiality can work together to support embodied interaction in everyday life. These insights – clarifying how control and bodily influence can be deliberately configured in bodily extensions – inform the broader framework developed in Chapter 7 of this thesis.

4.7 Limitations of the PneuMa Case Study

This case study has several limitations that point to opportunities for future research. First, while it enabled customisation, the fabrication process for the pneumatic bodily extensions exhibited a moderate failure rate. The PVA-less moulding technique (Moradi & Torres, 2020) occasionally resulted in trapped air bubbles, leading to defective extensions. Although mitigation strategies were identified, such as compressing silicone layers prior to curing, future work could explore automated or semi-automated fabrication processes to improve consistency and reduce manual error.

Second, participants reported occasional challenges related to system wearability, particularly due to the pneumatic tubing and the size of the controller housed in a waist-mounted bag. These issues stemmed from adapting a pneumatic controller into a wearable configuration. Future implementations could benefit from custom hardware designs, such as dedicated printed circuit boards and integrated pneumatic components, to reduce system weight and improve mobility.

Additionally, limitations were observed in the speech recognition used for the “Greetings” and “Pardon?” scenarios. Variability in accents and speaking styles affected detection reliability, which suggests that future work should explore more robust speech recognition approaches or alternative explicit input modalities.

4.8 Implications for the Framework

The PneuMa case study informed the bodily extensions framework by foregrounding the role of prompting explicit bodily movements in shaping embodied experience with pneumatic bodily extensions. The bodily extensions designed in this case study initiated movement directly on the user's body, illustrating how system-driven actuation can draw attention to bodily action as it unfolds in everyday situations.

Participants' experiences indicated that embodiment in this context was closely tied to the immediacy and explicitness of bodily intervention. The actuations were described as noticeable, sometimes surprising, and strongly situated in the moment of interaction. This immediacy (except in the case of "Take a break") heightened bodily awareness and encouraged movement by making bodily change difficult to ignore. However, this immediacy also shaped how embodiment was experienced: rather than being sustained over time, embodiment tended to be episodic and event-based, emerging primarily during moments of actuation and receding once the interaction concluded.

These observations positioned system-initiated bodily influence as a critical dimension within the framework. The PneuMa case study demonstrated that explicit prompting can be effective in foregrounding the body and supporting momentary embodied engagement, while simultaneously constraining the extent to which a bodily extension becomes integrated into users' ongoing bodily experience. In this sense, PneuMa occupies a region of the design space characterised by a high sense of bodily influence combined with a high degree of user control over system intervention.

This insight directly informed the structure of the framework by highlighting how the timing and explicitness of actuation and bodily influence shape users' experiences of embodiment. It also motivated a deliberate progression in the thesis toward bodily extensions that rely less on explicit prompting and more on implicit bodily signals. This shift led to the design and investigation of the subsequent case study, Pneunocchio, which explored how embodiment is shaped when bodily influence is mediated through physiological coupling rather than direct user-triggered actuation.

CHAPTER 5: CASE STUDY 2 - PNEUNOCCHIO

Figure 25: Wearing the pneumatic nose of the Pneunocchio system.

5.1 Overview

This chapter presents the second case study, Pneunocchio, which investigates how implicitly controlled pneumatic bodily extensions shape embodied experience in everyday life (Figure 25). Building on the findings of the PneuMa case study, which foregrounded explicit bodily prompting, Pneunocchio shifts the design toward bodily extensions that operate with reduced user control.

Rather than initiating movement through explicit user commands, Pneunocchio employs physiological signals associated with internal states to drive actuation. The bodily extension was inspired by the cultural narrative of Pinocchio (Collodi, 1916) and takes the form of a playful, nose-based pneumatic augmentation that inflates in response to physiological arousal. With a focus on this design, the case study explores how bodily extensions can make internal states perceptible and social.

This chapter comprises seven more sections. Section 5.2 introduces the research motivation and positions Pneunocchio within the broader aims of the thesis. Section 5.3 details the design and implementation of the pneumatic nose-based bodily extension. Section 5.4 describes the field study design, data collection, and analysis methods specific to this case study. Section 5.5 presents the field study findings as themes. Section 5.6 reflects on how participants perceived and interpreted Pneunocchio across social and personal contexts, followed by a discussion of limitations and future work in Section 5.7. Finally, Section 5.8 articulates how this case study informs and extends the bodily extensions framework.

This chapter builds upon two publications:

- Aryan Saini, Srihari Sridhar, Aarushi Raheja, Rakesh Patibanda, Nathalie Overdevest, Po-Yao (Cosmos) Wang, Elise van den Hoven, and Florian Floyd Mueller. 2023. Pneunocchio: A playful nose augmentation for facilitating embodied representation. In Adjunct Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology (UIST '23 Adjunct). Association for Computing Machinery, New York, NY, USA, Article 40, 1–3. https://doi.org/10.1145/3586182.3616651

- Aryan Saini, Srihari Sridhar, Maria F. Montoya, Rakesh Patibanda, Nathalie Overdevest, Elise van den Hoven, Florian 'Floyd' Mueller. Pneunocchio: Understanding the Design of a Nose-based Bodily Extension that Suggests Lying. (Under submission)

5.2 Case Study Motivation and Positioning

This case study explores how pneumatic bodily extensions driven by implicit physiological signals can shape embodied experience in everyday life. While the previous case study (PneuMa) explored prompting bodily movement through explicit, user-initiated input, Pneunocchio shifts the design toward biosensor-driven actuation, in which bodily change is triggered by internal bodily states.

This shift was motivated by a gap in existing research on bodily extensions and embodied interaction. Prior work on embodied and tangible interaction has largely focused on explicit interaction, where users intentionally initiate bodily engagement through movement, gesture, or direct manipulation (Hartman et al., 2020; Svanaes & Solheim, 2016). In contrast, many physiological processes that shape everyday experience, such as stress, arousal, or emotional response, operate implicitly and are often difficult to perceive without technological mediation. While biosensors have been widely used in HCI to visualise internal states through dashboards, notifications, or abstract representations (for example, see Rapp and Tirabeni

(2020) and Yu et al. (2024)), there remains a limited understanding of how embedding such signals directly through a bodily extension form influences embodiment over time.

Pneunocchio explores this approach through a speculative and conceptual bodily extension: a pneumatic nose that inflates in response to physiological indicators of stress. Inspired by the cultural narrative of Pinocchio (Collodi, 1916), the design does not aim to function as a diagnostic or truth-detecting device. Instead, it uses a familiar and playful metaphor as an entry point for examining how biosensor data can be translated into bodily change that is felt, seen, and socially interpreted as part of everyday interaction.

This approach is intentionally non-instrumental, and it aims to foreground ambiguity, interpretation, and reflection by making internal bodily states publicly and bodily visible. By situating physiological data on a highly expressive and socially salient body part (the face), Pneunocchio raises questions about how users understand and perceive control when their own bodies become sites of data representation (Benford et al., 2020).

Through this design, the case study addresses the broader research question of how do we design pneumatic bodily extensions to promote embodied experiences in everyday life by examining implicit bodily change that users experience through a response as a part of their bodies rather than through intentional activation. In doing so, Pneunocchio extends the exploration of pneumatic bodily extensions beyond movement facilitation and toward bodily extensions as mediators of awareness and reflection. A video explanation of the Pneunocchio case study can be found here: https://youtu.be/UIsmo1oYweM.

5.2.1 Contributions to the Design Framework

This case study contributes to the bodily extensions framework by complementing the insights from the previous case study on prompting explicit bodily movements and extending it towards implicit mapping.

First, Pneunocchio contributes to the framework by demonstrating how implicit physiological input reshapes agency in bodily extensions. As the actuation is driven by biosensor data rather than deliberate user commands, participants experienced agency as distributed between themselves and the system. This experience resulted in a tension between perceived and actual control, highlighting agency as a dynamic, situational experience rather than a fixed one. This insight informed the framework by positioning agency as a continuum influenced by input modality and users' ability to interpret system behaviour.

Second, the case study advances the framework's understanding of bodily awareness and embodiment by externalizing internal states. Participants reported heightened awareness of their bodies through the physical manifestation of physiological stress rather than through movement facilitation. The nose inflation acted as a bodily prompt for reflection, making normally imperceptible internal processes evident. This contribution extends the framework beyond bodily extensions that support movement to emphasise bodily change as a medium for reflection.

Third, Pneunocchio contributes insights into social and expressive meaning. The visibility of the bodily extension transformed it into a socially interpreted part of the participant's bodies, and it was described as functioning like a "social organ" (section 5.6). The extension invited curiosity, humour, concern, and discomfort, all of which illustrated how bodily extensions simultaneously operate at personal and interpersonal levels. These insights informed the framework by foregrounding social exposure as a critical design consideration, particularly when bodily extensions communicate ambiguous or sensitive internal states.

Finally, the case study contributes to the framework by clarifying the role of bodily change's immediacy in promoting embodied experiences. Embodiment in Pneunocchio was experienced in the moment, emerging during moments of actuation. This insight highlighted how the timing of actuation influences how the bodily extensions are experienced as a part of users' bodies.

Together, these contributions position Pneunocchio as a contrasting case to PneuMa within the framework, and they articulate how implicit input and physiological ambiguity shape embodied experiences. These insights directly motivated the subsequent case study exploration of bodily extensions that engage the body through longer-term, gradual, and accumulative processes: Pneumusculus.

5.3 Designing Pneunocchio

Pneunocchio was designed as an exploratory bodily extension that embodies users' physiological responses in a playful manner. The system explores how biosensor-driven actuation can translate internal bodily states into outward bodily change, thereby enabling reflection, social interpretation, and altered bodily awareness in everyday life. This section outlines the design rationale underpinning Pneunocchio, which is articulated via a set of design goals derived from prior work on playful bodily extensions, embodied interaction, and augmentation of the human body.

5.3.1 Design Goals

The design goals for Pneunocchio were informed by prior research on playful bodily extensions (Buruk et al., 2023; Peng, 2021; Svanaes & Solheim, 2016), and they align with the objectives of this research. Together, these goals guided the design toward exploring implicit, biosensor-driven bodily change.

Goal 1 - Inherent playfulness (DG 1):

Playfulness was embedded into Pneunocchio through exaggerated bodily transformation and zoomorphic qualities. The design drew inspiration from mechanisms such as a chameleon's tail and a party whistle, both of which emphasise elastic expansion and expressive motion. These characteristics, combined with the cultural familiarity of the Pinocchio narrative (Collodi, 1916), frame the bodily extension as humorous and evocative rather than diagnostic. This playful framing was intended to lower barriers to engagement and invite interpretation rather than judgment.

Goal 2 - Open-ended usage (DG 2):

Prior work suggests that tightly scoped use cases can limit how users explore bodily extensions (Buruk et al., 2023). Pneunocchio was therefore designed to be scenario-agnostic, thereby allowing users to encounter and interpret bodily change across a wide range of everyday situations. This open-endedness supports the exploration of emergent meanings and practices, rather than constraining interaction to predefined contexts.

Goal 3 - Leveraging physiological responses (DG 3):

Physiological signals were selected as the primary input modality to enable implicit coupling between bodily state and form. Drawing inspiration from the Pinocchio narrative and prior work on physiological sensing (Meijer & Verschuere, 2014; Pavel et al., 2011; Peng, 2021; Yu et al., 2024), heart rate (HR) and electrodermal activity (EDA) were used as indicators of physiological stress. Instead of functioning as diagnostic indicators, these signals serve as ambiguous triggers for bodily change, prompting users to interpret their own internal states through an embodied experience.

5.3.2 Implementation

To cater to the design goals outlined in the previous section, Pneunocchio was implemented through a combination of pneumatic fabrication techniques and a sensing pipeline that

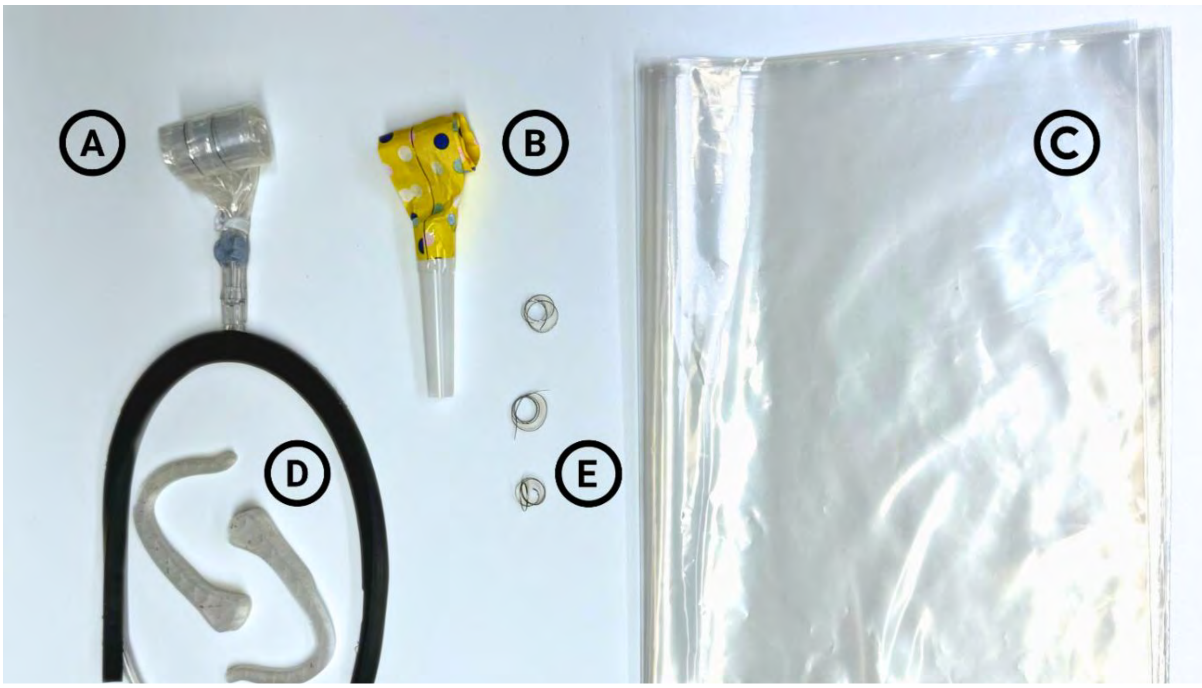

Figure 26: Materials used to fabricate the pneumatic nose in Pneunocchio: (A) the final version of Pneunocchio attached to the 3D printed holding base, (B) party whistle used in first explorations, (C) the 0.8 mm thick PE sheet, (D) ear hooks, and (E) metal spring coils.

supports implicit, body-conforming actuation. This section describes the key implementation decisions that shaped the final system.

5.3.2.1 Fabricating the Pneumatic Nose

The pneumatic nose was fabricated using a 0.8 mm thick polyethylene (PE) sheet, forming an inflatable structure approximately 10 cm in length and 3.5 cm in width when fully inflated (Figure 26 C). A heat sealer was used to create sealed joints along the edges of the PE sheets. To guide and stabilise the inflation behaviour, three metal spring coils were laid flat along the inner surface of the inflatable, parallel to its longer edge (Figure 26 E). These coils constrained deformation and enabled controlled elongation.

A 0.5 mm opening was created to insert pneumatic tubing, allowing air to flow into and out of the inflatable. Furthermore, a resin-based seal was applied around the air tubing interface to minimise air leakage during repeated inflation cycles.

The inflatable nose was mounted onto a custom-designed holder worn on the face using adjustable ear hooks (Figure 26 D). The holder was fabricated using TPU95A, a flexible 3D-printing filament that allows for deformation and comfort during wear. Adjustable ear hooks

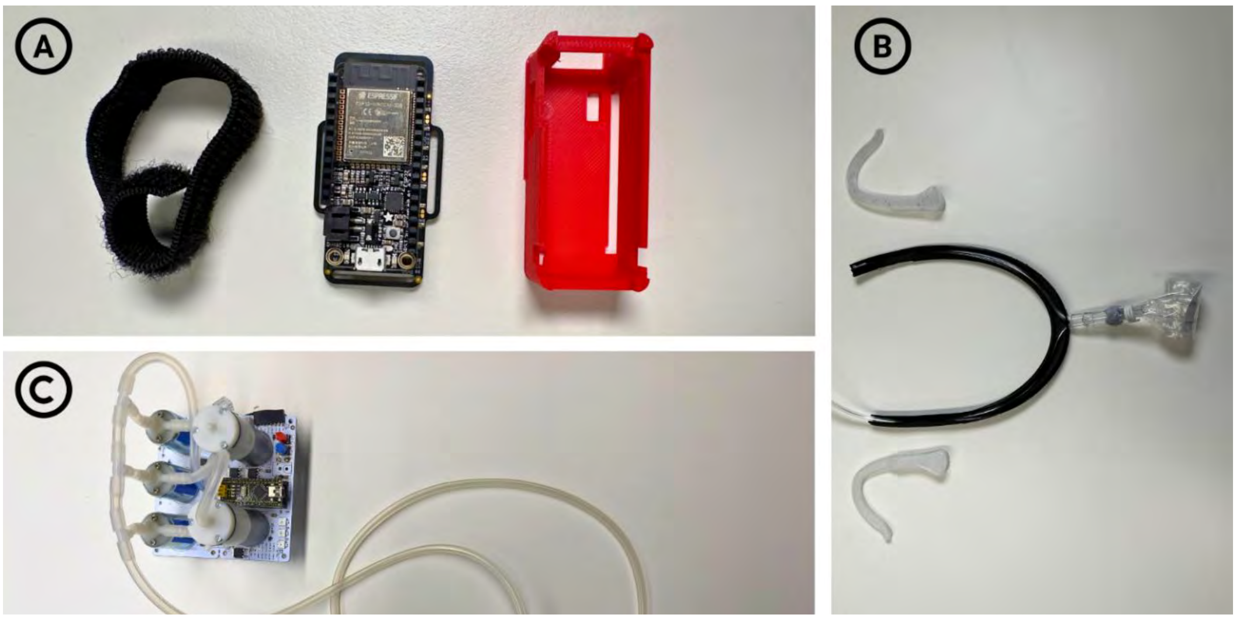

Figure 27: Components of the Pneunocchio system: A) Emotibit with strap and case. B) Pneunocchio's 3D-printed holding base, ear hooks, and nose. C) Pneumatic controller.

enabled accommodation of different facial geometries and preferences, further supporting body conformity by allowing users to adapt the extension to their own bodies.

5.3.2.2 Sensing Pipeline

Pneunocchio employs a sensing pipeline based on heart rate (HR) and electrodermal activity (EDA), drawing on prior work, which associates these signals with physiological arousal and stress responses (Barral & Jacucci, 2014; Dirican & Göktürk, 2011; Peng, 2021; Yu et al., 2024). The pipeline was designed to detect relative changes in physiological state and translate them into actuation through the bodily extension.

Upon activation, the system establishes an individual baseline for both HR and EDA during the first 30 seconds of use, allowing calibration to the wearer's current physiological state (Meijer & Verschuere, 2014; Yu et al., 2024). After baseline acquisition, the system continuously computes a rolling 10-second average of HR and EDA values. A stress response is detected whenever either signal exceeds the baseline by 10%.

Physiological data are captured using an EmotiBit microcontroller (Emotibit, 2026) (Figure 27A), which streams sensor data to a pneumatic controller (Programmable Air, 2026) via a serial connection through a laptop (Figure 27C). When the threshold condition is met for either HR or EDA, the pneumatic controller inflates the Pneunocchio bodily extension.

5.4 Pneunocchio Study Design and Analysis

To understand the user experience associated with Pneunocchio, a seven-day field study was conducted with 12 participants. Participants (N = 12) were aged between 21 and 35 years (M = 26.1, SD = 3.7) and comprised six female and six male participants. The study was designed to capture how a biosensor-driven bodily extension is experienced, interpreted, and negotiated as part of everyday life. The field study allowed participants to encounter Pneunocchio across a range of situations and social contexts, allowing experiences to emerge beyond those anticipated during the design process.

This study included three phases: an onboarding phase, a field study phase, and a post-study phase. These phases were designed to support participants in becoming familiar with the system, engaging with it in everyday contexts, and reflecting on their experiences after prolonged use.

The onboarding session began with an introduction to the study kit (Figure 28) and an overview of the study procedure. The Pneunocchio system was then demonstrated, and participants were given the opportunity to ask questions and clarify system functionality. Each onboarding session lasted approximately 17 minutes (mean = 17.09 minutes, SD = 1.19 minutes).

Participants were then provided with the Pneunocchio system, a Wi-Fi router without active internet access (Figure 28E), and an action camera (GoPro) to document interactions with the system. Participants were instructed to use Pneunocchio whenever appropriate and convenient, over the seven-day period. Participants were also invited to record themselves using the action camera during interactions with the system (Figure 28G). System logs captured each interaction, enabling analysis of physiological responses, frequency of use, and temporal alignment with the recorded videos. During the study period, participants were contacted twice to ensure the system was functioning correctly and to remind them to continue engaging with Pneunocchio.

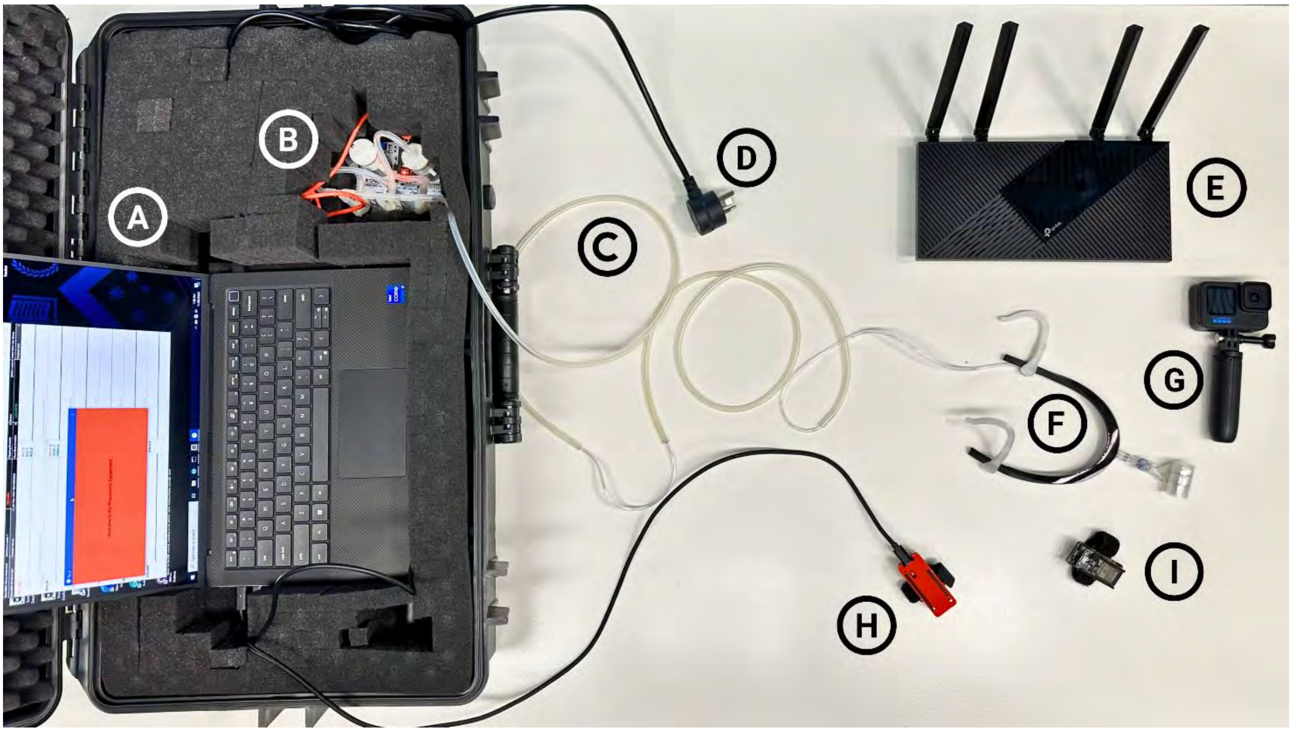

Figure 28: Study kit for participants: A) The serial interface to a laptop; B) Pneumatic controller; C) Air tube; D)Power supply connector; E) Wi-Fi router; F) Pneunocchio's holding base, ear hooks, and nose; G) GoPro camera; H) Emotibit strap; and I) Emotibit microcontroller.

