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CatLike

Emotion-Responsive Wearables

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