After the field study concluded, the study kits were collected from participants, and individual interviews were scheduled. The interviews lasted 47 minutes on average (mean = 47.21 minutes, SD = 5.33 minutes). All interviews were audio-recorded, transcribed verbatim, and analysed using inductive thematic analysis (Braun et al., 2019; Braun & Clarke, 2006). A collaborator and I independently coded the transcripts using NVivo (“NVivo,” 2025).

This methodology facilitated an in-depth understanding of how participants perceived and interpreted Pneunocchio in everyday life. The following section presents the findings of this analysis in the form of themes derived from participants’ accounts.

5.5 Findings from the Pneunocchio Field Study

The results of the field study are presented in this section to provide insights into the participants’ experiences with the Pneunocchio bodily extension.

5.5.1 Quantitative Results

Quantitative analysis of logged data from the Pneunocchio system was conducted. The analysed data included weighted averages of heart rate (HR) and electrodermal activity (EDA) following established approaches for interpreting physiological stress responses (Meijer & Verschuere, 2014; Yu et al., 2024), as well as the total number of inflations and the duration of system use per day for each participant.

Participants exhibited varying levels of physiological responses across different days. For example, participant P1 had a weighted average HR and EDA ranging from 21.03 on Day 5 to 79.03 on Day 7, reflecting the individualistic nature of the user experience and changes in physiological stress response. Similarly, participants P4, P6, and P11 showed higher average values, such as P4's 100.66 on Day 1 and P11's 105.72 on Day 3, indicating elevated physiological responses.

The number of inflations of the pneumatic nose varied significantly among participants. Participant P3, on Day 1, recorded the highest number of inflations (138), highlighting the potential of usage across different scenarios over an extended period. In contrast, other participants, such as P7 on Day 4, had significantly fewer inflations (2), suggesting either fewer stress-inducing events or differences in participant behaviour and interaction with the system.

The average duration of use per participant per day also varied, with notable differences in engagement levels. For example, participant P3 had the longest duration of use (00:44:56) on Day 1, while participant P12 had a much shorter duration (00:01:15) on Day 4. This suggests that some participants engaged more deeply or for longer periods, potentially due to personal interest, social dynamics, or the novelty of the experience.

5.5.2 Qualitative Results

The results of the interview analysis are presented as three overarching user experience themes that characterise how participants experienced Pneunocchio in everyday life: (1) Pneunocchio as a social organ; (2) a dichotomy of perceived control; and (3) heightened bodily self-awareness.

Figure 29: A participant using Pneunocchio at their home.

Theme 1: Pneunocchio as a social organ

This theme comprised 112 coded units and captures participants' experiences of using Pneunocchio in social settings. Across these accounts, the bodily extension was described as revealing aspects of the wearer's "inside" and functioning analogously to an exposed organ that externalises otherwise hidden physiological states. At the same time, participants reported that this visibility afforded moments of social engagement and bonding because the extension became a shared point of attention and interpretation within social interactions.

Sub-theme 1: Initial perceptions by onlookers

Ten of the 12 participants said that they had engaged the Pneunocchio system with a person in their surroundings. Participants reported that, at first, without the inflation, onlookers seemed to be amused by the appearance of the system, with some thinking it served a medical function. For example, P3 stated that "*when I was first testing the system, my flatmate came* *into my room and immediately started laughing while pointing at my nose."* This quote seems to suggest that onlookers perceived it as *"funny"* when they saw the participants wearing Pneunocchio. In contrast, P5 noted that *"my partner was quite curious as to what I was wearing [...] he thought it was some medical equipment."* These quotes seem to indicate that Pneunocchio's appearance piqued onlookers' interest owing to its appearance and placement on the nose.

In addition, P11, while describing the potential effect of Pneunocchio in a social setting, observed that *"it looked like a party trick; I will be the black hole of a party if I were to wear it to one."* This quote seems to indicate that the participants perceived Pneunocchio as something that draws people's attention towards them.

Sub-theme 2: Pneunocchio to enable a social "truth or lie" game

Eight participants used Pneunocchio as a lie detector in a social setting. In particular, participants used Pneunocchio in a new version of "truth or lie"-type games they had played in the past. Such games are played with multiple players. Each player has to make three statements to the others, and it is up to the other players to guess which two statements of the three are lies and which one statement is true (Gelman, 2023). P1 compared their experience to using an electric shock toy for such a "truth and lie" game: *"it was like a lie-detector game I had played ages ago, only that instead of getting shocked, the lie would appear on my nose."* Participants reported that playing such a *"truth and lie"* game with others became a recurring social event. For example, for P7, *"it became a dinner-time ritual; I enjoyed it more than using it alone."* Additionally, P3 used Pneunocchio for a social ritual. They thought it could help them learn more about their friends: *"Oh, I asked my friends to play two truths and lie every time they were around; I thought it would help us to [get to] know each other better."* These quotes indicate that participants employed Pneunocchio as a medium for social engagement with their peers.

Figure 30: A person using Pneunocchio in a social context with friends.

Sub-theme 3: Pneunocchio was used by others to reveal insights about the wearer

In these social game events, the co-players saw in Pneunocchio an opportunity to reveal personal insights about the wearer. For example, P4 explained how their friends used the system: *"The game got intense; they [my friends] were asking me some serious, controversial questions, trying to get me cancelled."* This quote suggests that the participant felt a sense of exposure when Pneunocchio inflated when they did not want it to. Additionally, P3 observed that their friends used Pneunocchio to *"tease"* them: *"my friends were pretty keen on finding out which nerve to pinch."* This potential to reveal personal insights led P6 to think about how they would feel about playing with an audience besides their co-players: *"I was really nervous about playing with people around me, I didn't want to be seen."* These quotes suggest that participants, when playing a "truth or lie" game with Pneunocchio, felt exposed and nervous because they were uncertain when Pneunocchio would inflate.

Sub-theme 4: Pneumatic inflation invoked laughter

Reflecting on the instances of the game when Pneunocchio inflated, P11 commented that *"while I was already feeling funny wearing this, people were laughing at me whenever the nose would blow up [...] they did not seem to care if I lied or not."* This response suggests that observing the action of inflation could be a source of laughter, irrespective of whether the wearer was lying or not. This laughter prompted participants to question the system's functionality. P4, describing their belief, commented that *"I was constantly getting exposed and laughed at, I don't know how the system was catching it all the time."*

Sub-theme 5: Perceived functionality of the system

P6 thought about how their co-players' questions made them sweat and how this could have influenced the sensor: *"It constantly sold me out, even when I wasn't lying. I don't know why; maybe the questions just made me sweat; they got really personal."* This quote suggests that participants questioned the system's functionality or accuracy in response to inflation.

Sub-theme 6: Pneumatic Inflation within these social game settings resulted in a wide range of feelings

According to participants, pneumatic inflation in these social game settings resulted in a wide range of feelings. For example, when asked about how they felt during these games, participants used words like *"conscious"* (P6), *"exposed"* (P4), and *"transparent"* (P9), while also reporting that these games could be *"stressful"* (P7). P4 commented that the nose inflated not only in response to intimate questions, but sometimes also in response to *"stupid"* questions, making them feel like they were being laughed at: *"I was constantly being laughed at, the nose acted like a party pooper, kept on blowing up even at the most stupid question. It was kind of confusing."* These quotes suggest that participants experienced a wide range of feelings due to Pneunocchio's inflation response in a social setting.

Sub-theme 7: Pneunocchio made participants feel like others took an interest in them

Participants said they felt put under the *"spotlight"* during these games. For instance, P7 commented that *"it felt like I was under a spotlight; other people seemed to take an interest in my responses."* This quote suggests that Pneunocchio's inflation made participants feel like subjects of the onlookers' attention.

Sub-theme 8: Participants tried to control their stress response

Participants reported that they tried a couple of techniques to better manage their stress response while playing these games. P3 explained: *"I was trying to stress myself at every* *question to create confusion."* In contrast, P1 tried to calm themselves: *"After a time, I gave up, I didn't think much, just tried keeping myself calm, breathe more."* P1 prepared for these social events by exercising beforehand: *"After a couple of days, to stop the nose blowing, I went jogging before to get my heart rate up."* These quotes suggest that Pneunocchio induced a bodily response in the participants rather than altering the system's response.

Sub-theme 9: Participants appreciated the social bond arising from playing with Pneunocchio

Participants shared their thoughts on the effects of playing Pneunocchio with others. They particularly appreciated the social bond that arose from the "truth or lie" games. For example, P7 felt that *"it was a playful way to connect to my peers, similar to an ice-breaker activity, we took turns asking each other questions, really funny questions."* P3 said that they felt that the system was not accurate in detecting the lies in these games, but that the bonding occurred nevertheless: *"even though it was wrong half the time, I felt like a bonding experience."* These quotes suggest that, regardless of the system's perceived accuracy, participants felt it was a source of social engagement between themselves and their peers.

Additionally, P7 said that they were also not sure why the nose sometimes inflated: *"It was an interesting concept; we had a blast even though we were always confused about why it was blowing up."* These quotes seem to indicate that participants and their peers may have collectively enjoyed Pneunocchio's responses in some social situations, even though they were confused by those responses."

Sub-theme 10: Pneunocchio promoted empathy

Participants' wearing of Pneunocchio outside the context of a game also revealed interesting insights. In particular, participants shared how it affected their dialogue with other people present in the same location. For example, P9 stated that *"I remember the nose blew up one time I was wearing it while working on my laptop; my partner saw it and gently tapped my shoulder and told me to stop stressing."* Here, the system not only made others aware of the wearer's current stress level but also promoted sympathetic behaviour in the form of body contact (shoulder tapping) and encouraging words.

Interestingly, P6 perceived Pneunocchio as a way to facilitate empathy and envisioned an application scenario in which the nose would be preferred over words: *“I would have loved to take it to my office to show my boss what I feel whenever he stresses me out without using any words.”* P1 added that the system could even be suitable for people with specific needs: *“It would be great for people who have difficulty in expressing emotions, maybe even an introvert, to socialise more.”* These quotes suggest that participants perceived Pneunocchio to be beneficial for eliciting empathy among onlookers.

Figure 31: A participant using Pneunocchio while in front of an onlooker.

Sub-theme 11: Pneunocchio made people feel vulnerable

Participants shared their concerns about using Pneunocchio in front of other people outside a gaming context. P2 expressed their concerns: *“I am not sure if I would use it generally because I don't want to show other people the things that stress me out; it would make me feel naked.”* This feeling of *“nakedness”* appeared to be amplified if the wearer is already an anxious person. For instance, P12 stated that *“being someone with social anxiety, it was sometimes uncomfortable to put my feelings out there.”* These quotes suggest that participants also perceived Pneunocchio as an agent that would make them feel vulnerable and uncomfortable in social settings due to its placement and visible response.

Theme 2: Dichotomy of perceived control

This theme was derived from 92 units of code and describes the contrasting, dichotomous perceptions of control that the participants experienced while using Pneunocchio. The participants suggested that their perception of control over Pneunocchio's Inflation was influenced by experiences such as *"feeling in control", "not feeling in control", "drawing comparison of feeling in control", "negotiating control", "external factors affecting control",* and *"long-term impact on the body"*.

Sub-theme 1: Feeling in control

Seven participants shared their thoughts on how they perceived the control of the bodily extension when alone. P10 commented that *"when I was using it alone, it quickly reflected on what I was thinking at that moment."* In addition, P12, sharing their experience of controlling Pneunocchio, noted that *"I felt like a psychic, as in I could make it blow just by thinking about something stressful."* These quotes suggest that participants thought that they could control Pneunocchio as its actuation may have served as a reflection of their internal thoughts.

Finally, when sharing an anecdote from their "truth or lie" game, P8 shared that "*I wasn't sure about it, but I tried to trick my friends, hoping the nose wouldn't catch me. I was glad when it did not inflate, ... maybe I could be a great liar."* These quotes seem to indicate that, in some situations, the inflation led participants to believe that they were in control of the bodily extension through their bodily stress response.

Sub-theme 2: Not feeling in control

Four of the other participants believed that they had "*almost no control"* over the inflation and sometimes felt *"confused"* and *"unsure"* whether they had control over the system, leading them to be *"curious"* about the extent to which they could influence inflation. For example, P3 stated that *"it was never really up to me, honestly, I would have liked to be more deceitful, but it (the nose) kept going on."* P12 noted, while sharing a moment using Pneunocchio alone, that *"I was just looking at some photos, there was nothing stressful about it. It got me by surprise when the nose grew bigger."* Participants also found themselves wondering about the accuracy of the system as a result of the inflation, with P8 saying that they even tried relaxation exercises to regain control over the system: *"It kept blowing up while I was watching TV, … couldn't stop it even by relaxing and taking deep breaths."* These quotes seem to indicate that, owing to the inflation across some situations, participants sometimes did not feel in control but, in response, tried to regain control through bodily activities.

Sub-theme 3: Drawing comparisons between perceiving ownership due to control over the bodily extension

Five participants compared the experience with Pneunocchio to other familiar bodily modifications. For example, P6 said that *"I felt like a clown wearing a funny nose in front of my friends as it drew their attention."* Other participants compared Pneunocchio to a *"tattoo"* and *"spectacles"*, citing the *"lightweight"* nature and placement on *"the nose and ears"*. P11 described this experience as follows: *"I sometimes forgot that I was wearing the device while working; it was very similar to the tattoo on the back of my hand; you remember it when you see it."* These quotes indicate that, after overcoming their initial impressions of Pneunocchio, the participants seemed to accept it as a part of their body.

On the other hand, P8, while describing their experience of not being able to control the inflation in a social setting, noted that *"it was similar to when you have guests coming over, and your pet can't seem to follow your orders."* This quote suggests that the participant formed a nuanced personal relationship with the bodily extension, projecting ownership of a *"pet"* onto a system that was sometimes difficult to control.

Sub-theme 4: Negotiating regaining control

Ten participants reported employing strategies to seemingly regain control of the bodily extension after inflation. One strategy was deep breathing, as P7 commented: *"I tried taking it easy, stop doing what I was doing and breathing deeply."* P11 stated that they tried to focus on themselves: *"I was tuning out everything, just focusing on myself and trying to be as calm as possible."* These quotes suggest that participants mostly attempted to regain control over their bodies as a result of the extension's inflation. This response might have arisen, possibly due to the participants' sudden *"awareness"* (P11) of their bodies responding to stress owing to the inflation. In other words, the inflation made participants aware of a bodily response that they were not in control of, and they then tried calming strategies to regain control.

Sub-theme 5: External factors affecting control over bodily responses

Four Participants reported instances in which they did not feel in control of the bodily extension due to external factors they could not directly influence. While reflecting on using Pneunocchio in a social setting, P1 recalled that *"other people were making me really nervous; I could not do much to stop it from unveiling."* P4 abdicated control to the system: *"There was nothing to stress me out, but it still blew up."* These quotes suggest that participants felt that factors beyond their control could influence the bodily extensions across different scenarios, leaving them *uncertain* and *nervous*.

Sub-theme 6: Long-term impact on the body

P10 reflected upon the implications of using such a system, owing to the feeling of being in control of the bodily extension: *"Maybe if I understand how my body deals with these situations, I can try to control it. ...[It] will help me become a good liar in the longer run."* This response suggests that the participant felt that gaining control over the inflation of the bodily extension was a direct consequence of gaining control of their bodily responses, leading to thoughts about learning to control physiological responses.

Theme 3: Heightened self-awareness of the participants' bodies

This theme was derived from 154 units of code and reflects on participants' experience using Pneunocchio to understand their bodily response through visual and tangible means. As Pneunocchio leveraged HR and EDA data, participants seemed to take advantage of the opportunity to reflect on everyday activities through the system. They suggested that they gained a *"higher awareness"* of the *"subtle"* and *"often overlooked"* changes in their bodies.

Sub-theme 1: Perceiving Pneunocchio as a stress awareness tool

Participants shared that they found Pneunocchio to be *"useful"* (P9) and a *"nifty tool"* (P5) for understanding the stress response of their bodies. For example, P9 shared that *"I was working* *on a job application, and a tool was constantly making suggestions. Seeing the nose blow up was similar to my watch reminding me to stand up."* This quote suggests that the participant perceived Pneunocchio as a useful reminder for them to act. However, as Pneunocchio did not reveal much detailed information (unlike a watch that might display precise sensor numbers and/or contextual information), the system appeared to facilitate self-reflection on the cause of stress. For example, P7 noted that, *"whenever the nose blew up, it made me wonder what was going on in my body. Why am I getting stressed?"*

The fact that the system came in the form of a nose increased participants' awareness. For example, P5 suggested that owing to Pneunocchio's placement on the nose, the stress seemed hard to avoid: *"it was right in front of me, which was pretty hard to miss because you can always see if something is on your nose."* These quotes seem to indicate that Pneunocchio may have served as a difficult-to-overlook, physical manifestation of stress.

Sub-theme 2: The body responding in a playful way to internal changes

The participants appreciated Pneunocchio's pneumatic-based design. In particular, they seemed to enjoy the playful inflation of the bodily extension. For instance, P2 commented that *"I like the fact that [it] activated in a funny way. It reminded me of party whistles at kids' parties."* Participants also enjoyed that Pneunocchio was similar to a part of their body, with P4 noting that *"it was different to the reminders I get on my phone or watch to stand up, for the first time I could see and touch it on my body."* Unlike a smartwatch displaying stress data, participants appreciated the tangibility of the pneumatic nose that formed the core of Pneunocchio, especially P1, who compared the pneumatic inflation of the nose to stress building up in their body: *"It was interesting; it made me think about how my body will be accumulating all the stress, similar to the nose filling with air."* These quotes suggested that the participants seemed to experience the visual and tangible response of Pneunocchio as playful and that they formed analogies to understand their experiences.

Participants also appreciated that the system could help them monitor their stress, while not coming in the traditional form and shape of common health monitoring devices. For example, P6 mentioned health monitoring devices, albeit they noted that their body, rather than the device, told them to take a break: *“I am not someone who uses a lot of health monitoring devices; seeing the nose go, it felt like my body was telling me to take a break.”*

These quotes seem to indicate that some of the participants took a liking to the fact that it was their *“own”* body that responded in a playful and tangible way to changes in their bodies.

Sub-theme 3: Inflation prompted reflection on everyday activities

Pneunocchio offered participants an opportunity to reflect on how their bodies responded to certain everyday activities. For instance, P9 explained that *“I was trying to cut perfect shapes while making some art using toilet paper rolls. I never thought a pastime activity could make me feel annoyed or stressed until I saw the nose blow.”* P9 also shared their experience of how using Pneunocchio during a painting session prompted reflections about the activity: *“I was at peace while colouring a sketch when it sneaked up on me. I was quite surprised and began to wonder what I was doing that might have felt stressful.”* P10 explicitly used Pneunocchio to understand the different scenarios that might stress them out, including watching a movie: *“I generally watch a lot of thriller movies. It was cool to see what happens in my body every time I do it.”* These quotes suggest that, when using Pneunocchio, some participants were able to identify and gauge, either passively or actively, a deeper understanding of everyday activities that may have induced a stress response.

Sub-theme 4: Reflecting while reliving stressful scenarios

Participants shared that Pneunocchio offered deeper reflection while *“thinking”* about tasks that may have been stressful. One such instance was when P9 shared their experience of taking a note in their daily journal while using Pneunocchio: *“I was writing in my diary about the job application I was working on. The nose blew up while I was writing about it, reminding me of the same stressful experience I had earlier.”* This response suggests that Pneunocchio helped some participants by reminding them of the effects of past activities and how their bodies responded. Participants seemed to have formed associative bonds between Pneunocchio's inflation and their internal feelings.

Sub-theme 5: Amplifying stress

Three participants reported that the frequent inflations provided an unpleasant experience by amplifying their current stress level. For example, P12 recalled that *"I just had an argument with my partner; I knew I was tense. I did not like the nose blowing up again and again; [....] it made me more stressed."* This quote suggests that, while Pneunocchio brought awareness of the participant's current body state, it also seemed able to reinforce an unpleasant situation. This experience was exacerbated by the fact that participants could not choose to ignore Pneunocchio's response due to its prominence in their faces, and its visibility to them and others in their social surroundings.

Sub-theme 6: Confusion about inflation without being stressed

Participants also expressed their confusion when Pneunocchio blew up when they did not feel stressed. For instance, P5 recalled that *"I got really confused in the situations it blew up when I did not feel stressed. I was just playing my guitar, which to me is peaceful. The nose was constantly blowing up for some reason. It got me thinking [whether] I might be singing the wrong lyrics."* This response suggests that Pneunocchio may have provoked participants' thoughts about their current activity. P2 reported a similar experience of confusion: "*even though I knew I was stressed, the inflation made me doubt myself. It was like thinking of something so much that it becomes your reality rather than what's actually happened."* These quotes indicate that some participants questioned the response of their bodies in some specific instances due to the inflation. It appears that in these instances, there was a conflict between how participants felt and how Pneunocchio responded. Participants could have assigned this feeling to the improper functioning of the bodily extension. However, they sometimes questioned their own bodily responses, which suggests that bodily responses are not always obvious but are riddled with uncertainty, and that Pneunocchio facilitated engagement with this uncertainty.

Sub-theme 7: Reflecting on Pneunocchio-driven bodily awareness

Participants also reported on strategies they employed once Pneunocchio made them aware of the stressed state of their body. For example, P10 commented that *"whenever the nose would blow up, my go-to response was to take a step back from whatever I was doing and try* *to relax my body by consciously breathing."* This response suggests that Pneunocchio prompted participants to act to *"improve"* the state of their bodies. P8 reflected on how awareness of stress was an important call to action: *"I was aware, so I could do something about it. The awareness is key here, so if I didn't know, I wouldn't do anything. I didn't see a sign before. Now, I am more mindful about these situations, close my eyes, and try to remain calm."* Finally, P9 appreciated being able to understand their body: *"it helped me realise monitoring your physical as well as physiological health is crucial. It's like you are really, really empowered with the information. I think I need to buy something soon."* These comments suggest that Pneunocchio may have served as a vehicle for understanding and taking action in stressful situations by making participants more aware of their bodies.

The findings from the field study provide valuable insights into participants' user experience of Pneunocchio, and they reveal three themes: Pneunocchio as a social organ; dichotomy of perceived control; and heightened self-awareness of the participants' bodies. These themes highlight the multifaceted engagement enabled by Pneunocchio between participants and their social setting, as well as the internal reflections it enables. The following discussion delves deeper into these themes and contextualises them within existing literature to further dissect how the participants' engagement was facilitated by particular design decisions.

5.6 Discussing Pneunocchio Study Results

This section discusses the study results, situates them in relation to the existing literature through the lens of dimensions (perception of control and environmental context), and uses the insights to inform the future design of bio-sensor-driven bodily extensions. Drawing on prior work that has employed dimensions to unpack complex, embodied interactions (Mueller et al., 2020; 2021), this approach enables a systematic deconstruction of the multifaceted experiences reported by participants using Pneunocchio. Framing the results through dimensions provides a structured means of examining interaction dynamics, including how bodily extensions shape agency, social meaning, and bodily awareness over time. Building on this analysis, this section concludes by articulating four design strategies derived from the empirical findings and their relationship to prior research, offering guidance for the design of future bio-sensor-driven bodily extensions.

5.6.1 Dimensions and Implications

Building on the findings of the field study and the craft knowledge gained through the design of Pneunocchio, this section presents two key dimensions that emerged from participants' interactions with Pneunocchio. Drawing on prior work that employs dimensions to analyse interactive systems (Mueller et al., 2020; 2021), these dimensions are used here as analytical lenses to unpack how Pneunocchio was experienced across contexts.

The two dimensions identified are: (1) environmental context of use and (2) perceived control over the bodily extension. Rather than functioning as prescriptive categories, these dimensions describe experiential tensions that emerged repeatedly in participants' accounts. As such, they offer designers a way to understand the parameters available when creating bodily extensions that leverage physiological input, particularly where interaction unfolds implicitly, and bodily change becomes socially visible.

Environmental context in which the bodily extension is used

The first dimension concerns the environmental context in which the bodily extension is used, specifically whether interaction occurs in social or personal settings. The study's findings indicate that participants' experiences with Pneunocchio varied substantially across contexts, and that this distinction was particularly evident in the themes of Pneunocchio as a social organ and heightened self-awareness.

In social contexts, Pneunocchio was frequently described as a catalyst for interaction. The visibility and placement of the pneumatic nose drew attention from onlookers, prompting curiosity, humour, and playful experiences. Participants reported that the bodily extension became a topic of conversation, facilitating social bonding. At the same time, this visibility of the nose seemed to introduce vulnerability. The public exposure (Paulos & Goodman, 2004) of physiological responses led some participants to feel embarrassed or self-conscious, especially when the nose inflated unexpectedly. These experiences suggest that Pneunocchio externalises internal states while simultaneously enabling social connection and provoking discomfort, depending on how onlookers interpret its response.

In personal or private contexts, Pneunocchio was more often experienced as a reflective tool. Participants described inflation as a prompt to understand their internal states, such as stress or emotional arousal, and to reflect on their current situation. During such instances, the bodily extension functioned less as a social organ and more as an embodied cue for introspection. However, this awareness was not always perceived as positive. Some participants reported that inflation occasionally heightened stress or caused confusion when bodily feedback did not align with their understanding of the situation. These experiences indicate a tension between supporting self-awareness and inadvertently intensifying negative affect.

This dimension aligns with prior work that emphasises the importance of considering whether a bodily extension is primarily experienced by the wearer or by others (Walmink et al., 2014). That work highlighted how placement on the body can privilege onlookers' perception over the wearer's awareness. Pneunocchio extends this understanding by demonstrating that not only placement, but also inflation must be considered when designing for different contexts. Since the pneumatic nose entered the wearer's visual field during actuation, participants became aware of the bodily extension as it unfolded. This finding extends prior theory by demonstrating that context sensitivity must account for how bodily extensions transition between states over time, rather than accounting only for where they are located on the body.

Perception of control over the bodily extension

The second dimension is concerned with participants' perceived control over the bodily extension, defined here as the extent to which users felt able to anticipate, interpret, or influence Pneunocchio's behaviour. Study findings indicate that perceived control played a central role in shaping engagement and comfort.

Participants described the experience as empowering and engaging when Pneunocchio's inflations aligned with their own interpretations of stress or situational tension. In these instances, the bodily extension was experienced as responsive and informative; reinforcing a sense of agency despite the implicit nature of physiological input. Conversely, when inflations occurred without a clear or interpretable cause, participants reported confusion, frustration, or vulnerability. This dichotomy highlights that perceived control is not solely determined by whether input is explicit or implicit, but by how legible and timely system responses are in relation to the user's lived experience.

This dimension aligns with prior research on bodily extensions that emphasises the importance of control for supporting agency and engagement (Buruk et al., 2023; Hartman et al., 2020; Morris et al., 2023). Systems such as Monarch have shown that tighter coupling between user action and system response can enhance perceived control and ownership (Hartman et al., 2020). However, Pneunocchio demonstrates that in systems driven by physiological processes, perceived control is influenced by factors such as timing, context, and social setting.

Findings from this study suggest that the timing of actuation is a particularly critical design parameter. Participants reported higher perceived control when inflation followed an experience they recognised as stressful, and lower perceived control when bodily change appeared delayed or unmotivated. This finding extends prior work by emphasizing that, for bio-sensor-driven bodily extensions, designers must carefully consider temporal relationships between sensing and actuation (Comber et al., 2019). While earlier research has advocated for real-time feedback to enhance control (Hartman et al., 2020; Morris et al., 2023), the results here indicate that immediacy alone is insufficient. Instead, bodily extensions responding to physiological input must support interpretability, thereby allowing users to meaningfully connect the system's response to lived experience.

This dimension extends existing theory because it indicates that perceived control in biosensor-driven bodily extensions emerges from an interplay between system timing, contextual cues, and the user's ability to make sense of bodily feedback. Designing for control in such systems, therefore, requires not only technical responsiveness but also sensitivity to how bodily change is experienced and interpreted across different contexts of use.

Four quadrants

In this section, the two dimensions, environmental context of use and perceived control over the bodily extension, are combined to articulate four experiential regions (Figure 32). These regions describe recurring patterns in how participants experienced Pneunocchio, and they offer a way for designers to anticipate how different configurations of context and control may shape user experience when designing bodily extensions. Rather than fixed categories, the quadrants represent tendencies that emerged across participants' accounts.

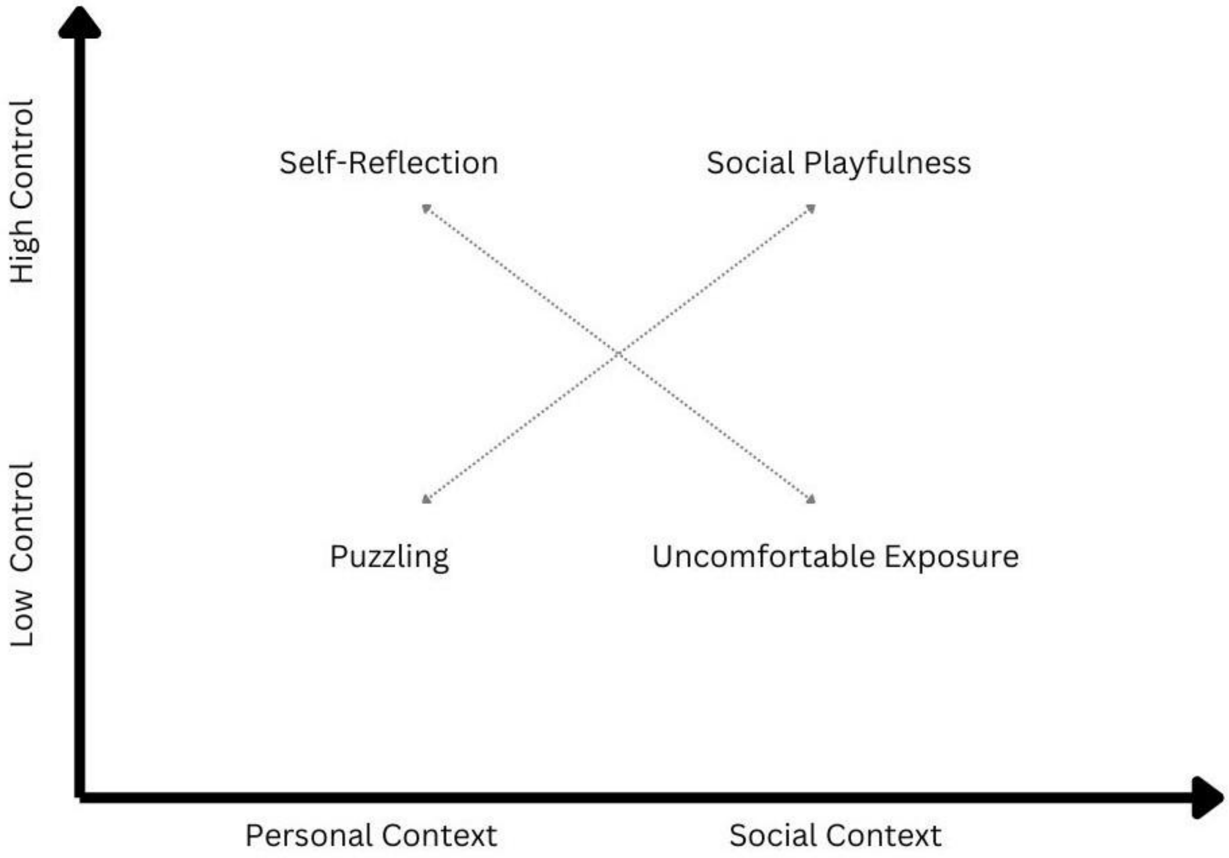

Figure 32: The user experience framework considers two design dimensions: Context and Perception of control.

Self-Reflection (Upper-left)

The upper-left quadrant represents experiences characterised by personal context and a higher perceived sense of control over the bodily extension. The user experience associated with this region is described as self-reflection because it captures moments in which participants engaged with Pneunocchio privately and interpreted its behaviour as a prompt for attending to their own bodily and emotional states.

Participants reported becoming more aware of physiological responses, such as stress or arousal, and reflected on how these responses related to everyday situations. In these moments, Pneunocchio functioned less as a social signal and more as an embodied cue that invited introspection. The bodily extension was experienced as supportive rather than intrusive, allowing participants to observe, interpret, and make sense of bodily feedback at their own pace.

Experiences in this quadrant align with prior work that positions bodily awareness and reflection as central outcomes of embodied interaction (De Kock et al., 2021; Fdili Alaoui et al., 2015). Bodily extensions designed to occupy this region may be particularly relevant for designers aiming to promote attentiveness to bodily states, support reflective practices, or explore embodiment as a means of self-understanding.

Social Playfulness (Upper-right)

The upper-right quadrant represents experiences characterised by social context and a higher perceived sense of control over the bodily extension. The associated user experience is described as social playfulness, reflecting participants' accounts of Pneunocchio becoming a resource for playful interaction, humour, and shared meaning-making with others.

In social settings where participants felt able to anticipate or explain Pneunocchio's behaviour, the bodily extension was often incorporated into games, jokes, or performative exchanges, such as playful "truth or lie" scenarios. Participants described enjoyment in using Pneunocchio as a prop that facilitated engagement, curiosity, and amusement among peers. In these cases, bodily change was experienced as an opportunity for expression and interaction.

This quadrant highlights how bodily extensions can function as socially expressive artifacts when users retain a sense of ownership over their behaviour. It aligns with prior research on playful bodily extensions, which leverages exaggeration and visibility to create engaging social experiences (Buruk et al., 2023; Mueller et al., 2025).

Puzzling (Lower-left)

The lower-left quadrant represents user experiences characterised by a personal context combined with a lower perceived sense of control over the bodily extension. The experience associated with this region is described as puzzling, reflecting participants' experiences of uncertainty and ambiguity when Pneunocchio's inflation did not align with their perception of their physiological state (Figure 26).

In such situations, participants reported difficulty interpreting the meaning of the bodily extension's behaviour, particularly when inflation occurred without an accompanying conscious experience of stress. This misalignment often led to a reduced sense of ownership, as participants struggled to associate Pneunocchio's response with their current situation. Therefore, the extension was sometimes experienced as confusing or arbitrary.

This quadrant highlights an important challenge for biosensor-driven bodily extensions: when the response lacks interpretability or contextual grounding, it may undermine rather than support embodiment. Designers aiming to promote self-reflection through bodily extensions should therefore be cautious about experiences that are ambiguous without offering users an understanding of the situation to make sense of the bodily extension's response, especially when moving beyond utilitarian perspectives.

Uncomfortable Exposure (Lower-right)

The lower-right quadrant captures experiences characterised by a social context and a lower perceived sense of control. The associated user experience is described as uncomfortable exposure, reflecting participants' feelings of vulnerability when Pneunocchio behaved unpredictably in the presence of others.

Participants described moments when the inflation of the pneumatic nose felt erratic or poorly timed, leaving them feeling exposed and lacking sufficient agency over the response and the situation. In social contexts, this lack of control intensified feelings of self-consciousness, as bodily changes were publicly visible while remaining difficult to explain. These experiences were particularly evident when participants felt unable to influence or anticipate the system's behaviour.

While such experiences may be uncomfortable, they also reveal a provocative opportunity in which bodily extensions surface tensions between visibility, agency, and social interpretation. Designers should be mindful of the risks associated with involuntary exposure, especially in social settings. However, such configurations may also be meaningful in contexts where expressing vulnerability or prompting social awareness is intentional.

Synthesis of Quadrants

Taken together, these four experiential regions illustrate how the interplay between context of use and perceived control shapes user experience with biosensor-driven bodily extensions. Experiences characterised by higher perceived control supported self-reflection and social playfulness, while lower perceived control introduced challenges related to puzzlement and uncomfortable exposure. These findings underscore the importance of designing bodily extensions that can accommodate shifts in context and agency, balancing engagement, ownership, and comfort.

Rather than functioning solely as representational tools, bodily extensions such as Pneunocchio make the body perceptible as both a mirror, making physiological states perceptible, and as a mediator, shaping how users relate to their bodies and others. Understanding these dynamics provides a foundation for articulating design strategies that attend to the experiential consequences of biosensor-driven bodily change.

5.6.2 Design Strategies

Drawing on the analysis above, this section outlines a set of design strategies intended to support designers in creating playful bodily extensions that leverage physiological responses. These strategies emphasise the role of context and perceived control in shaping user experience and are grounded in both the study findings and prior work.

Strategy 1 - Facilitate a heightened sense of control to promote ownership over the bodily extensions.

A heightened sense of perceived control emerged as a critical factor in fostering ownership and engagement with Pneunocchio. When participants felt able to anticipate or make sense of the system's behaviour, the bodily extension was experienced as empowering and playful across both personal and social contexts. This finding aligns with prior work emphasizing perceived control as central to ownership and engagement in wearable systems (Buruk et al., 2023; Jain et al., 2020).

Designers are encouraged to support a heightened sense of control. For example, designers could allow users to calibrate or customise aspects of the sensing pipeline. Such configurability may enable users to develop trust in the system's behaviour, supporting longer-term engagement and a stronger sense of ownership over the bodily extension.

Strategy 2 - Allow for an open-ended design of bodily extensions to allow the users to switch context.

Participants' ability to move fluidly between personal and social contexts was facilitated by Pneunocchio's open-ended design. Rather than prescribing a single use case, the system allowed participants to appropriate it for self-reflection, playful interaction, or both. This flexibility enabled users to switch contexts according to situational needs and social comfort.

Designers may benefit from creating bodily extensions that support open-ended use, allowing users to negotiate when and how the system is engaged. This strategy confirms prior recommendations that bodily extensions can serve multiple contexts when designed with adaptable communication modes (Buruk et al., 2023).

Strategy 3 - Use the delay between the physiological sensors and bodily extensions to allow for in-the-moment bodily awareness, while being aware of the potential for it to serve as a distraction.

The timing between physiological sensing and bodily actuation played a significant role in shaping perceived control. While modest delays sometimes supported reflection, larger or poorly aligned delays contributed to confusion and frustration. These findings reinforce prior work, which suggests that balancing responsiveness with interpretability is essential for maintaining trust and comfort in biosensor-driven systems (Hartman et al., 2020).

Designers should carefully consider temporal dynamics, treating delay not merely as a technical constraint but as an experiential design parameter that can either support or undermine in-the-moment bodily awareness.

Strategy 4 - Allow users to customise the appearance of the bodily extensions that may serve as a playful, exaggerated organ for social interaction, but be aware of a potential feeling of exposure.

The exaggerated appearance of Pneunocchio's inflatable nose contributed to playful social engagement but also amplified feelings of vulnerability in certain contexts. Participants' experiences suggest that visibility and expressiveness can be both enabling and uncomfortable, depending on context and perceived control.

Designers should consider allowing users to customise the appearance, placement, or visibility of bodily extensions to better manage exposure across contexts. This strategy extends prior work, which highlights the importance of appearance and placement in shaping social comfort and interpretation (Walmink et al., 2014).

Strategy 5 - Leverage bodily extensions as tools for social engagement.

Finally, the study demonstrates that bodily extensions can act as catalysts for social interaction and bonding when designed with playful affordances. Pneunocchio enabled shared experiences, such as games and performative exchanges, that fostered communication and connection among participants and their peers.

Consistent with prior research (Buruk et al., 2023; Svanaes & Solheim, 2016), this finding suggests that bodily extensions can be intentionally designed as tools for social engagement. By embedding playfulness and shared meaning-making into bodily change, designers may support the integration of bodily extensions into everyday social life.

5.7 Limitations of the Pneunocchio Case Study

This case study has several limitations that should be considered, particularly in relation to implementation and the sensing pipeline. First, participants reported that the footprint of the overall system introduced inconvenience. While the nose extension itself was described as "lightweight" and "easy to wear," the complete setup was tethered and therefore restricted mobility, which limited the range of everyday contexts in which Pneunocchio could be carried and used. This limitation stemmed from the EmotiBit microcontroller requiring a wired interface and a laptop connection to communicate with the pneumatic controller. Future iterations could reduce this constraint by using wireless sensors and an embedded, wearable processing and control setup.

Second, Pneunocchio leveraged heart rate (HR) and electrodermal activity (EDA) as indicators of physiological arousal, drawing inspiration from polygraph-style approaches. However, the reliability and interpretation of such indicators have been debated in prior work (Meijer & Verschuere, 2014). In this case study, the intention was not to construct a lie detector or diagnostic tool, but to explore the user experience of a bodily extension that responds to biosensor-driven input through a playful, speculative metaphor. Participants were informed of this limitation, and the inflations were treated as prompts for interpretation rather than as definitive assessments of honesty or stress.

Third, participants did not all begin the study on the same day. Prior work suggests that HR and EDA can fluctuate across the week due to factors such as work fatigue, which may have contributed to differing baseline levels across participants. In addition, the system did not account for external influences such as caffeine and alcohol consumption, unexpected stressors, physical activity, or social interference, all of which may affect HR and EDA. Sensor placement and fit may also have varied across participants, potentially influencing data quality. Environmental conditions (e.g., heat) may have increased sweating and elevated EDA, while emotions beyond stress (e.g., excitement or anxiety) may have influenced both HR and EDA.

Finally, the calibration approach established baselines per use instance using HR and EDA, enabling adaptation to individual and situational variability but remaining limited in its ability to distinguish among overlapping physiological causes. Future work could explore more robust calibration and interpretation approaches, including participant-specific tuning and additional contextual controls, to better align actuation with users' situated expectations.

These limitations underline the fact that the findings are mostly interpreted as insights into the experiential and social implications of biosensor-driven bodily extensions, rather than as evidence of accurate physiological inference.

5.8 Implications for the Framework

The Pneunocchio case study contributed to the bodily extensions framework by foregrounding the role of interpretation and ambiguity in embodied experiences with bodily extensions. In contrast to PneuMa, which relied on explicit system-driven prompting, Pneunocchio externalised internal bodily states, requiring users to actively interpret the meaning of the extension's behaviour rather than simply responding to direct actuation.

Participants' experiences showed that embodiment in this context emerged through an ongoing negotiation between bodily sensation, system behaviour, and social context. The visibility of the bodily extension prompted reflection not only on one's own bodily state but also on how that state might be perceived by others. This interpretive process introduced moments of uncertainty, playfulness, and self-consciousness; revealing that embodied experience can be shaped as much by social exposure and meaning-making as by physical sensation alone.

These insights informed the framework by demonstrating that bodily extension experiences are not solely determined by direct bodily control or physical actuation, but also by the extent to which users must interpret and make sense of the system's influence on their bodies. Pneunocchio therefore expanded the framework to account for bodily extensions that operate through implicit signalling, physiological coupling, and social visibility, highlighting interpretation as a central experiential dimension.

At the same time, while Pneunocchio emphasised moment-to-moment reflection and interpretive engagement, it offered limited insight into how embodiment develops through prolonged or cumulative bodily change (as Pneunocchio either inflated fully or not at all). This limitation directly informed the design of the subsequent case study, Pneumusculus, which shifted the research focus toward bodily extensions that support sustained, gradual, and temporally unfolding embodied experiences over time.

CHAPTER 6: CASE STUDY 3 - PNEUMUSCULUS

Figure 33: Two people comparing their physical activity through Pneumusculus, highlighting how the physical activity can be "felt", even by others.

6.1 Overview

This chapter presents the third case study, Pneumusculus, which investigates how pneumatic bodily extensions can support sustained and cumulative embodied experiences through physical activity tracking (Figure 33). Building on the previous case studies, Pneumusculus shifts the research focus from momentary prompting (PneuMa) and interpretive ambiguity (Pneunocchio) toward bodily extensions that unfold gradually over time.

This section (6.1) provides an overview of the chapter. Section 6.2 introduces the motivation and conceptual framing of Pneumusculus and explains the rationale for designing a bodily extension that translates physical activity data into tangible bodily change. Section 6.3 describes the design and implementation of the Pneumusculus system. Section 6.4 details the field study design, including data collection and analysis methods. The findings from the post-study interviews are presented in Section 6.5 as themes derived from participants' accounts. Section 6.6 reflects on these findings. Section 6.7 discusses the limitations of the system and study, along with opportunities for future work. Finally, Section 6.8 concludes the chapter by explaining how Pneumusculus contributes to and extends the final framework.

This chapter is based on two publications:

- Aryan Saini, Sabari VS, Maria Fernanda Montoya, Nathalie Overdevest, Rakesh Patibanda, Don Samitha Elvitigala, Elise van den Hoven, and Florian 'Floyd' Mueller. 2025. Inflated Exertion: Designing a Bodily Extension that Embodies Physical Activity. In Proceedings of the Nineteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '25). Association for Computing Machinery, New York, NY, USA, Article 76, 1–7. https://doi.org/10.1145/3689050.3706069

- Aryan Saini, Sabari VS, Maria Fernanda Montoya, Nathalie Overdevest, Rakesh Patibanda, Don Samitha Elvitigala, Elise van den Hoven, and Florian 'Floyd' Mueller. 2026. Pneumusculus: Understanding the design of bodily extensions through a pneumatic bicep that embodies physical activity. (Under submission)

6.2 Case Study Motivation and Positioning

There is increasing interest within HCI in supporting people's engagement with physical exercise and everyday physical activity (Ahtinen et al., 2010; Kouaho & Epstein, 2024; Rapp & Tirabeni, 2020). Interactive systems, such as smartwatches, fitness bands, pedometers, and smartphone applications, are widely used to track and present physical activity metrics, including step count, heart rate, and calories burned (Gerling et al., 2020; Harrison et al., 2014; Rapp, 2018). While these systems can raise awareness of activity levels, they predominantly rely on screen-based representations that require users to actively seek out abstract numerical data (Jones et al., 2023; Stusak et al., 2014).

Prior research suggests that this screen-centric mode of engagement has notable limitations. Many users disengage from activity-tracking data over time, with studies reporting high rates of abandonment and neglect of quantified feedback (Lazar et al., 2015; Ullmer et al., 2022). One reason for this disengagement is that numerical representations often remain detached from lived bodily experience, despite physical activity being an inherently embodied, body-centric practice (Mueller et al., 2018). As a result, activity data may fail to meaningfully connect to how users sense, understand, and inhabit their bodies in everyday life.

Embodied interaction research offers an alternative perspective by emphasizing bodily engagement as a means of bridging digital information and physical experience (Dourish, 2001; Loke & Robertson, 2011; Svanæs, 2013). Rather than externalizing activity data on screens, embodied approaches suggest that bodily change itself can become a medium through which information is experienced. This perspective resonates with the ways in which physical activity naturally transforms the body over time. For example, fatigue, soreness, and muscle growth processes are gradual, cumulative, and felt rather than explicitly measured (Pearson, 1990; Tholander, 2025).

Building on this insight, this case study investigated how bodily extensions can be combined with physical activity tracking to support an embodied experience of personal activity data. Specifically, it explored how pneumatic actuation can translate accumulated physical activity into tangible bodily change. To this end, Pneumusculus was designed as a pneumatic bodily extension worn on the user's bicep that gradually inflates in response to physical activity throughout the day. Rather than prompting immediate action or revealing momentary internal states, Pneumusculus emphasises temporal accumulation, allowing bodily change to unfold slowly as a consequence of sustained activity.

Through this design, the Pneumusculus case study examined the opportunities and challenges of representing physical activity directly on the body. While such an approach may foster heightened bodily awareness and reflection, it also raises questions about interpretation, motivation, comfort, and long-term engagement. By situating physical activity tracking within the body itself, this case study extends the earlier presented examples of bodily extensions toward experiences that develop over time rather than emerging only in discrete moments. A video demonstration of the Pneumusculus case study can be found here: https://youtu.be/ZZ0Hbze0AaI.

6.2.1 Contributions to the Design Framework

The Pneumusculus case study contributed to the bodily extensions framework by foregrounding temporality and accumulation as central factors in shaping embodied experiences with bodily extensions. While the preceding case studies emphasised momentary prompting (PneuMa) and interpretive ambiguity through implicit signalling (Pneunocchio), Pneumusculus demonstrated how embodiment can emerge through gradual, sustained bodily change over time.

Participants' experiences showed that embodiment was developed through the progressive inflation of the bodily extension across hours and days rather than being tied to isolated moments of actuation. The pneumatic sleeve became a tangible manifestation of accumulated effort, transforming abstract activity metrics into a bodily state that was continuously present and slowly evolving. This design shifted the experience of embodiment from being episodic or reactive to being cumulative and longitudinal, thereby encouraging reflection on physical activity as an ongoing bodily process rather than a series of discrete events.

Importantly, Pneumusculus highlighted that bodily influence can remain strong even when user influence over moment-to-moment actuation is limited. Although inflation was driven implicitly by activity data rather than explicit commands, participants reported a strong sense of authorship because bodily change was directly attributable to their own actions over time. This finding revealed that perceived agency can emerge retrospectively, through recognition of accumulated bodily consequences, rather than solely through immediate control.

Pneumusculus demonstrated that bodily extensions can support embodiment not only by drawing attention to the body in the moment, but by staying with the body, allowing meaning, motivation, and bodily awareness to build gradually. This contribution completed the framework's conceptual progression across the three case studies: from explicit prompting (PneuMa), through interpretive and socially mediated embodiment (Pneunocchio), to sustained and time-based bodily transformation (Pneumusculus).

Together, Pneumusculus expanded the framework's capacity to account for bodily extensions that operate as long-term companions to bodily practice: emphasizing how pneumatic actuation can support embodied experiences that unfold across everyday life rather than within isolated interactions.

6.3 Designing Pneumusculus

This section describes the design considerations that guided the design of Pneumusculus (an amalgamation of "pneumatics" and the Latin term "musculus" for "muscle") based on learning from prior research on bodily extensions and embodied interaction (Buruk et al., 2023; Hartman et al., 2020; Loke & Robertson, 2011; Umezawa et al., 2022).

6.3.1 Design Considerations

The Pneumusculus design aimed to explore how bodily extensions can represent physical activity through sustained bodily change while remaining suitable for everyday use.

Non-restricting bodily movement

A central design consideration was ensuring that Pneumusculus could be worn during physical activity without restricting bodily movement. Prior systems have often separated physical activity from system interaction, requiring users to pause activity in order to engage with the interface (for example, Khot et al., 2017). In contrast, Pneumusculus was designed as a lightweight, wearable system that could be used continuously throughout the day.

To support this goal, the system was implemented as a largely wireless setup, thereby minimizing cables that might interfere with movement. While pneumatic tubing remained necessary for actuation, the tube length was deliberately constrained to allow for extended arm movements without introducing excessive drag or entanglement. This design choice sought to balance the physical requirements of pneumatic actuation with the need for unobtrusive integration (Rekimoto, 2001) into everyday physical activity.

Location on the body

Prior work has demonstrated that the placement of a bodily extension plays a significant role in shaping user experience and social interpretation (Hartman et al., 2020; Walmink et al., 2014). Accordingly, multiple locations were considered for both sensing input and pneumatic output.

For sensing physical activity, chest-worn heart rate straps were initially considered. However, wrist-worn smartwatches were ultimately selected. Smartwatches offer comparable signal quality for activity tracking (Pasadyn et al., 2019) while improving wearability and reducing the burden of additional under-clothing devices.

For actuation, the bicep and calf were explored as potential locations. The bicep was selected as the primary site because it is a highly visible muscle group commonly associated with physical strength and physical transformation (Musolino et al., 2022; Pearson, 1990; Tholander, 2025). Its visibility supports social legibility, while its soft tissue structure accommodates circumferential inflation. Although perceptions of muscle growth and strength vary across individuals and cultural contexts (Musolino et al., 2022), the bicep provided a recognizable and expressive location for initial exploration. Pilot testing also demonstrated that the system could be worn on the calf, suggesting opportunities for future studies investigating alternative body locations.

Physical activity tracking

People engage in physical activity in diverse and individual ways (Harrison et al., 2014). Rather than targeting a single form of exercise, Pneumusculus was designed to accommodate a broad range of activities. To support this flexibility, activity data was sourced from a commercially available smartwatch capable of detecting multiple activity types (Rapp & Tirabeni, 2020).

Physical activity was represented using active calories expended, a sport-agnostic metric familiar to many users. Participants were asked to define daily activity goals in terms of calorie expenditure, allowing bodily inflation to reflect cumulative effort rather than discrete workouts. While not all physical activity directly contributes to muscle hypertrophy, this approach enabled exploration of Pneumusculus as a research vehicle for understanding embodied engagement with physical activity data across everyday life.

The system did not support water-based activities due to hardware constraints, and this limitation was communicated to participants prior to the study.

Playful

Physical activity has been described in prior work as a form of bodily play (Elvitigala et al., 2024; Mueller et al., 2018; Mueller & Young, 2018). Inspired by this perspective, Pneumusculus was intentionally designed with an exaggerated and playful aesthetic. The inflation size was deliberately oversized, and any form of physical activity contributed to visible “muscle growth”, regardless of exercise type.

Focusing the inflation on a single arm further emphasised a superhero-like exaggeration rather than a realistic representation of muscle development. This design choice was not intended as a precise physiological model, but as a playful bodily representation that promotes engagement.

Body conformity

Body conformity has been shown to support ownership and acceptance of bodily extensions (Buruk et al., 2023; Steimle, 2016). Multiple materials were explored to achieve a balance between durability, comfort, and reliable inflation. While silicone offers desirable softness, the PneuMa case study and prior work highlighted challenges in fabricating large silicone inflatables reliably (Moradi & Torres, 2020). As a result, early iterations employed polyethylene (PE) and polyvinyl chloride (PVC)-coated polyester.

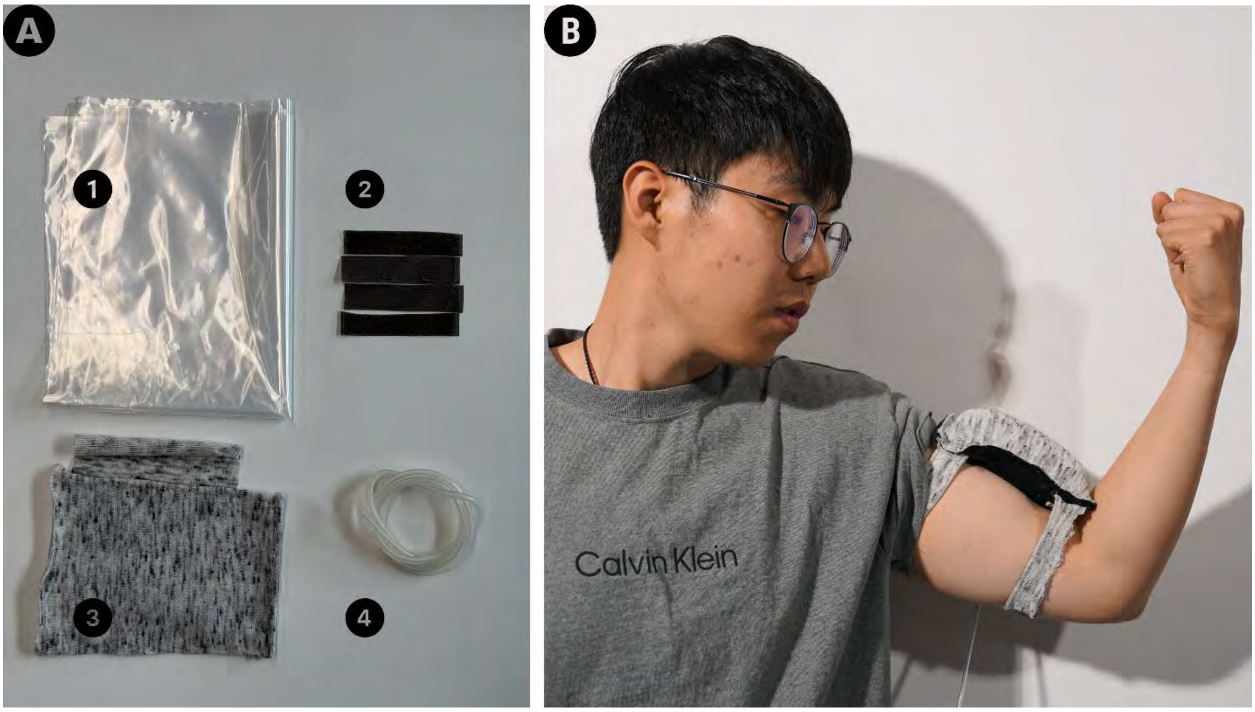

Figure 34: A. Materials used for the first iteration of Pneumusculus, including: 1. Transparent PE sheets for the inflatable component; 2. Black hook and loop fastener straps for securing the extension; 3. Loosely-knitted cotton fabric; and 4. Transparent air tubing for inflation. B. The first iteration of the system, with the loosely-knitted cotton fabric and air tubing visible.

The first iteration used PE sheets enclosed within a loosely-knitted cotton sleeve, secured with hook-and-loop fasteners (Figure 34). Pilot testing revealed difficulties in one-handed fastening (particularly when using the non-dominant hand) and slipping during movement. In response, the next iterations adopted PVC-coated polyester to improve grip and durability. The inflation of this iteration was designed to wrap around the bicep instead of along the length, increasing contact area and enhancing bodily sensation during inflation. The inflatable was enclosed within a tightly woven, water-repellent polyester layer and sewn onto a stretchable arm sleeve to accommodate different arm sizes while maintaining comfort and stability during movement. This design increased the overall size of the inflatable to approximately 25 cm × 10 cm. By wrapping around the bicep, the inflatable provided greater surface contact and more evenly distributed pressure compared to the first iteration.

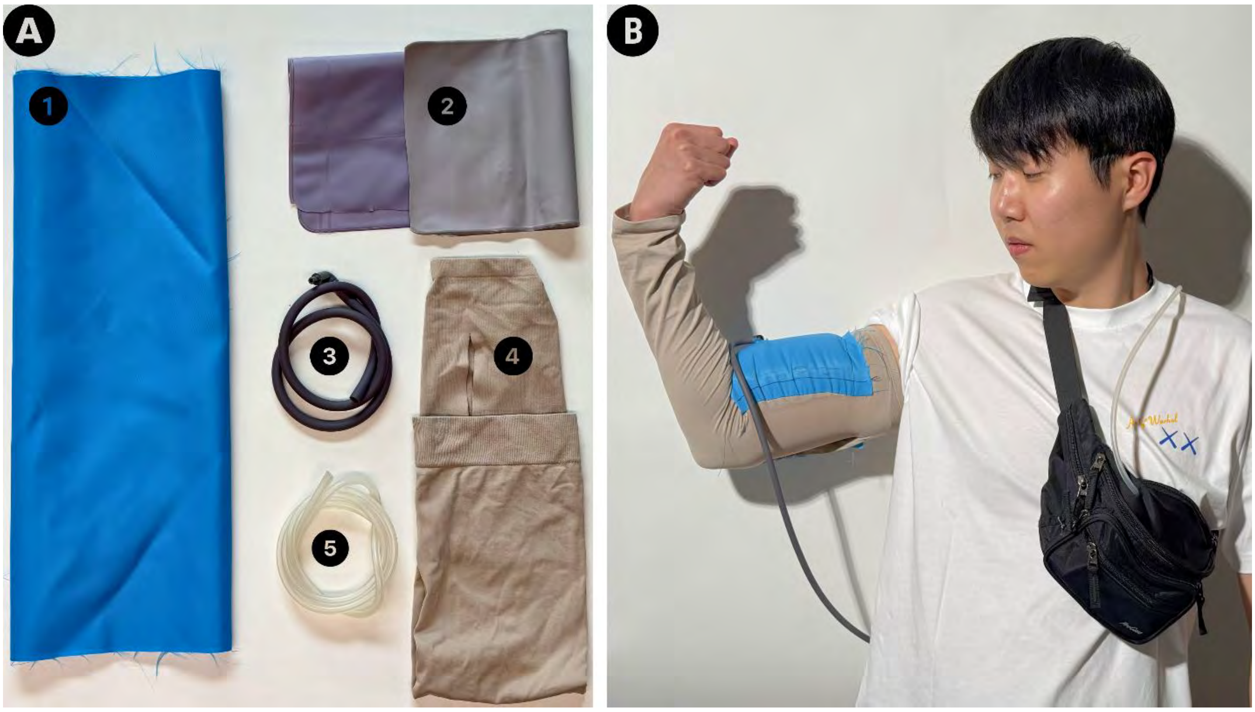

Figure 35: A. Materials used for the second iteration of Pneumusculus, including: 1. Blue tightly woven water-repellent polyester; 2. PVC-coated vinyl sheets; 3. L-shaped air tubing; 4. Beige fabric sleeve; and 5. Transparent air tube. B. The second iteration of Pneumusculus, demonstrating the blue inflatable component integrated into a beige sleeve. The pneumatic pump system is connected via tubing and housed in a waist bag worn across the torso.

The PVC-coated vinyl layers were sealed along the edges using a vinyl adhesive after integrating an L-shaped air tube (Figure 35A), which was secured with a resin-based adhesive to minimise air leakage. To protect the inflatable component and improve wearability, a tightly woven, water-repellent polyester fabric enclosure was added (Figure 35A). Finally, to accommodate variations in participants' arm sizes, the enclosure was integrated into a two-way stretchable arm sleeve made from a cotton–elastane blend (Figure 35A), supporting comfort and body conformity during extended use.

Figure 36: Study kit: A. The bodily extension with an air tube. B. Portable tripod for capturing study sessions (optional). C. Waist bag containing the pneumatic microcontroller and batteries. D. Battery charger. E. Spare rechargeable batteries. F. Pneumatic microcontroller setup with wiring and components. G. Smartwatch for physical activity tracking. H. Charging cable. I. Inflatable sleeve. J. Transparent air tube connecting the controller to the bodily extension. K. Power adapter for charging devices. L. Magnetic charger for the smartwatch. M. Mobile phone, used for recording the study experience (recording was optional for participants).

6.3.2 Technical Implementation

The Pneumusculus system leverages a combination of smartwatch-based activity tracking and pneumatic actuation to create an embodied representation of physical activity across everyday life. The setup utilises a smartphone application interfacing with the Apple Watch's HealthKit API (*HealthKit*, 2026) (Figure 36G) to track the wearer's energy expenditure throughout the day. These data are communicated via Bluetooth to a pneumatic controller (Programmable Air, 2026) (Figure 36C), which governs the inflation of the Pneumusculus bodily extension.

The pneumatic controller consists of an Arduino Nano and two 12 V micro air pumps, each capable of supplying up to 3.2 litres of air per minute while consuming a maximum current of 350 mA. In the current configuration, only one air pump is used for inflation. The controller is housed in a waist-worn bag (Figure 36C), weighs approximately 730 g, and is powered by three 3.7 V Li-ion batteries (2600 mAh each) connected in series, providing an operational voltage of 11.1 V. Under continuous operation, the system supports approximately 46 hours of use with periodic inflation cycles.

Physical activity is tracked using a metric chosen for its activity-agnostic nature and familiarity to users: cumulative active kilocalories expended per day. At the beginning of the study, participants defined a daily activity goal in kilocalories, which could be adjusted at any time. Pneumusculus translates progress toward this goal into bodily change by inflating the bicep-mounted extension across ten discrete levels. Inflation resets automatically at midnight, reinforcing a daily rhythm of accumulation rather than persistent bodily change across days.

Rather than continuously inflating in response to real-time fluctuations in activity data, the system checks for changes in energy expenditure at ten-minute intervals. This design choice reflects a deliberate trade-off between immediacy, wearability, interpretability, and long-term engagement. A continuous coupling between sensing and actuation could provide highly responsive feedback and reinforce short-term cause–and–effect relationships between exertion and bodily change. However, such continuous actuation would significantly increase power consumption, reduce battery life, and risk shifting users' attention toward micro-monitoring and activity optimization rather than embodied engagement. Prior work has shown that constant feedback can lead to distraction, cognitive overload, or disengagement, particularly in systems intended for everyday use (Odom, 2015). In contrast, periodic updates support a more cumulative and reflective experience of physical activity. Mapping gradual inflation to overall progress toward a daily goal emphasises sustained effort rather than momentary performance, allowing bodily change to unfold slowly over time. Physical activities that occur over longer intervals, such as gym sessions, walks, or exercise classes, are effectively captured, while shorter bouts of activity (such as "exercise snack" (Islam et al., 2022)) still contribute to cumulative inflation even if they do not immediately trigger bodily change.

The periodic actuation strategy also improves robustness and flexibility in everyday contexts. Because physical activity data are stored independently on the smartwatch, users can choose when to wear the sleeve part of Pneumusculus and still experience its embodied response later (such as during water sports). This decoupling supports appropriation and intermittent use, avoiding the perception that the system is constantly reacting to the body. When the pneumatic controller is switched on, a blue indicator LED signals successful connection to the smartwatch. The first inflation occurs ten minutes after activation and reflects the current completion percentage of the user-defined activity goal. For example, if a participant sets a goal of 1000 kilocalories and has expended 350 kilocalories, the bodily extension inflates to approximately 30% of its maximum volume (corresponding to ~1.63 atm). Pressure values range from approximately 500 at zero kilocalories to 650 at the user-defined goal, relative to an atmospheric baseline of approximately 508.

6.4 Pneumusculus Study Design and Analysis

To investigate the user experience associated with Pneumusculus, a seven-day field study was conducted with 12 participants. The study was designed to capture how the bodily extension was integrated into participants' everyday physical activity routines, allowing Pneumusculus to be experienced alongside naturally occurring variations in activity across the week. Participants engaged with the system in their own environments and incorporated it into activities of their choosing, enabling the study to surface situated and longitudinal aspects of embodied experience that emerge through repeated use.

Of the 12 participants, three identified as female (P5, P9, and P12), nine as male, and none as non-binary or self-described. Participants (N = 12) were aged between 21 and 36 years (M = 25.8, SD = 4.5). Eight participants had previous experience using physical activity trackers such as smartwatches, fitness bands, and mobile phone apps. All participants reported performing regular physical activities throughout the week, such as walking (all participants), running (P1, P7), yoga (P9), surfing (P3), playing badminton (P2, P5) or football (P5), working out at the gym (P1, P4, P6, P10, P12), and swimming (P7, P10).

The onboarding phase was conducted at participants' homes. Each session began with an introduction to the study kit (Figure 36). The Pneumusculus system was demonstrated, and participants were invited to ask questions. Participants were guided through the process of setting a physical activity goal on the smartwatch for “active calories exerted,” with the option to adjust it at any point during the study. Each onboarding session lasted approximately 21 minutes (mean = 20.67 min, SD = 1.92 min).

Participants were asked to use Pneumusculus whenever it was convenient and appropriate during the seven-day study period. They were optionally encouraged to video-record their interactions using the smartphone and tripod provided in the kit, when feasible and meaningful. System interactions were logged automatically to support subsequent analysis of usage patterns. Participants were contacted twice during the study period to check whether the system was functioning correctly and to address any questions or technical issues.

Following completion of the field study, the study kits were collected, and individual post-study interviews were scheduled. The interviews lasted approximately 42 minutes each (mean = 42.5 min, SD = 4.21 min). The interviews focused on participants’ experiences of using Pneumusculus and their interpretations of the bodily extension across different everyday contexts.

All interviews were manually transcribed and analysed using inductive thematic analysis (V. Braun et al., 2019; V. Braun & Clarke, 2006) with support from NVivo (“NVivo,” 2025). Two researchers conducted the analysis (myself and a collaborator). Each coded excerpt was treated as a unit of analysis, resulting in 454 initial codes. These codes were iteratively grouped and refined into higher-level themes that informed the findings presented in the following section.

6.5 Findings from the Pneumusculus Field Study

This section presents the results of the interview analysis in the form of four themes: (1) physicality of the representation; (2) motivation through in-body tracking; (3) delayed inflation as a resource for contemplation; and (4) sensations and social aspects of physical activity.

Theme 1: Physicality of the representation

This theme describes participants' experiences with the tangible representation of physical activity facilitated by Pneumusculus. This theme consisted of 89 units of code. It has three sub-themes: in-time physical awareness; simplifying physical activity tracking was appreciated; and enhanced awareness of physical activity throughout the day.

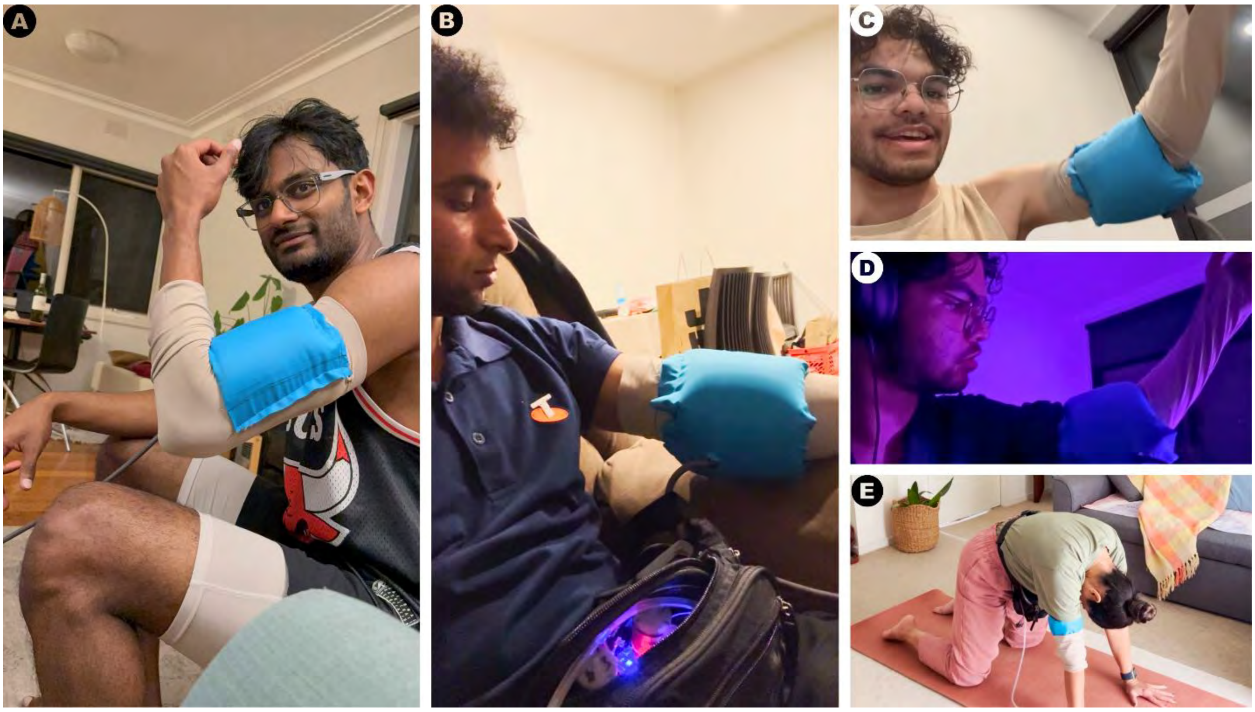

Figure 37: Study participants engaging with Pneumusculus: A. Participant flexing their arm, showing the inflated Pneumusculus extension on their bicep during casual activity. B. Participant interacting with the device while the pneumatic controller is visible in the waist bag. C. Participant raising their arm, showcasing the inflated bodily extension during a light activity. D. Participant using Pneumusculus while observing the inflation of the bodily extension. E. Participant on a yoga mat, performing a stretching exercise with the Pneumusculus extension.

Sub-theme 1: In-time physical awareness

Participants expressed how Pneumusculus made their physical activity feel immediate and tangible, unlike conventional activity trackers. For example, P3 shared that *"it was the first time I could feel my workout in real-time instead of just looking at numbers on a screen."* This ability to *"feel"* the physical activity (complementing the usual bodily responses to physical activity) seems to have added "depth" to participants' exercise routines, as P7 noted: *"the inflation was* *like a direct response to my effort, making it more rewarding."* P10 reflected on how this added clarity to their understanding of physical activity: *"It helped me connect my activity with how my body felt at that moment."* Regarding the physical sensation as a result of the inflation around the bicep, however, P1 commented that *"the pressure sometimes felt too intense, distracting me from focusing on the activity itself."* Taken together, it seemed that the pneumatics' ability to provide a physical tightening sensation strengthened the link between physical activity and the participant's bodily response to it. However, if the inflatable was tightened too firmly, it could also draw attention away from physical activity.

Sub-theme 2: Simplifying physical activity tracking was appreciated

Pneumusculus' ability to provide different haptic sensations based on inflation levels seems to have helped the participants with monitoring their physical activity, which they appreciated. P5 described this help: *"It [Pneumusculus] removed the mental effort of checking numbers; I just felt my progress."* P8 echoed this sentiment: *"It felt natural, almost instinctive, to rely on the inflation to gauge my activity."* Another reason why participants thought the system helped with tracking was that it did not require explicit input and did not *"get in the way"*, as P6 noted: *"it didn't demand much from me; it just worked in the background and did not get in the way."*, When comparing Pneumusculus to commercial devices, P4 felt that *"it was helpful to feel progress without needing to check a screen constantly."* These insights suggest that Pneumusculus may have offered an advantage over the cognitive burden associated with conventional activity trackers. The different haptic sensations based on inflation levels seem to have encouraged participants to leverage their bodily feelings to track physical activity.

Sub-theme 3: Enhanced awareness of physical activity throughout the day

Pneumusculus seemed to have deepened participants' understanding of their physical activity throughout the day. For example, P9 shared that *"it made me realise how even small actions added up to something meaningful."* Similarly, P2 commented that their view on physical activity shifted to become more holistic, going beyond individual workouts: *"I was more aware of my activity throughout the day, it wasn't just about workouts anymore."* P10 reflected on how this embodied response linked physical activity to immediate physical sensations: *"It helped* *me connect my activity with how my body felt in that exact moment."* However, P12 seemed to be a bit sceptical about the coupling between their physical activity and Pneumusculus' response: *"There were times when the inflation didn't seem proportional to my effort, which made me question its accuracy."*

These insights suggest that Pneumusculus fostered an awareness of physical activity, encouraging participants to find value in all movements. This newfound awareness may have enhanced participants' abilities to connect everyday life movements with long-term health outcomes.

Overall, learning from this theme, integrating real-time physical responses to activity tracking seemed to alter participants' awareness/understanding of their everyday life movements in relation to individual workouts. In other words, Pneumusculus seems to redefine how participants perceived and valued their physical activity by making it tangible. This finding suggests that representing physical activity through an embodied response may enhance the experience of physical activity tracking.

Theme 2: Motivation from in-built tracking

This theme describes how variance in the bodily response motivated participants to engage in or sustain their physical activities as a response to perceiving Pneumusculus' tracking as a reflection of themselves. This theme consisted of 94 units of code. It includes three sub-themes: bodily growth as an accomplishment, pushing limits as a response to on body sensations, and appreciated social motivation from inflation's visibility.

Sub-theme 1: Bodily growth as an accomplishment

Participants appeared motivated by the physical growth of their bodies as a result of inflation, which provided a sense of accomplishment. For example, P2 reported that *"when it inflated to 100%, it felt like my body had achieved something significant."* This physical growth of the body appeared to drive consistency when performing physical activity, as P8 explained: *"knowing I'd see the inflation on my body made me want to hit my targets every day."* P9 appreciated how it *"gamified"* fitness (Mueller et al., 2011) on their own body: *"it felt like unlocking a reward …*

each time I hit my goal." However, P4 noted a potentially discouraging characteristic: *"on days when I didn't meet the target, it could feel discouraging instead of motivating."* P11 felt differently: *"if I did not feel the inflation properly one day, I really wanted to do better the next day."*

Overall, Pneumusculus' ability to turn physical activity into bodily growth that was visible and felt seemed to motivate participants to strive toward their goals.

Sub-theme 2: Pushing limits as a response to body sensations

Participants suggested that the inflation of the bicep, which is finite, unlike a tracking number on a screen, encouraged them to push beyond their usual limits but also to not exceed limits (which was associated with bursting the inflatable; however, this was technically not possible due to the implemented threshold). For example, P10 reflected that *"feeling the inflation on my body made me want to work harder and achieve a stronger and tighter response."* P5 went further and noted that they felt accountable for the inflation: *"It created a sense of accountability; I didn't want to fall short of my previous day's effort."* P11 described how looking forward to the inflation around the bicep helped them: *"on long office days, I pushed through because it was like somewhat like a reward."* However, P3 reflected upon maintaining balance: *"while it motivated me, I also had to be mindful not to overdo it just for the sake of inflation."* Pneumusculus seemed to promote a sense of accountability among participants by connecting felt bodily sensations to progress. The bodily extension may have served as a motivation for participants to push their boundaries or achieve consistency in physical activity. However, some participants also became aware of not *"overdoing"* it just for the sake of inflation.

Sub-theme 3: Appreciated social motivation from inflation's visibility

Participants noted that the visibility of the bodily extension, especially when inflated, created opportunities for social interaction. For example, P4 shared that *"watching this [Pneumusculus] inflate at the gym, a child came up to me to ask about what it was."* P6 speculated on how the size of the inflation could fuel comparison conversations: *"Comparing the size of the pump with my friends would be a fun thing to do. It will motivate me to do my* *best."* P1 described how Pneumusculus encouraged them to engage more: *"Knowing others could see my effort on my bicep added an extra layer of motivation when I wore it to the gym."* However, P12, wary of negative social perception, commented that *"I probably won't wear this in public as it might look weird to have a very big arm."* These experiences suggest that Pneumusculus introduced a social co-location dimension to fitness tracking (unlike smartwatch tracking, which is mostly private, thanks to its small screen, in co-located settings, where any sharing mostly occurs over the internet with remote people), fostering social interactions that could even lead to external validation. By making physical activity efforts visible to others, Pneumusculus seemed to support participants by creating opportunities for motivation through social engagement. However, participants also pointed out that the inflation's visibility was restricted to one arm, which was considered peculiar and hence hindered more social engagement.

Overall, the embodied response facilitated by Pneumusculus seemed to serve as an accomplishment indicator and provide social motivation.

Theme 3: Delayed inflation appreciated for contemplation

This theme describes how the delayed inflation response acted as a prompt for reflection and served as a behaviour reinforcement. This theme consisted of 112 units of code. It includes three sub-themes: reminder to reflect on physical activity in their day; encouraging behaviour change; and reflecting on the association between effort and response.

Sub-theme 1: Reminder to reflect on physical activity in their day

Participants described how the delayed inflations acted as a reminder to think about the intensity and duration of physical activity and well-being throughout their day. For example, P3 explained that *"the inflation forced me to pause and think about what I had done, which I don't usually do."* P7 confirmed this experience and added that it was interesting that it was their body itself (in contrast to a mobile phone or another tool) that facilitated this reflection: *"It was like my body talking back to me, reminding me to notice my movements."* Meanwhile, P9 commented that the delayed inflation even led to contemplating how much to eat: *"When it* *inflated after work, it made me stop and realise how much I had actually exerted myself. I should probably eat more."* However, P1 highlighted how the delayed inflation also interrupted them in certain situations: *"Sometimes the inflation felt like it came at the wrong time, making it more of an interruption. It distracted me from my current thought."*

These insights suggest that Pneumusculus' delayed response enabled moments of introspection and reflection on participants' physical activity in everyday life. However, the bodily extension could also distract participants from their ongoing activities.

Sub-theme 2: Encouraging behaviour change

Participants described how the delayed physical sensation of inflation nudged them to reconsider their habits and adapt their routines. For example, P10 observed that *"the device made me realise I needed to balance my physical activity better, especially when it inflated to the max."* P4 added that the expectation of delayed inflation encouraged them to plan their physical activity for the rest of the day: *"It encouraged me to plan my day more thoughtfully, knowing I'd get [a] response later."* It seemed important that this delayed inflation was *"felt"* (rather than, for example, seen). For example, P6 shared how this encouraged them to be more consistent with their physical activity: *"It made me want to be more consistent with my efforts, knowing I'd feel the difference."* However, this effect could also backfire. For example, P1 noted that the delayed inflation could also come across as badgering: *"sometimes it felt like it was pushing me too hard, almost like a nag."*

These participant responses suggest that Pneumusculus' delayed inflation promoted behavioural changes, particularly by encouraging participants to reflect on their routines and strive for a healthier balance. Participants felt Pneumusculus functioned as a *"subtle"* (P3) and *"haptic"* (P12) coach, helping them align their actions with their physical activity goals.

Sub-theme 3: Reflecting on the association between effort and response

Participants often connected the delayed inflation mechanism to their exertion levels, using it as a measure of their effort. For example, P8 explained that *"feeling the inflation after working out gave me a sense of accomplishment; it was like proof that I had worked hard."* Meanwhile, P2 noted that the delayed inflation served them as embodied confirmation of their physical activity, especially when their bodily response was not very strong: *"the inflation was a physical reminder of how much I'd done, even if I hadn't noticed during the activity itself."* Moreover, P9 added that the delayed inflation helped them assess which parts of their physical activity contributed to their progress: *"It made me more aware of which movements were contributing the most to my progress."* P5, however, raised concerns about accuracy: *"sometimes it felt like it inflated even when I hadn't done much, which made me question how it was tracking effort."*

By creating a delayed coupling between effort and response, Pneumusculus seemed to reinforce the connection between physical activity and its outcomes. This association appeared to help participants understand their physical activity and encourage them to reflect on how their movements contributed to their overall well-being.

Overall, the participants' responses suggested that the delayed inflation of Pneumusculus can serve as a tool for reflection by prompting them to consider their activity levels and make adjustments to their routines, thereby transforming activity tracking into a more reflective experience.

Theme 4: Sensations and social aspects of physical activity

This theme describes how the physical sensations created by Pneumusculus' position on the arm appeared to deepen participants' connection to their bodies and physical activity, highlighting physical activity as a lived experience. This theme consisted of 86 units of code. It includes three sub-themes: embodied awareness of effort; feeling the change in body schema; and perceiving social contexts with Pneumusculus in everyday life.

Sub-theme 1: Embodied awareness of effort

Participants described how the changing physical sensations provided by Pneumusculus' inflation (from wearing the un-inflated device – like a piece of clothing – to a slow inflation that tightened around their arm) shifted their perception of the physical effort they underwent from conventional numerical data (if they tracked their physical activity with wearables) to a more evolving embodied awareness of their physical effort. For example, P3 explained how the process of inflating the device heightened their *"feeling"* of having engaged in physical activity: *"it wasn't just numbers anymore; I could actually feel what I had done in my muscles."* P7 reflected on how the changing physical sensations as a result of the inflation amplified this connection between how their body felt and the physical activity they did during the day: *"When it inflated, I became more aware of how much my body had worked that day."* Interestingly, P6 added how Pneumusculus' relatively slow inflation process went beyond the immediate physical sensations and rather stood for an entire day's physical activity: *"it made me more mindful of how each movement contributed to my overall effort."* However, P12 expressed their concerns about using Pneumusculus' slow inflation by noting that *"sometimes the inflation felt too intense, and instead of awareness, it became a distraction."* These insights suggest that Pneumusculus' rather slow (at least compared to the dynamic display of numbers on a tracker) inflation fostered an embodied awareness of effort thanks to the changing physical sensations, thereby allowing the participants to *"feel"* the impact of their day's physical activity.

Sub-theme 2: Feeling the change in body schema

Participants reported that using Pneumusculus influenced their perception of their bodies and shaped how they experienced their body schema – an internal model of their own body (Gallagher, 1985; Pitron et al., 2018). For example, P10 reflected on how using the system allowed them to figure out who they want to become: *"It was like seeing my future self; how my body might feel if I was more muscular or less flexible."* P5, while talking about how it felt to use Pneumusculus, commented that the change in body schema helped to shift their focus onto often neglected body parts: *"the sensation made me realise the parts of my body I didn't usually think about, like how my biceps felt after carrying something heavy."* P9, while thinking deeply about their body schema, noted that they paid more attention to details that were previously unnoticed: "*I started paying attention to details, like how the left side of my body felt was different from the right."* However, P4 pointed out that the change in body schema might also highlight *"unimportant"* sensations, which could lead to distractions in everyday life: *"while it was interesting, it sometimes made me overly focused on small sensations that might not matter."* These reflections suggest that Pneumusculus enabled participants to feel a change in their body schema by highlighting previously unattended areas of bodily sensations.

Sub-theme 3: Perceiving social contexts with Pneumusculus in everyday life

Participants reflected on how Pneumusculus influenced their interactions within social contexts in everyday life. For example, P8 shared how the system affected their confidence: *"It helped me feel more confident and show my progress in front of others, especially as I am trying to gain [muscle]."* This response suggests that Pneumusculus can play the role of a tool for social communication. Furthermore, P11 described its impact on social perceptions: "*I would just want to show to others that I am working out or making progress."* This response suggests that Pneumusculus can signal the user's dedication. Furthermore, some participants found joy in discussing the bodily extension with others. For example, P6 shared their enthusiasm: *"I was also, like, a bit excited to tell them that, oh, you know, it's like tracking and based on my daily output, it's going to tell me."* This response suggests that Pneumusculus can foster positive conversations and curiosity, thereby enhancing the social experience. On the other hand, some participants reported feeling vulnerable. For example, P7 explained that "*I would not wear it if I was not planning to work out. I don't need to show that to others. I am feeling bad as it is."* This response suggests that the social implications of the Pneumusculus bodily extension could be complex, and that they intersected with participants' self-perceptions and willingness to share progress.

Taken together, these insights suggest that Pneumusculus shaped participants' social lives. By navigating these social contexts, participants experienced physical activity as inherently connected to their relationships.

This theme, overall, indicates that participants experiencing the physical sensations through Pneumusculus facilitated the understanding of physical activity as a lived experience. Pneumusculus appeared to encourage the study participants to reflect on their body's capabilities and limitations by fostering a deeper connection between sensation and effort.

6.6 Discussing Pneumusculus Study Results

In this section, the results of the field study and the process of designing Pneumusculus are reflected upon. The discussion is structured around van Manen's four bodily perspectives:

corporeality, temporality, spatiality, and relationality (2016). Each perspective is used to interpret participants' experiences with Pneumusculus and to surface insights relevant to embodied interaction. This section concludes each perspective with a corresponding design strategy intended to support practitioners interested in designing future bodily extensions for physical activity.

6.6.1 Understanding the User Experience Facilitated by Pneumusculus Through a Phenomenological Lens

Inspired by prior work in HCI on the design of physical activity experiences (Mueller et al., 2011), this section adopts a phenomenological lens to develop a deeper understanding of the subjective nature of the study findings. Phenomenology offers a means to examine interactive systems in relation to users' embodied and lived experiences; moving beyond functional performance to foreground experiential qualities (Loke & Robertson, 2011; Svanæs, 2013). In particular, this reflection draws on van Manen's framework (2016), which articulates four perspectives – corporeality, temporality, spatiality, and relationality – for understanding how individuals experience the world through lived experience.

Applying van Manen's framework enables an examination of how the Pneumusculus bodily extension shaped participants' embodied sense of self (corporeality), their relationship with time and progress (temporality), their perception and occupation of space (spatiality), and the social dimensions of physical activity (relationality). This reflective analysis contextualises the empirical findings and situates them within broader theoretical discussions of embodiment and the lived body; offering insights into how bodily extensions may become integrated into everyday life.

Embodied sense of self (Corporeality)

This dimension describes how the body senses and experiences the world through the use of the system (Manen, 2016). Specifically, within the scope of this case study, it concerns how individuals experienced their own bodies through Pneumusculus. Participants directly engaged with their bodies through the physical sensations of wearing the bodily extensions on their bicep. Participants noted that the inflation made them feel their activity in a visceral way, deepening their connection to it (theme 1: subtheme 3). Some reflected on how the nature of the response fostered a more intimate understanding of their physical condition, particularly in areas such as muscle engagement and fatigue (theme 2: subtheme 1). In this regard, Pneumusculus seemed to have heightened the participants' awareness of their own bodies, creating a bridge between their actions and responses. Participants also highlighted the potential for such systems to evoke a deeper awareness of their body schema, such as imagining how their physical form might evolve with sustained effort (theme 3: subtheme 3 and theme 4: subtheme 2). This response aligns with the phenomenological perspectives on embodied interaction proposed in prior research, such as Merleau-Ponty's theory of the lived body, which posits that technology can serve as an extension of the self (1962). However, ensuring comfort (theme 4: subtheme 1) and allowing for more granularity of control (theme 1: subtheme 2) over the response of the bodily extension are essential for a tighter action and response coupling, as evidenced by the discomfort experienced by one of the participants due to extensive inflation (theme 1: subtheme 1). Therefore, the findings of this case study seem to extend prior theory that states that the body is an active perceiving object through which humans engage with the world (Merleau-Ponty, 1962). These findings extend prior theory by examining how bodily perception and the extent of bodily response are reconfigured when the body is modified through a bodily extension. Hence, **designers should consider allowing the user to adjust the response of the bodily extension to foster a deeper connection with the bodily extension.** This capability could be achieved, for example, by allowing the user to adjust the inflation stages (in this case, 10% intervals) themselves.

Relationship with time and progress (Temporality)

Referencing van Manen's temporality (2016), this dimension describes how participants experienced time when interacting with Pneumusculus, specifically in regard to connecting their short-term actions to long-term outcomes. Pneumusculus' design allowed participants to experience the physical activity they performed throughout the day in an embodied way, thereby helping them become aware of their progress (theme 2: subtheme 2). Participants noted that the bodily extension motivated them by enabling them to reflect on their activities over a longer span of time, rather than just during the interaction (theme 3: subtheme 3). Participants perceived the inflation offered by Pneumusculus to be a reward for their physical activity (theme 1: subtheme 1 and 2). In this regard, the design of Pneumusculus helped participants reflect on their experiences over a longer period (a day), thereby enabling them to come to a deeper understanding of their activity (theme 3: subtheme 1). Prior research has suggested the importance of temporal systems in encouraging reflection on both real-time and long-term action (Löwgren & Stolterman, 2004). While the in-action reflection allowed the user to understand the current state of the system (and their bodies), post-action reflection promoted their understanding of progress over time (Rapp & Tirabeni, 2020). Therefore, the findings from this case study confirm the importance of longer-term responses in promoting deeper temporal engagement with both the body and the system through reflection. Hence, **designers should consider creating bodily extensions that respond over extended time periods, such as a day or a week, to strengthen the coupling between users' actions and the system response**. This capability could be achieved, for example, by designing bodily extensions sturdy enough that they can be used over very long periods.

Perception of space (Spatiality)

Referencing van Manen's spatiality (2016), this dimension describes the significance of an individual's interaction with their surrounding environment. Pneumusculus shaped participants' spatial experiences by physically embodying their activity through inflation (theme 4: subtheme 1). This interaction altered the participants' awareness of their bodies in relation to their environment, with some noting that they felt motivated by and aware of their physical activities (theme 2: subtheme 3). However, some participants also shared that Pneumusculus' visibility may have led it to stand out, particularly in non-fitness settings, where they felt it might feel "weird" to wear (theme 4: subtheme 3). Pneumusculus was designed to be "always available" to account for the physical activity participants performed throughout the day.

This case study also moves beyond the current means of seeking information to understand one's physical activity. Pneumusculus allowed participants to experience their actions seamlessly throughout the day. However, as the findings made evident, the inflation did not always feel appropriate to participants, given the space they were in. Prior HCI research has also highlighted the need to consider the context for designing interactive systems (Oulasvirta et al., 2003). Specifically, findings from the first two case studies (chapters 4 and 5) highlighted the importance of explicit control over interactions when designing bodily extensions to allow participants to feel more in control of their responses, thereby enabling adjustments to the environmental context (spatiality). While the strategies emerging from the findings of the two previous case studies were prescribed for bodily extensions to consider explicit input, this case study considers the user's physical activity implicitly (by accumulation over time). Therefore, the findings from this case study propose the addition of framing bodily extensions as dynamic systems that adapt to the context of use. Hence, the study findings suggest that **designers should consider creating bodily extensions that offer a dynamic and adaptable response to allow users to navigate different spaces across their everyday lives without the extensions being too visible**. This design outcome could be achieved by adding multiple zero or minimal inflation modes into the bodily extension. For example, the extension might have a "do not disturb" or "reduced inflation" mode, which would allow users to conveniently alter the response of the bodily extension based on their surroundings.

Navigating social contexts (Relationality)

Referencing van Manen's relationality (2016), this dimension describes how technology mediates interpersonal relationships and social contexts. Pneumusculus seemed to serve as a facilitator of social interactions, with its visible inflation creating opportunities and challenges in social settings. Participants noticed that Pneumusculus served as a "conversation starter", sparking curiosity among onlookers (theme 2: subtheme 3). Furthermore, participants noted their willingness to share the bodily extension's response. While some participants appreciated the attention that Pneumusculus brought to their bodies, owing to their good progress, participants were also keen to point out that the social interaction would "feel bad" if they did not have significant progress made evident by the inflation (theme 4: subtheme 3). This duality highlights the effects of progress towards the goal and the visibility of the bodily extension as contributors to social perception. Prior research has already identified the potential of bodily extensions as social organs. For example, Buruk et al. discuss the importance of social engagement when designing playful bodily extensions (2023). The authors suggest that, autonomously responsive bodily extension can function as a facilitator of social interaction. While this potential function seems to be confirmed by some participants' responses (they described feeling confident to show Pneumusculus' response to people around them), other participants felt uncomfortable engaging in social settings because of the bodily extension's inflation. Therefore, these findings extend Buruk et al.'s (2023) recommendation to consider bodily extensions as social organs as follows: **designers should consider the uninitiated behaviour of the bodily extension to promote social interaction, while also designing features that temporarily restrict its visibility (e.g., by hiding it)**. This design outcome could be achieved, for example, by designing bodily extensions that can be temporarily hidden when participants do wish to hide them, such as by embedding them in clothing.

6.7 Limitations of the Pneumusculus Case Study

This study primarily involved participants who already engaged in some form of regular physical activity and had normative bodies. As a result, the findings reflect how generally active individuals experienced and interpreted Pneumusculus. While this study provided valuable insight into how bodily extensions may integrate into existing activity routines, future work could investigate how similar bodily extensions are experienced by individuals with sedentary lifestyles, older adults, or people with physical limitations, in order to better understand the adaptability and inclusivity of such systems.

A further limitation concerns the reliance on goal-setting theory as the primary framing for physical activity engagement. Participants were required to set a daily physical activity goal at the beginning of the study, which structured how Pneumusculus responded through its incremental inflation. While participants could adjust their goals over time, the system did not support experiences outside a goal-oriented model. Consequently, this case study does not account for how bodily extensions for physical activity might function in non-goal-driven contexts. Future research could explore alternative mappings, such as inflation in response to absolute or cumulative activity levels without predefined goals, while carefully managing risks such as over-inflation or sensory fatigue.

Finally, the aesthetic and symbolic qualities of Pneumusculus may be interpreted as reinforcing masculine associations related to muscle growth and strength, as discussed in prior work (Musolino et al., 2022; Pearson, 1990). Future research could investigate how bodily extensions that engage with physical activity and bodily transformation are perceived across different genders and cultural contexts, and how alternative aesthetic or symbolic framings might support more inclusive forms of embodiment and body perception.

Taken together, these limitations suggest that while Pneumusculus offers valuable insights into embodied representations of physical activity, the findings should be interpreted with care. Addressing these limitations provides clear directions for future work aimed at expanding the experiential, social, and demographic scope of bodily extensions for everyday life.

6.8 Implications for the Framework

The Pneumusculus case study added to the framework by considering longer input streams (physical activity throughout a day) as a factor in the embodiment of bodily extensions. By gradually inflating in response to physical activity across the day, Pneumusculus shifted away from an experience involving momentary interaction toward an experience that unfolded over extended periods of everyday life.

Participants' experiences revealed that delayed and aggregated actuation fostered reflection, anticipation, and a growing sense of bodily integration. Rather than responding to immediate system prompts, users encountered the extension as a slowly changing part of their body, which invited contemplation of their physical activity over time. This temporal unfolding supported a sense of continuity, which allowed the bodily extension to be perceived as an evolving bodily state rather than a discrete interaction.

These findings demonstrated that the sustainability of embodiment depends not only on the form or location of a bodily extension, but also on how its behaviour is distributed across time. Pneumusculus, therefore, informed the inclusion of temporal dynamics as a key dimension in the framework. These dynamics emphasise that gradual, cumulative actuation can support deeper bodily integration than immediate feedback alone. Together with insights from PneuMa and Pneunocchio, this case study helped consolidate the framework's focus on how timing, control, and bodily integration interact to shape embodied experiences with pneumatic bodily extensions.

CHAPTER 7: BODILY EXTENSIONS FRAMEWORK

7.1 Overview

This chapter presents a framework (Figure 38) for designing bodily extensions that promote embodiment in everyday life. The framework synthesises insights from the three case studies presented in Chapters 4 (PneuMa), 5 (Pneunocchio), and 6 (Pneumusculus), alongside craft knowledge gained through their design. Rather than proposing a taxonomy of artifacts, the framework articulates a design space defined by user influence (control) and bodily influence (modification). The framework supports both retrospective interpretation of existing systems and prospective exploration of new design possibilities. Section 7.1 of this chapter provides an overview of the framework. Section 7.2 introduces the design space and its dimensions. Section 7.3 describes four experiential regions that emerge from the interaction of these dimensions. Section 7.4 applies the framework to the three case studies to demonstrate its descriptive and generative power. Finally, Section 7.5 presents design strategies to guide future designs.

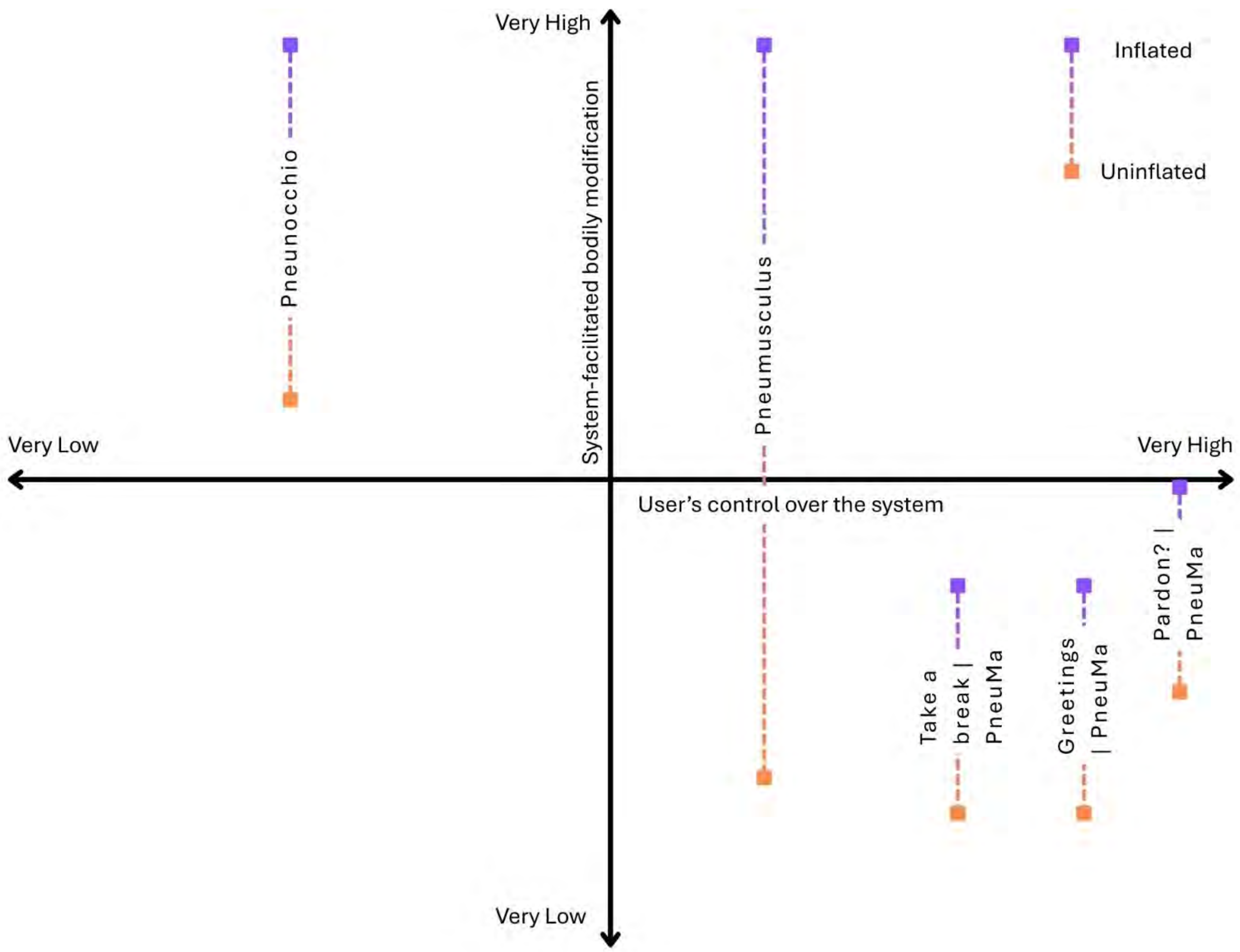

Figure 38: The Bodily Extensions Framework.

7.2 Design Space

This section synthesises insights from this thesis and prior work on bodily extensions and embodied interaction to propose a conceptual framework for designing bodily extensions. The framework is intended to support reasoning about how bodily extension designs distribute influence between users and systems, and how these distributions shape embodied experience.

This framework foregrounds the reciprocal relationship between user and system: bodily extension systems influence how bodies are perceived, felt, and enacted, while users influence how systems behave through action, intention, and context. To articulate this reciprocity, the framework defines two dimensions that together form a design space.

7.2.1 Framework Dimensions

The bodily extensions framework (Figure 38) is organised around two primary dimensions: User's Control over the System (X-axis) (Figure 39) and System-Facilitated Bodily Modification (Y-axis) (Figure 42). Each dimension describes a continuum rather than a binary distinction.

User's Control over the System (X-axis)

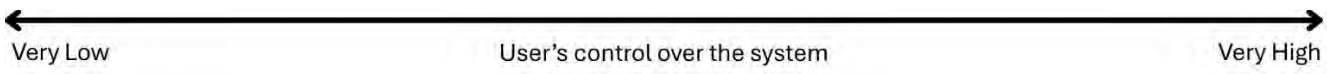

Figure 39: X-axis: User's control over the system.

The horizontal axis captures the User's Control over the System and describes the extent to which a user can intentionally influence a bodily extension system's behaviour. This dimension ranges from systems whose actuation is largely autonomous to systems whose behaviour is explicitly governed by user intention.

At one end of the axis are systems that afford limited user control because actuation is driven by external agents (Figure 40). For example, bodily extensions actuated by another person, such as Mehta et al.'s robotic arm controlled by a dining partner's facial expressions, afford minimal direct influence by the wearer, as the system's behaviour is determined externally (2018). Nevertheless, the user retains some control because they can orient their body towards or away from the dining partner. Hence, as long as the user has some control over their body, they have some control over bodily extension systems. Further away sit systems driven by physiological signals, such as galvanic skin response, and offer constrained user control because such signals are only partially volitional (Peng, 2021).

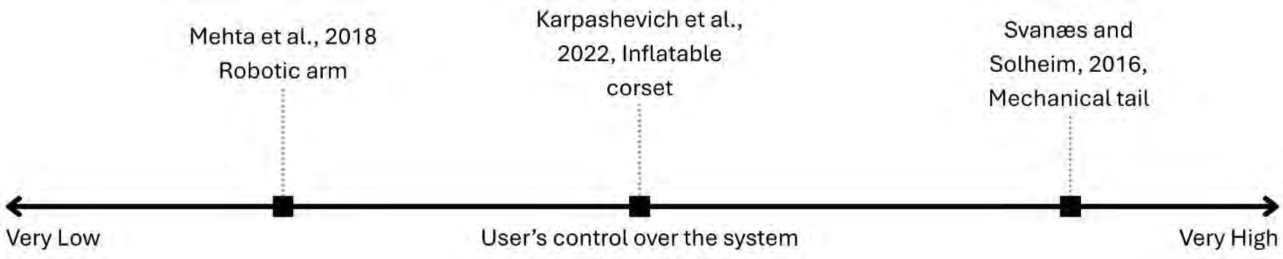

Figure 40: Plotting examples of bodily extensions explored in previous literature on the X-axis.

Moving along the axis, we find systems that respond to inputs, such as breathing or posture, that are implicit to some extent. These systems occupy intermediate positions (Figure 40). For example, Karpashevich et al. (2022) introduced an inflatable corset that responded to the user's breathing patterns. This system made the users aware of their breathing by inflating in proportion to the intensity of their breath. While the users could explicitly control their breath, the system was intended to offer the users a reflective understanding of their bodies. Therefore, this system sits more to the right of the axis.

At the right extreme of the axis are systems that afford high user control through explicit input (Figure 40). For instance, Svanæs and Solheim's mechanical tail maps waist movement directly to tail motion, thereby enabling users to intentionally control actuation through bodily action (Svanaes & Solheim, 2016).

In summary, the dimension of User's control over the system captures how bodily extension systems distribute agency between user and system, shaping whether control is experienced as explicit, negotiated, or largely autonomous (Mueller et al., 2025).

Applying the dimension to the case studies

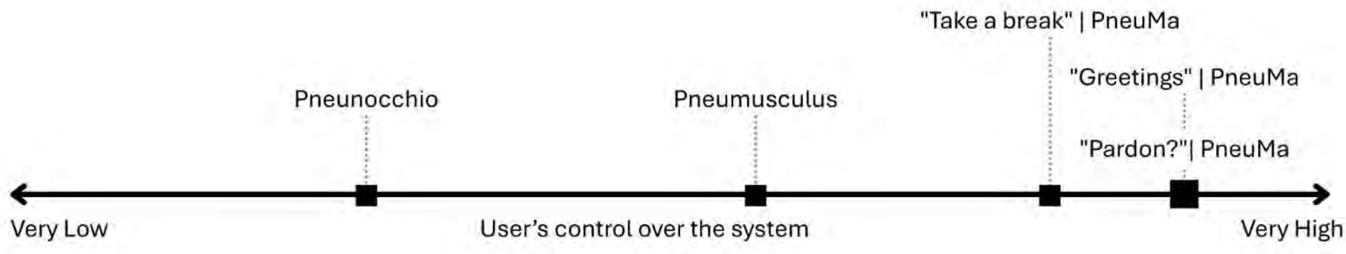

Figure 41: Plotting the case studies on the X-axis.

This section discusses the bodily extensions proposed in this thesis in relation to their position on the X-axis: the user's control over the system (Figure 41). First, the "Greetings" and the "Pardon?" bodily extensions sit on the far right of the axis , as they are explicitly controlled by voice cues and the immediacy of the interaction. Furthermore, "Take a break" is slightly left of its counterparts in PneuMa due to the timer-based control and delayed inflation. Second, Pneunocchio sits towards the left end of the axis, where the user experiences implicit control over the bodily extension. Finally, Pneumusculus sits slightly towards the right side of the axis. While the user's bodily movement allows for an explicit act of control, it responds to accumulated input over time, which means that the control experienced over the system is lower than the PneuMa bodily extensions.

System-Facilitated Bodily Modification (Y-axis)

Figure 42: Y-axis: System-facilitated bodily modification.

Borrowing from the notion of shape-changing interfaces as proposed in HCI research (Alexander et al., 2018), the vertical axis captures system-facilitated bodily modification and describes the extent to which the system influences changes to the shape of users' bodies (Figure 42).

At the lower end of the axis are systems that offer minimal modification to the user's body (Figure 43). For example, Walmink et al.'s LumaHelm displays physiological data on an illuminated helmet surface that is primarily visible to onlookers rather than the wearer

(Walmink et al., 2014). While the system alters the wearer's social perception, it provides only limited changes to the user’s body because it is similar to commercially available helmets.

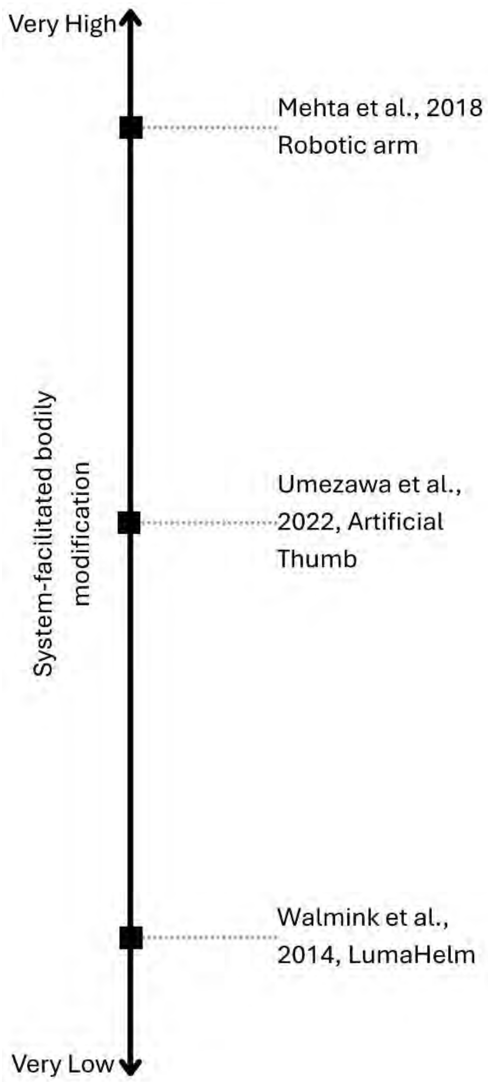

Figure 43: Plotting examples of bodily extensions explored in previous literature on the Y-axis.

Moving upward along the axis, we find systems that increasingly facilitate bodily modification (Figure 43). For example, Umezawa et al.’s artificial thumb, controlled via toe movements, creates a novel mapping between foot and hand that modifies the user’s body through an additional thumb (Umezawa et al., 2022). However, since this extension is designed similarly to a thumb, the bodily modification is considered to be moderate.

Finally, we find systems at the upper end of the axis that strongly facilitate bodily modification by introducing a very high degree of change to the user's body (Figure 43). For example, Mehta et al.'s Arm-a-dine (2018) uses a robotic arm attached to the user's torso. This system induces a large change to the user's body, owing to the extra arm, which reconfigures the user's body to a significant extent.

In summary, this system-facilitated bodily modification dimension captures how bodily extension systems support, amplify, or constrain users' perception of bodily change, ranging from minimal modification to substantial reconfiguration.

Applying the dimension to the case studies

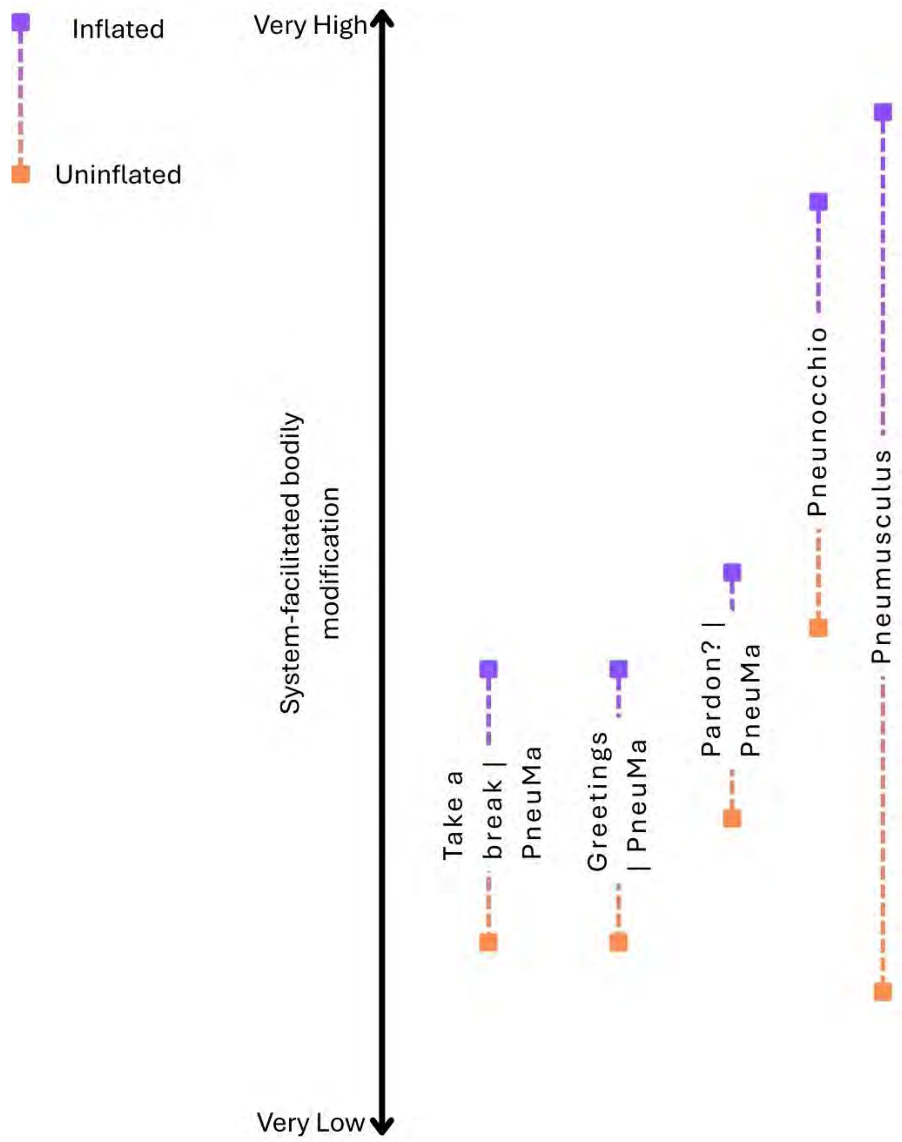

Figure 44: Situating the bodily extension from the case studies on the Y-axis.

This section discusses the bodily extensions proposed in this thesis in relation to their positioning on the Y-axis (Figure 44). First, with PneuMa, the “Greetings” and “Take a break” bodily extensions sit at the lower end of the axis, owing to their size and bodily location on the palm. The “Pardon?” bodily extension from the PneuMa case study, however, sits slightly above them due to its larger size and greater visibility behind the user’s ear. They are at the lower end when uninflated and move upwards when inflated (section 4.6). Second, Pneunocchio sits much further up the axis, owing to its bodily location (on the nose). It moves even higher when inflated because it moves into the user's field of view more prominently, making it hard to ignore (section 5.6). Finally, when uninflated, Pneumusculus is a sleeve on the bicep, similar to an orthosis, which situates it at the lower end of the axis. However, when inflated, Pneumusculus' increased size and prominent location on the body move it toward the higher end of the axis.

7.2.2 Combining the Axes into a Design Space

Together, users' control over the system and system-facilitated bodily modification span a design space for bodily extensions. The design space does not classify systems into fixed categories. Rather, the design space provides a conceptual structure for analysing how different design choices give rise to different embodied experiences. In the following sections, this design space is used to articulate experiential regions and to analyse how bodily extension systems may move through the space over time.

7.3 The Quadrants

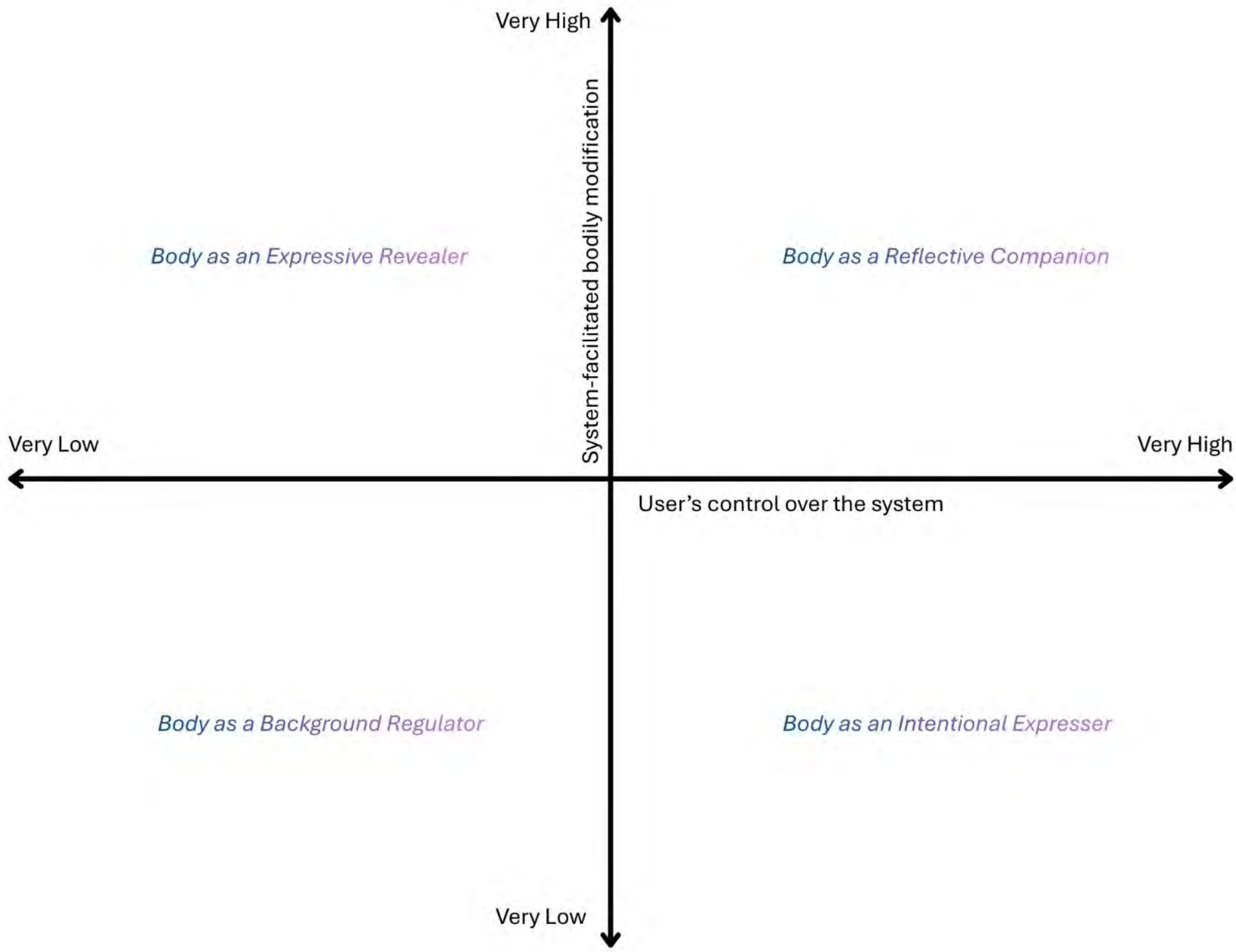

Figure 45: User experience associated with each quadrant of the bodily extensions framework.

Following prior work (Moros Ortiz, 2024; Mueller et al., 2021, 2025; Patibanda, 2024), the two dimensions of the bodily extensions framework interact to define four experiential types, corresponding to the four quadrants of the design space (Figure 45). These quadrants should be understood as experiential regions, not discrete categories. A single bodily extension may occupy different regions depending on its interaction configuration or temporal state. The following sections describe each user quadrant and position that quadrant in relation to relevant prior work.

7.3.1 Body as an Expressive Revealer (upper-left)

In the upper-left region sits an experience type characterised by low user control over the bodily extension and high modification of the user's body. In this quadrant, bodily extensions typically respond to implicit inputs (e.g., physiological signals) and manifest changes that are highly visible, socially legible, or difficult to ignore. This experience type is called the *Body as an Expressive Revealer* because the bodily extension reveals aspects of the wearer – often internal, affective, or physiological – in an expressive form that becomes available to others. The term 'revealer' emphasises that the extension functions as an outward-facing disclosure mechanism and frequently operates without the wearer's direct intention or explicit control. The term 'expressive' foregrounds that what is disclosed is data that turns the body into a stage performance.

This user experience is visible in work where physiological data drives externally observable actuation. For example, the Wigglears prototype uses galvanic skin response to wiggle the user's ears, turning internal arousal into visible motion (Peng, 2021). In such systems, the wearer's influence is limited because the extension's behaviour is driven by bodily processes. However, the bodily extension can exert a strong influence on the body schema by altering the body's shape or prompting movement, including in ways that may feel playful. This design, therefore, aligns with broader discussions of playful bodily extensions, where exaggeration can be leveraged (Buruk et al., 2023; Mueller et al., 2025).

7.3.2 Background Regulator (lower-left)

In the lower-left region sits an experience type characterised by low user control and low system influence on bodily modification. Here, the bodily extension operates largely in the background, often delivering subtle actuations that do not demand sustained attention or reshape the body in a pronounced way. This experience type is called the *Body as a Background Regulator* because the bodily extension system functions as a quiet, peripheral agent, regulating or communicating in ways that remain available but are not demanding. The term 'background' emphasises that the extension is not persistently foregrounded in experience, while the term ‘regulator’ indicates that the system’s contribution is often supportive, stabilizing, or gently guiding rather than transformative.

This quadrant is supported by work in pneumatic and wearable feedback that aims to minimise disruption and maintain comfort. For instance, Pohl et al.’s Squeezeback system provides subtle pneumatic compression for notifications, which are valued precisely because they are less intrusive than vibrotactile alternatives and can fade into the periphery of attention (2017). Similarly, when explicitly attending to questions of agency and bodily ownership and designing for minimal experiential disruption, Morris et al. (2023) explored coupling physiological signals with subtle pneumatic feedback in a garment. These systems exemplify how a bodily extension may be present and functional without strongly reshaping the body. For example, they can be worn underneath clothing, and their influence is often situational and intermittent, becoming meaningful primarily when users direct their attention toward them. While this experience resonates with traditions of calm, peripheral interactions (Nordby & Morrison, 2016), within the bodily extension framing, it emphasises how minimal bodily influence can still support everyday regulation when designed to remain non-demanding.

7.3.3 Body as a Reflective Companion (upper-right)

In the upper-right region of the design space sits an experience type characterised by high user control and high bodily modification facilitated by the system. In this quadrant, users intentionally control the system’s behaviour and, in return, the system affects how the users sense, inhabit, or understand their bodies. This experience type is called the *Body as a Reflective Companion* because the bodily extension becomes a companion to bodily experience: it responds to the user’s intentional engagement while prompting reflection on bodily states and capabilities. The term ‘companion’ emphasises a relational stance, while the term ‘reflective’ signals that the experience involves attentiveness and interpretation rather than just control.

Svanæs’ mechanical ears, which were explicitly informed by phenomenology of the lived body, foreground the challenges and potentials of designing bodily extensions that can feel “part of the body”, enabling bodily-kinaesthetic engagement through intentional movement coupling

(Svanæs, 2013; Svanæs & Barkhuus, 2020; Svanaes & Solheim, 2016). When such extensions are shaped by explicit and learnable mappings, they can be incorporated into the body schema through repeated sensorimotor coordination (van Dijk et al., 2014). This work suggests that the extension physically alters bodily experience either immediately or over time. Therefore, this type of interaction can promote reflective bodily understanding.

7.3.4 Body as an Intentional Expresser (lower-right)

In the lower-right region of the design space sits an experience type characterised by high user control over the system and low system-facilitated bodily modification. Here, users explicitly control the bodily extension, but the effect on the body remains limited. This experience type is called *Body as an Intentional Expresser* because the user's relationship to the extension is primarily one of directing movement, while the bodily extension does not significantly affect bodily perception; hence, it is called an expresser. The term highlights a clear asymmetry of influence: control is located primarily with the user, and bodily transformation remains minimal or transient.

This quadrant is visible in bodily extension work that prioritises control and interactional expression without necessarily producing strong incorporation into body schema. For example, Monarch, a shoulder-worn bodily extension that responds to the user's muscle activity, preserves comfort, avoids disruption, but supports momentary expression in everyday life contexts (Hartman et al., 2020). When it comes to pneumatic interfaces more broadly, toolkits and prototyping approaches (e.g., rapid fabrication methods and compression-based prototyping) can enable designs that make explicit control and predictable actuation central, while keeping bodily impact light-touch or peripheral(Endow et al., 2021; Morita et al., 2023).

7.3.5 From Quadrants to Trajectories

These four user experiences provide a vocabulary for describing how bodily extension systems distribute influence between the user and the system, and how the body is reshaped through interaction. Crucially, experiences with bodily extensions are rarely confined to a single quadrant of the design space. Instead, they may evolve, oscillate, or migrate as users adapt, contexts shift, and, critically for this thesis, as the system's actuation unfolds over time. This dynamic is particularly evident in pneumatic bodily extensions, whose material transformations unfold over time and can be negotiated through bodily action, such as resisting pressure, covering the extension, or modulating movement.

To capture this dynamic nature, the framework adopts the notion of trajectories, drawing on prior work that conceptualises interaction experiences as unfolding across time rather than existing as fixed states (Benford et al., 2009, 2020). Prior body-centric research has already used trajectories to make sense of novel designs (Mueller et al., 2025; Patibanda, 2024; Tennent et al., 2021). Within the bodily extensions framework, trajectories enable bodily extension systems to be represented as evolving configurations within the design space, rather than static points. This design choice explicitly accommodates the interplay between user control and system-facilitated bodily modification, particularly as it is shaped by the temporal characteristics of pneumatic inflation. In the following section, the framework is applied to the three case studies to illustrate how each system can be understood as a trajectory through the design space.

7.4 Applying the Bodily Extensions Framework

In this section, the framework is applied to the three case studies developed in this thesis (PneuMa, Pneunocchio, and Pneumusculus) to demonstrate how it accounts for observed user experiences and informs future design directions.

Each case study is discussed in two parts. First, the framework is used to explain how each bodily extension can be understood as moving across the design space over time. Second, the analysis examines how the framework enables designers to extend, reconfigure, or reorient bodily extensions by adjusting the balance between the user's control over the system and system-facilitated bodily modification. Through this analysis, the framework is shown to support not only retrospective interpretation of existing designs but also prospective exploration of future bodily extension concepts, demonstrating both its descriptive and prescriptive value.

7.4.1 Explaining PneuMa Through the Framework

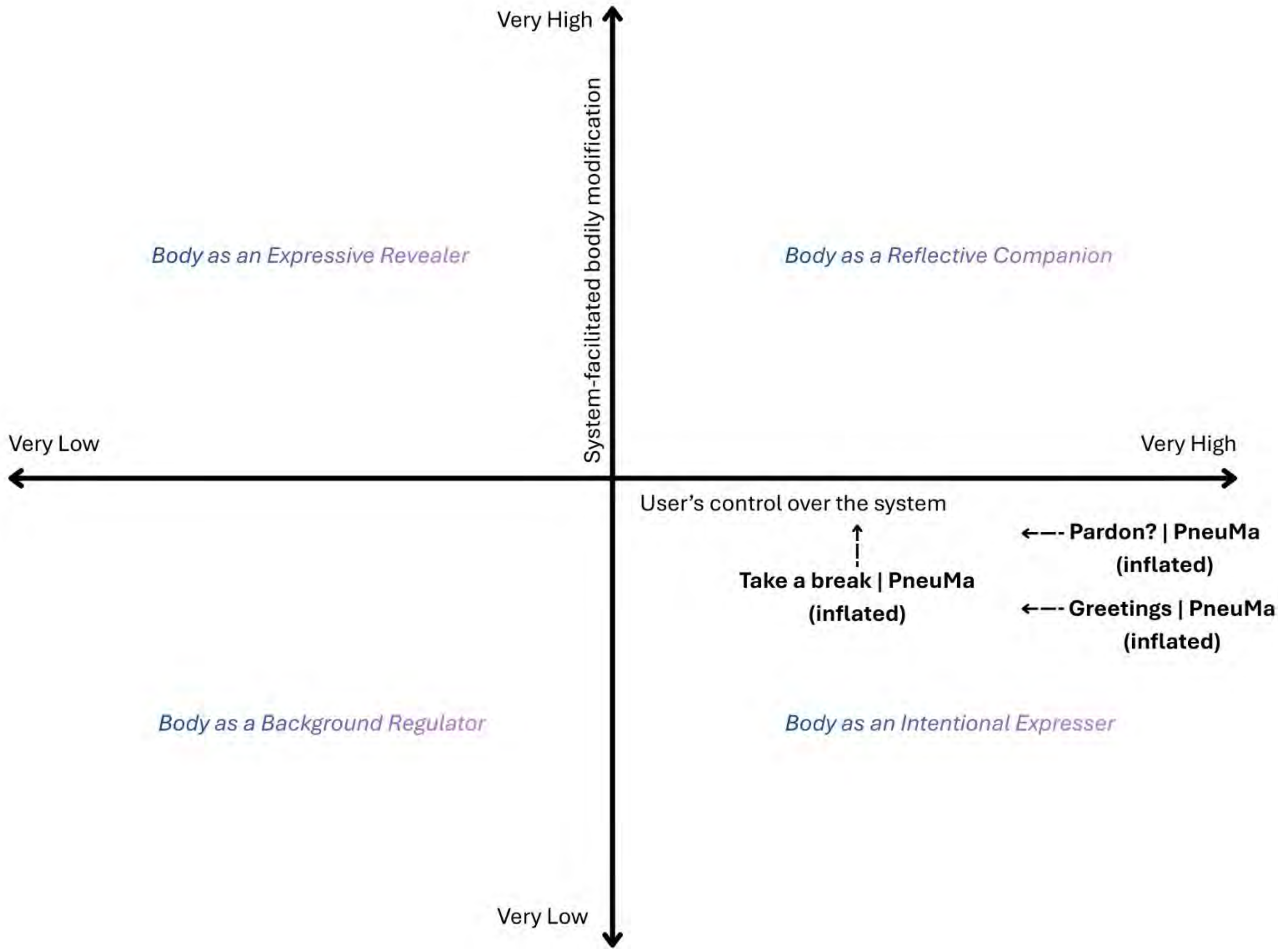

Figure 46: Situating PneuMa bodily extensions in the bodily extensions framework.

PneuMa's three bodily extensions can be understood as primarily occupying the lower-right region of the design space (Figure 46), which is characterised by high user control over the bodily extension and relatively limited bodily modification facilitated by the extension. Users exercised clear agency over when and how actuation occurred, via their use of voice commands or timed interactions to control the bodily extensions. This experience of high control positioned the user as the primary initiator of movement, while the bodily extension served as an intentional expresser that affected bodily modification only when called upon.

At the same time, the bodily modification of PneuMa was intentionally subtle. The pneumatic extensions were designed to prompt or accompany movement without demanding sustained attention or significantly reshaping the body. Participants described the extensions as integrating smoothly into everyday activities and offering gentle prompts for movement. As such, PneuMa offers an experience in which explicit control does not necessarily lead to strong bodily transformation, placing it in the *Body as an Intentional Expresser* region of the design space.

Extending PneuMa Through the Framework

Using the framework, PneuMa could be extended from the lower-right region towards the upper-right ("Take a break") or lower-left ("Greetings" and "Pardon?"). For instance, prolonging actuation could encourage users to attend more closely to bodily sensations by making a more pronounced attempt to draw the user's attention, thereby shifting the experience towards the Body as a Reflective Companion region. Alternatively, reducing explicit triggers and introducing implicit coupling, such as introducing EMG-based (electromyography) (Kaneko, 2008) sensing for the "Greetings" and "Pardon?" bodily extension to pre-empt movement, or by using EEG (Electroencephalogram) (Karim et al., 2023) to sense the user's fatigue, could move PneuMa toward the left side of the design space, enabling new experiential configurations where control becomes negotiated rather than commanded.

7.4.2 Explaining Pneunocchio Through the Framework

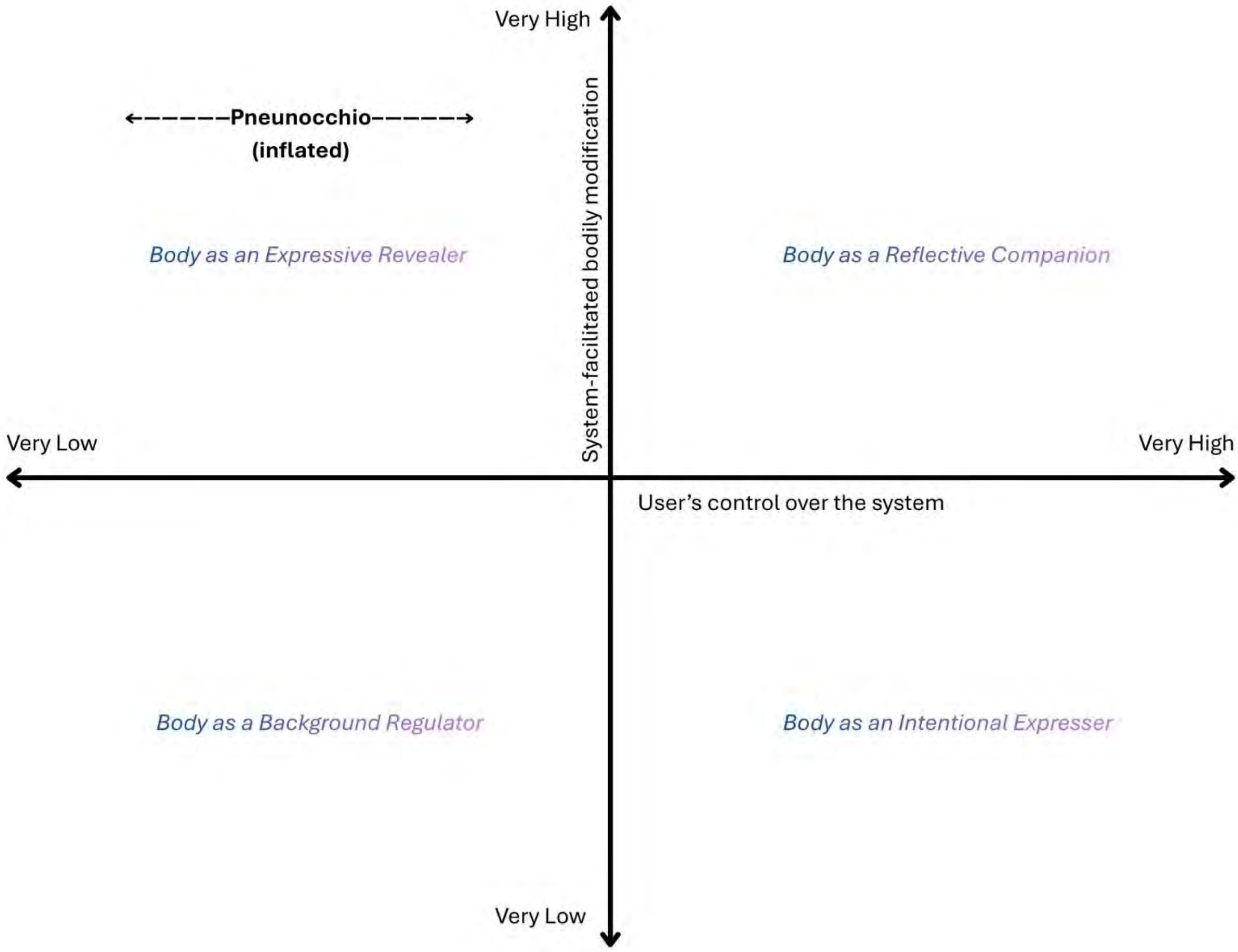

Figure 47: Situating the Pneunocchio case study in the bodily extensions framework.

Pneunocchio can be understood as a system that predominantly occupies the upper-left region of the design space (Figure 47), where the user's control over the bodily extension is limited, and the bodily extension facilitates high modification on the user's body. The system responds implicitly to physiological signals associated with stress, triggering inflation without requiring explicit user input. As a result, users are not able to directly decide when or how the bodily extension actuates.

Despite this limited user control, the bodily modification afforded by Pneunocchio is substantial because the exaggerated inflation of the nose makes internal physiological states publicly visible in playful, provocative, and sometimes vulnerable ways.

The bodily extension does not merely communicate information; it actively reshapes how users are perceived and how they experience their own bodies in social contexts. Over time, participants reported becoming increasingly attuned to the bodily and social implications of inflation, which indicated that the extension had a strong influence on bodily awareness.

Extending Pneunocchio Through the Framework

The framework allows designers to explore alternative trajectories for Pneunocchio by redistributing influence (both users' control and bodily modification facilitated by the system). For example, introducing moments of explicit user intervention, such as allowing users to delay or modulate inflation by guiding the inflation of the nose, could shift the system further right in the design space, creating a more negotiated relationship between user and extension. Conversely, amplifying the autonomy of the system, or increasing the visibility and duration of inflation (for example, absurdly lengthening the inflated nose), could push Pneunocchio further left into the Body as an Expressive Revealer region, intensifying its social and bodily impact. These ideas illustrate how the framework can be used to come up with design variations of these bodily extensions.

7.4.3 Explaining Pneumusculus Through the Framework

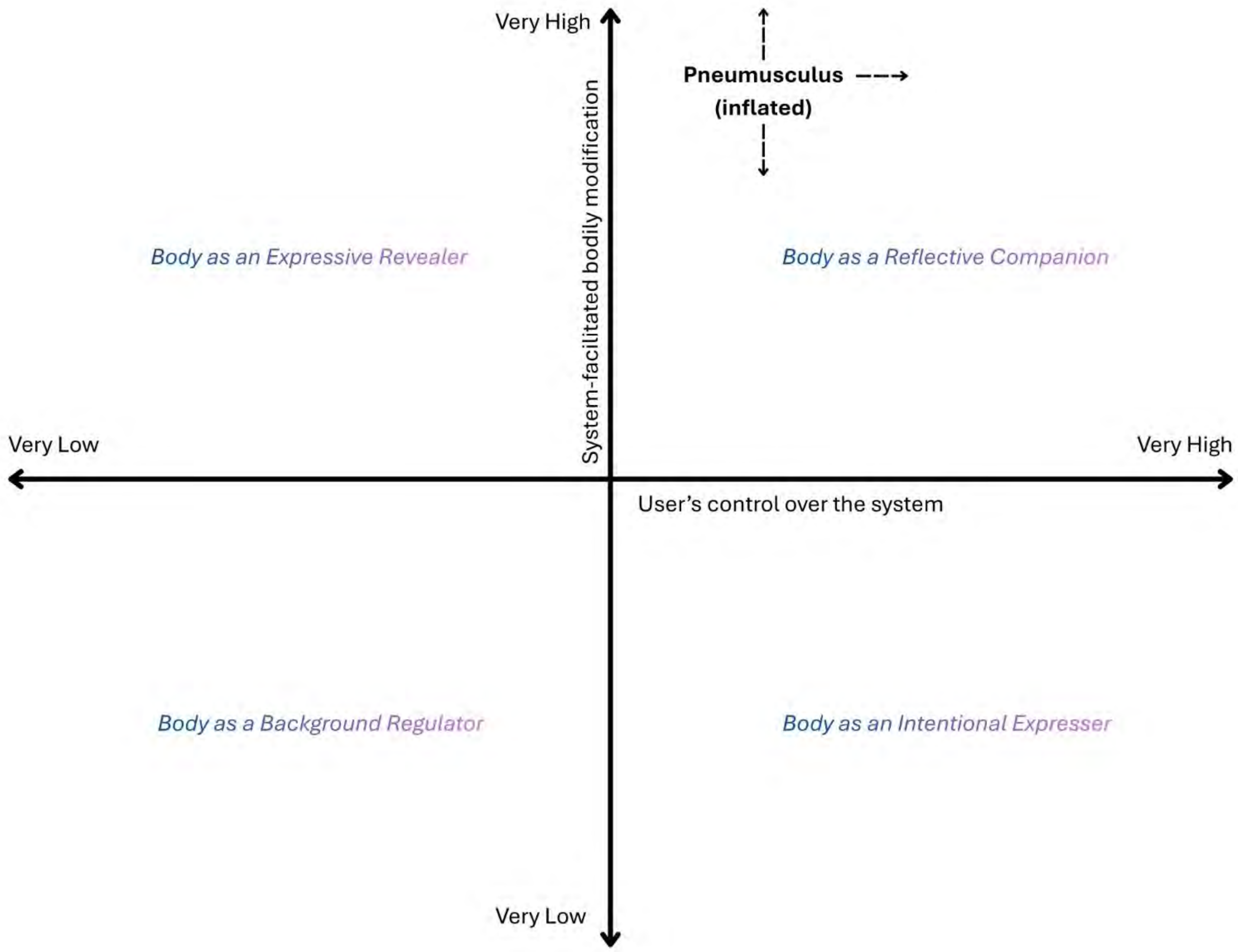

Figure 48: Situating the Pneumusculus case study in the bodily extensions framework.

Pneumusculus sits in the upper-right quadrant of the design space (Figure 48). Although the inflation of Pneumusculus is driven implicitly by accumulated physical activity data, users experienced a strong sense of control because the extension's behaviour was a direct outcome of their own actions over time. The system does not require moment-to-moment commands; instead, it reflects sustained bodily effort through gradual pneumatic inflation.

The bodily modification of Pneumusculus is pronounced. By translating abstract physical activity metrics into tangible bodily change, the extension reshapes the body, making exertion visible and felt rather than merely quantified. The gradual nature of pneumatic inflation reinforces this effect, as bodily change unfolds over time rather than instantaneously. Participants reported becoming increasingly aware of their physical activity through the presence of the inflated extension, positioning Pneumusculus as a bodily extension that both reflects and reshapes lived bodily experience.

Extending Pneumusculus Through the Framework

Using the framework, Pneumusculus could be extended in multiple directions. Increasing opportunities for explicit user intervention could shift the system further toward explicit control while maintaining bodily impact. For example, users could be allowed to manually modulate inflation, and the user could be prompted to give their permission before each inflation cycle. Alternatively, designing for slower deflation or cumulative, multi-day inflation could amplify the temporal dimension of bodily influence. For example, users could be allowed to carry over the Pneumusculus' inflation (progress) to the next day, reinforcing long-term bodily reflection. Conversely, reducing the visibility or tactility of inflation could reposition the system toward the *Body as an Intentional Expresser* quadrant, offering embodied feedback that remains present yet unobtrusive. For example, the singular inflation location could be replaced by multiple smaller locations across the user's body.

7.5 Design Strategies

Based on the craft knowledge gained from designing the bodily extensions in this thesis, this framework also includes a set of strategies aimed at helping designers of future bodily extensions facilitate similar user experiences discussed above.

These design strategies aim to support designers who do not know where to start. The strategies are not prescriptive or exhaustive rules but guiding principles that articulate how different experiential regions can be supported through design decisions. The designers do not have to follow all of the strategies, nor must they follow them in any particular order.

7.5.1 Designing for the Body as an Expressive Revealer

Systems in this quadrant respond directly to bodily signals and often operate without explicit user input. Designers should therefore consider how such interactions are framed: exaggeration, playfulness, and material expressivity can soften vulnerability and invite social interpretation, whereas overly precise or clinical representations may amplify discomfort. The bodily extension should convey something about the user, without necessarily revealing everything, thereby allowing ambiguity and interpretation to remain part of the experience.

At the same time, designers must consider the ethical implications of limited user control. As bodily extensions reveal aspects of the user without their explicit consent, considerations of reversibility, temporality, and contextual constraints become important. For example, in Pneunocchio, participants indicated that, by framing nose inflation as a playful exaggeration, the bodily extension sometimes facilitated social interaction marked by curiosity (section 6.5). Therefore, such designs are less concerned with instilling control and more focused on inviting users to reflect on how changes in their bodies and emotions are made publicly visible through technology.

"Consider designing bodily extensions as exaggerations of existing body parts." (DS 1)

7.5.2 Designing for the Body as a Background Regulator

Designers focusing on this quadrant might benefit from aiming for low-intensity, non-intrusive actuation that remains available without becoming dominant. Pneumatic systems, in particular, can offer opportunities for such actuation that can fade into the background while still influencing the body. An extreme example of this characteristic could be a hidden location, requiring the user to actively seek out the transformation. While the designs in this thesis did not appear to facilitate such user experiences, an inference can be made from the results of the PneuMa study on the "Take a break" bodily extension (section 4.6). Participants in that study highlighted that the extension "*did not feel distracting,*" and "*forgot about the extension when I started working*". Based on these results, if the inflation in "Take a break" was made more gradual and was located at a place away from the user's view, the experience would shift towards the *Body as a Background Regulator* quadrant. Therefore, instead of a visible location on the body, these systems could allow users to forget about the extension until they make an explicit effort.

However, this invisibility may come with risks of its own. Systems that remain hidden may undermine users' awareness of technological influence, potentially limiting trust or accountability. Designers should therefore consider subtle reminders or periodic disclosures that re-establish the presence of the bodily extension without overwhelming the user. The goal of Body as a Background Regulator design is not absence but supporting bodily experience by maintaining favourable conditions rather than provoking transformation.

"Consider designing for bodily locations that are away from the user's view." (DS2)

7.5.3 Designing for the Body as a Reflective Companion

Based on the lessons learned from designing the systems studied in this thesis, designers are advised to create mappings that are learnable and responsive, thereby enabling users to intentionally shape an extension while experiencing meaningful bodily modification. Gradual actuation can be particularly important because it allows bodily change to unfold over time rather than appear instantaneously. Pneumatic bodily extensions are particularly well-suited to this quadrant because inflation and deflation introduce temporal dynamics that mirror bodily processes, such as fatigue or exertion. For example, the results of the Pneumusculus study (section 6.6) indicated that participants appreciated the inflation of the bodily extension, allowing them to take "a pause" and reflect on their own actions throughout the day.

Reflection is central to this experience. Designers should consider how bodily extensions can prompt users to notice, interpret, and re-evaluate their bodily state without prescribing meaning too rigidly. The extension should neither disappear into transparency nor dominate attention; instead, it should remain present as a companion that invites reflection through sustained bodily engagement. The design goal is not efficiency but understanding, thereby supporting users in developing a richer relationship with their bodies.

"Consider designing bodily extensions that respond to accumulated input." (DS3)

7.5.4 Designing for the Body as an Intentional Expression

Based on the results of this thesis, designers are advised to prioritise clarity, responsiveness, and intentionality when designing for Intentional Expresser experiences. Designers should ensure that input–output mappings are legible and reliable, thereby reinforcing the user's sense of authorship over the extension's behaviour. This quadrant is particularly appropriate when designers aim to support expressiveness, performance, or momentary interaction without demanding deep bodily reflection.

More importantly, relatively low bodily modification facilitated by the system should be understood as a deliberate design choice rather than a limitation. In many everyday contexts, users may prefer bodily extensions that integrate smoothly without drawing sustained attention or disrupting experience. For example, the results of the PneuMa study (section 4.6) indicated that participants felt the bodily extensions were *"really accurate, direct, and helpful"*. Designers can support these experiences by limiting actuation duration, reducing physical intensity, or placing extensions in locations that minimise interference with daily movement. Furthermore, the design of bodily extensions could allow users to suppress or ignore their responses to limit disruption. For example, a participant from the field study (section 4.6) noted that *"the choice to ignore or just not initiate"* the response felt *"reassuring"*. Therefore, the design goal of Intentional Expresser experiences is not transformation, but control, thereby allowing users to act through the bodily extension without being acted upon by it.

"Consider designing for body locations where the bodily extension's response can be suppressed or ignored." (DS 4)

7.5.5 Designing for Trajectories

Across all of the user experience quadrants, a key design insight is that bodily extensions should be designed for movement through the design space, rather than for static placement within a single quadrant. This insight is particularly evident for pneumatic bodily extensions, whose material properties inherently introduce temporal delays because injecting or releasing air usually takes time (especially compared to the screen, which is dominant in HCI (Petty &

Benedicenti, 2010) and can change output within commonly less than 10 milliseconds). Moreover, the responses of the bodily extension may be considered inappropriate by the user or an onlooker in certain social contexts because they might induce feelings of vulnerability for the user. For example, participants in the Pneunocchio study (section 5.6) indicated that the bodily extension would prompt a feeling of "*nakedness*" in front of strangers. This user experience could be mitigated by allowing Pneunocchio to adapt its response to the user's social context. This adaptation could be achieved by adding an option that lets the user select the level of *"vulnerability"*.

Designers should consider how bodily extensions transition between everyday social and personal contexts, and how to enable the user experience to move between quadrants. By designing for trajectories rather than endpoints, bodily extensions can support more adaptable experiences that evolve alongside the user's body and everyday life.

"Consider designing bodily extensions that transition between social and personal contexts." (DS5)

7.6 Conclusion of the Chapter

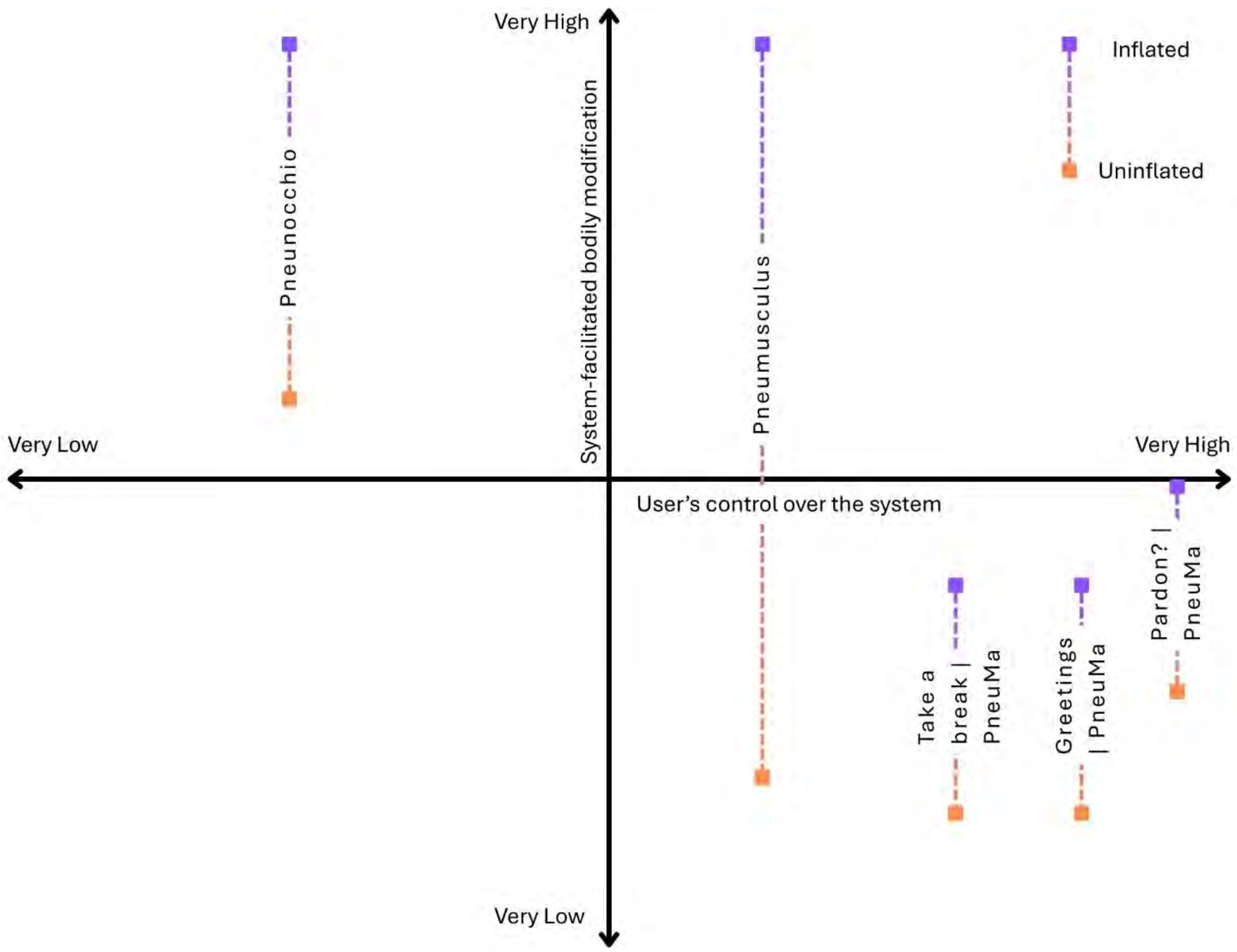

Figure 49: The bodily extensions framework with the bodily extensions from the three case studies.

This chapter synthesised insights from the three case studies into a unified framework (Figure 49) for understanding and designing bodily extension that promotes embodiment in everyday life. By conceptualizing bodily extensions as systems situated within a design space defined by user control over the system and system-facilitated bodily modification, the framework provides a structured lens through which we can examine how embodied experiences emerge. The framework, therefore, functions as an initial contribution: offering conceptual clarity and design guidance for designing bodily extensions.

Next, chapter 8 reflects on the limitations of the framework and the thesis, outlines directions for future research, and identifies opportunities to extend and refine this research.

CHAPTER 8: LIMITATIONS AND FUTURE WORK

8.1 Overview

This chapter reflects on the limitations of the research presented in this thesis and outlines opportunities for future work. Section 8.1 provides an overview of the chapter. Section 8.2 positions the thesis by defining its research scope and by framing the boundaries within which the contributions should be interpreted. Sections 8.3, 8.4, and 8.5, respectively, discuss the technical, methodological, and conceptual limitations of the research. Rather than treating these limitations solely as shortcomings, this chapter uses them to identify directions for future research, outlined in Section 8.6.

8.2 Research Scope

The scope of the thesis was intentionally exploratory rather than evaluative or prescriptive. The bodily extensions presented were not positioned as finished products, medical devices, or behaviour-change interventions. Instead, they functioned as research instruments that aimed to understand the experiential qualities of bodily interaction that are difficult to access through abstract representations or short-term laboratory studies. Consequently, the findings emphasise experiential richness, interpretation, and design insight rather than generalizable behavioural outcomes.

This positioning of this research necessarily introduces boundaries. The thesis prioritises felt experience over performance metrics, everyday appropriation over controlled task performance, and qualitative understanding. While these choices limit generalizability, they enable the investigation of embodiment as a lived, situated phenomenon, which is an approach consistent with embodied interaction and soma design research in HCI (Dourish, 2001; Höök, 2018, 2016; Kirsh, 2013; Svanæs, 2013). Therefore, the discussion of limitations in the following sections should be understood as reflections that shape both the contributions and the opportunities for future work, not as flaws.

8.3 Technical Limitations

Across the case studies, the implementation of pneumatic bodily extensions revealed a set of technical constraints that shaped the resulting user experiences. The bodily extensions relied on external pneumatic controllers, air tubing, and battery units housed in waist bags. While these configurations enabled reliable actuation and supported week-long field deployments, their combined weight (approximately 0.7–0.9 kg) occasionally affected participants' comfort and freedom of movement, particularly during more physically dynamic activities, such as exercise. Therefore, although pneumatic actuation enabled soft, body-conforming design, the supporting hardware constrained wearability and mobility in some situations. Future work could investigate miniaturised pneumatic controllers or alternative power solutions to reduce these burdens.

Material choices also introduced fabrication challenges. While polyethylene (PE), polyvinyl chloride–coated nylon (PVC), and silicone were selected for their softness and capacity to conform to the body, each material choice introduced trade-offs. Silicone-based inflatables (used in PneuMa) provided rich tactile sensations but were prone to fabrication inconsistencies due to manual moulding processes, as noted in prior work (Moradi & Torres, 2020). PE-based inflatables (used in Pneunocchio) offered lightweight alternatives but demonstrated reduced durability across repeated inflation cycles, occasionally resulting in minor air leaks. PVC-coated textiles (used in Pneumusculus) improved robustness but introduced sewing-related variability during fabrication. Emerging fabrication techniques, such as multi-material additive manufacturing (Everitt et al., 2022) and woven pneumatic textiles (Ojala et al., 2025), present promising directions for addressing these limitations.

The responsiveness of pneumatic actuation required further design trade-offs. For example, Pneunocchio employed a delayed inflation (10 seconds) strategy to encourage reflection on physiological processes, whereas Pneumusculus relied on periodic inflation to support cumulative interpretation of physical activity. While these temporal strategies successfully shaped reflective engagement, they also introduced ambiguity regarding causality. Participants occasionally struggled to identify which bodily events triggered specific actuations. This tension between actuation and reflection highlights an opportunity for future systems to incorporate adaptive responsiveness, thereby allowing users to modulate temporal behaviour to suit different experiential goals.

Finally, the sensing pipelines posed additional challenges. Pneunocchio relied on heart rate and electrodermal activity sensing, which are susceptible to noise and contextual interference, while Pneumusculus relied on commercial smartwatch data, limiting control over sensing fidelity. Future work could explore custom or hybrid sensing systems that integrate multiple data streams to improve robustness.

8.4 Methodological Limitations

Each case study involved 12 participants over a seven-day field deployment, aligning with exploratory research practices in HCI (Caine, 2016). While this approach provided in-depth qualitative insights into experiences with bodily extensions, the relatively small and demographically narrow sample (predominantly young adults aged 20–35) limited the broader generalizability of the research findings. Some participants' familiarity with experimental technologies and physical comfort with wearables may have influenced their receptivity to the unconventional nature of the bodily extensions. Future studies could include a wider range of ages, body types, and levels of experience with experimental technologies and wearables to better understand how bodily extensions are perceived across diverse populations.

The seven-day study duration for each case study provided insights into appropriation and reflection but did not capture longer-term processes, such as habituation, normalization, or long-term shifts in body schema. Prior research suggests that bodily adaptation and social normalization may only emerge through prolonged engagement (Harrison et al., 2014). Longitudinal studies extending over months or even years could therefore offer a deeper understanding of how bodily extensions become integrated into everyday bodily experience.

The open-ended nature of the field studies allowed participants to use the bodily extensions across varied contexts, which generated rich experiential accounts (Oulasvirta, 2009; Rek et al., 2013; Wong & Blandford, 2003). However, this contextual variability complicated systematic comparison across participants and situations. Future work could combine open-ended field studies with structured lab studies in specific contexts to balance ecological validity with comparative rigour.

Finally, the bodily extensions framework has not been formally validated. Consequently, the framework should not be interpreted as a definitive or exhaustive model of bodily extension experiences, nor as a predictive tool applicable across all forms of embodied interaction.

8.5 Conceptual and Theoretical Limitations

The thesis is grounded in theories of embodied interaction and embodied cognition (Dourish, 2001; Kirsh, 2013), and draws upon phenomenological perspectives (Merleau-Ponty, 1962; Svanæs, 2013) to interpret participants' first-person experiences. While this framing effectively supports analysis of bodily awareness and reflection, it places less emphasis on the broader sociocultural, ethical, and intersubjective dimensions of embodiment. For instance, while Pneunocchio and Pneumusculus elicited socially situated responses, the analysis did not deeply examine how cultural norms or gendered interpretations of bodily extensions unfold. Future research could incorporate feminist (Strengers et al., 2021), post-phenomenological (Ihde, 2017), or critical perspectives (Han et al., 2016) to address these dimensions.

Furthermore, a key conceptual limitation of this work is an emphasis on a more literal symbolic mapping, such as associating nose growth with lying. While such mappings have been designed through a playful, ambiguous lens to elicit novel user experiences, they may constrain interpretation. This suggests that future work could explore less culturally significant expressions that enable more open-ended bodily vocabularies.

The framework developed in this thesis conceptualises bodily extensions as reciprocal systems in which both the user and the extension influence one another. However, the bodily extensions themselves did not exhibit adaptive or learning behaviour; their responses were reactive rather than evolving. While this limitation does not undermine the framework's validity, it does clarify its current scope: the framework aims to articulate experiential dimensions of wearing bodily extensions. Future work could extend this foundation by implementing adaptive or closed-loop systems that learn from users' bodily patterns over time.

A further conceptual limitation lies in the broad treatment of "everyday life." While the case studies spanned work, social, and leisure contexts, the analysis did not systematically differentiate between these domains. Future work could focus on specific settings, such as workplaces or commuting, to examine how bodily extensions can be used in different contexts.

8.6 Future Work

The limitations identified in the earlier sections present several opportunities for future work beyond the ones noted above. First, advancing the technical design of pneumatic bodily extensions remains a significant opportunity. Future work could investigate fabric-based or textile-integrated pneumatics that embed air channels within garments, thereby enabling lightweight, air-tubeless implementation.

Second, understanding social and multi-user engagement with bodily extensions could yield new insights. The results of the Pneunocchio case study indicated that bodily extensions could act as a *social organ*, eliciting reactions from bystanders and shaping interpersonal engagement. Building upon this finding, future implementations could explore synchronised bodily extensions across multiple users, creating shared experiences. Such systems could help us understand how connected bodily extensions, and thereby connected users, perform in currently underexplored scenarios.

Furthermore, the framework could be extended by incorporating additional dimensions, such as those along the public-to-private, overt-to-subtle, and literal-to-ambiguous continua. In addition, future work could examine how social dimensions could inform control, for example, if environmental data influences the shape of the bodily extension, or if groups of people control someone's bodily extension(s) (Ilstedt, 2003). Moreover, such dimensions could also be concerned with aspects of subtlety and privacy, considering that the design explorations often involved wearing the bodily extension under clothing. This could be, for example, captured in a dimension concerned with public and private experiences, reflecting that some of the experiences described earlier were rather public and performative, while others were more private and introspective. The same could be said about literal versus ambiguous mappings.

Another avenue for future work is to explore what more refined versions of the prototypes might look like if designed for everyday use. For example, advancing engineering efforts could result in quieter, smaller, and more wearable form factors that could support different use cases and also allow investigation of usage changes over time.

Future work could also investigate additional opportunities across various application domains. For example, the knowledge presented could inform the design of bodily extensions to support arts practice, assist in physical rehabilitation, aid gait alterations for health, support dance training, etc. Specifically, the role of bodily extensions in regards to arts practice that explore the coming together of the artists' body and a computational wearable or shape-changing technology (*STELARC | EAR ON ARM*, 2008). Moreover, the use of bodily extensions in more "serious" contexts is another area that could be studied. For example, what happens to bodily extension experiences during job interviews, dating, or interactions with strangers?

Another area for future research is a discussion of the mechanical and material contexts of pneumatics as a design medium. In particular, as pneumatics usually require a specific mechanical system, future work could focus more on these systems' advantages and limitations. Such reflections would most likely also include discussions of the actuation infrastructure, including trade-offs between compressed-air systems and individual pumps, as well as guidance for designers on choosing between different pumps or electrical systems. The same applies to helping designers consider the noise of the pumps, tubing materials, the range of the bladder's expansion, etc.

Furthermore, future work could explore bodily extensions with mappings that go beyond symbolic ones and allow for more playful and ambiguous interpretations, potentially resulting in, for example, ripples, bulges, or striations on parts of the body, opening up novel and emergent interpretations. Such investigations could also consider different ways people might want to change their bodies, such as puffing out their chests, altering their height, or pushing their shoulders back. This might also lead to a better understanding of which body locations are most suitable for different kinds of bodily extensions.

Finally, further validation is needed to consolidate the framework emerging from this thesis. Future work could apply this framework as an analytic lens to other bodily extension studies or empirically examine whether designers and users interpret experiences in ways that align with the proposed dimensions and quadrants. These validation efforts could help clarify the framework's transferability while preserving its role as a flexible, design-oriented contribution rather than a fixed taxonomy. For example, future work could validate the framework by making it available to designers and asking them to report on how useful they found it in their practice.

CHAPTER 9: CONCLUSION

This thesis investigated how bodily extensions can be designed to promote embodied experiences in everyday life. Motivated by prior HCI research, which has predominantly examined bodily extensions in constrained, task-specific, or short-term settings, this research focused on understanding how such extensions can be worn, experienced, and interpreted as part of daily routines. Through three case studies, this thesis contributes empirical insights, design knowledge, and a conceptual framework for understanding how pneumatic bodily extensions can shape embodied experience beyond momentary interaction.

9.1 Addressing the Research Question

The overarching research question guiding this thesis was:

"How do we design bodily extensions that promote embodied experiences in everyday life?"

This thesis demonstrates that embodiment emerges from experiences through an ongoing negotiation between bodily sensation, system behaviour, material qualities, temporal dynamics, and social context. Pneumatic bodily extensions enabled users to experience bodily change directly, without relying on abstract representations or screens. However, embodiment did not manifest as an immediate outcome of use. Rather, it emerged gradually, evolving as bodily extensions became a part of users' movements, environments, and social encounters. These findings reinforce the central claim, introduced in Chapter 1, that designing for promoting embodied experiences in everyday life is a non-trivial design challenge that requires attention to temporality, materiality, and lived experience and that design work should not assume that bodily extensions inherently promote embodiment.

9.2 Revisiting the Research Objectives

To answer the research question, this thesis articulated three research objectives in Chapter 1. Each objective was addressed through iterative design and empirical investigation across the three case studies.

Objective 1: “To understand how materials and actuation approaches for bodily extensions can be designed for exploration within everyday life contexts.”

The first research objective focused on understanding how bodily extensions can be designed with materials and actuation approaches suitable for everyday life. This thesis addressed this objective through extensive material exploration grounded in Research-through-Design (Zimmerman et al., 2007), iterative prototyping, and field studies.

The case studies revealed how material properties, such as softness, conformity, and durability, directly affected embodied experience. Pneumatic actuation, combined with fabrication materials, enabled gradual bodily modifications. These qualities supported comfort, wearability, and prolonged use, which are critical for everyday integration.

Through this work, materials are positioned as active contributors to promoting embodied experiences in everyday life. This reframing extends prior work by demonstrating how material choices shape functionality, along with how bodily extensions are felt and interpreted by the user over time (Buruk et al., 2023; Mueller et al., 2025).

Objective 2: “To understand how users experience, interpret, and negotiate bodily extensions.”

The second research objective examined how users interact with and perceive bodily extensions on, or as part of, their bodies. Through seven-day field studies, this thesis found that users interpret, negotiate, and attribute meaning to understand the response of the bodily extensions.

Across the case studies, bodily extensions were experienced as prompts for movement (PneuMa), expressive and social bodily signals (Pneunocchio), or cumulative representations of physical activity (Pneumusculus). Participants' experiences shifted from novelty toward familiarity and reflection, depending on context and duration of use.

These findings suggest that bodily extensions need not become fully incorporated into the body schema to promote embodiment, confirming prior theory (Buruk et al., 2023). Instead, embodiment can emerge along a spectrum between being worn on the body and being experienced as part of the body. This nuanced understanding reinforces the importance of studying bodily extensions over time and in situ.

Objective 3: "To understand how experiential insights and design knowledge derived from these investigations can inform future design of bodily extensions."

The third research objective focused on how user experience accounts and design knowledge can guide designers of future bodily extensions. This objective was addressed through reflective synthesis across the case studies, which resulted in the development of the bodily extensions framework presented in Chapter 7.

The framework structures a design space around the relationship between the user and the bodily extension. This design space specifically addresses how the system influences the body and how the body influences the system. By foregrounding this reciprocity, the framework supports reasoning about how different configurations of actuation, control, timing, and visibility give rise to distinct embodied experiences.

The framework articulates experiential dimensions; it does not prescribe fixed categories. This approach allows designers to understand the trade-offs between explicit prompting and implicit input, immediacy and accumulation, and personal versus social contexts of use. In doing so, the framework transforms situated case study insights into conceptual and design knowledge.

9.3 Contributions to Knowledge

Taken together, this thesis makes three primary contributions to Human–Computer Interaction.

First, this thesis contributes empirical knowledge about how bodily extensions are experienced when worn in everyday life over extended periods. By moving beyond laboratory settings, this work reveals that embodied experiences involve temporal, situated, and social elements.

Second, this thesis contributes design knowledge for creating bodily extensions suitable for everyday use. This thesis articulates how material choices, actuation timing, bodily placement, and degrees of control shape user experiences. These insights support designers seeking to move beyond utilitarian wearables to design for embodied experiences.

Third, this thesis offers a conceptual framework that defines a design space and provides design strategies for bodily extension that promote embodied experiences in everyday life. By explicitly addressing the reciprocal relationship between user and system, the framework offers a tool for understanding how embodied experiences can be promoted through the design of bodily extensions.

9.4 Broader Implications and Impact

Beyond its immediate contributions, this thesis has broader implications for the design and study of wearable and embodied technologies. It challenges the dominance of screen-based and data-centric wearables by demonstrating the potential of actuation-based systems that engage the body directly (Mueller et al., 2020). The bodily extensions explored here actively participate in shaping bodily experience itself rather than informing users about their bodies.

Furthermore, framing bodily extensions as expressive and experiential opens a space for more reflective relationships with on-body technology. The bodily extensions presented in this thesis encouraged attention to movement, effort, honesty, and bodily awareness without enforcing norms of utility and performance. This focus positions bodily extensions as technologies that can support reflection and self-understanding in everyday life.

9.5 Closing Remarks

In conclusion, this thesis demonstrated that bodily extensions can be designed to promote embodied experiences in everyday life by embracing soft actuation and temporality. Through bodily extensions, the body becomes not merely a site of interaction but an active participant through which experience unfolds.

As interactive technologies continue to move closer to the body, this work argues for designs that respect the complexity of lived bodily experience. It is hoped that the insights and framework presented in this thesis will support future explorations of bodily extensions that do not merely augment function but meaningfully participate in how bodies are felt, interpreted, and lived.

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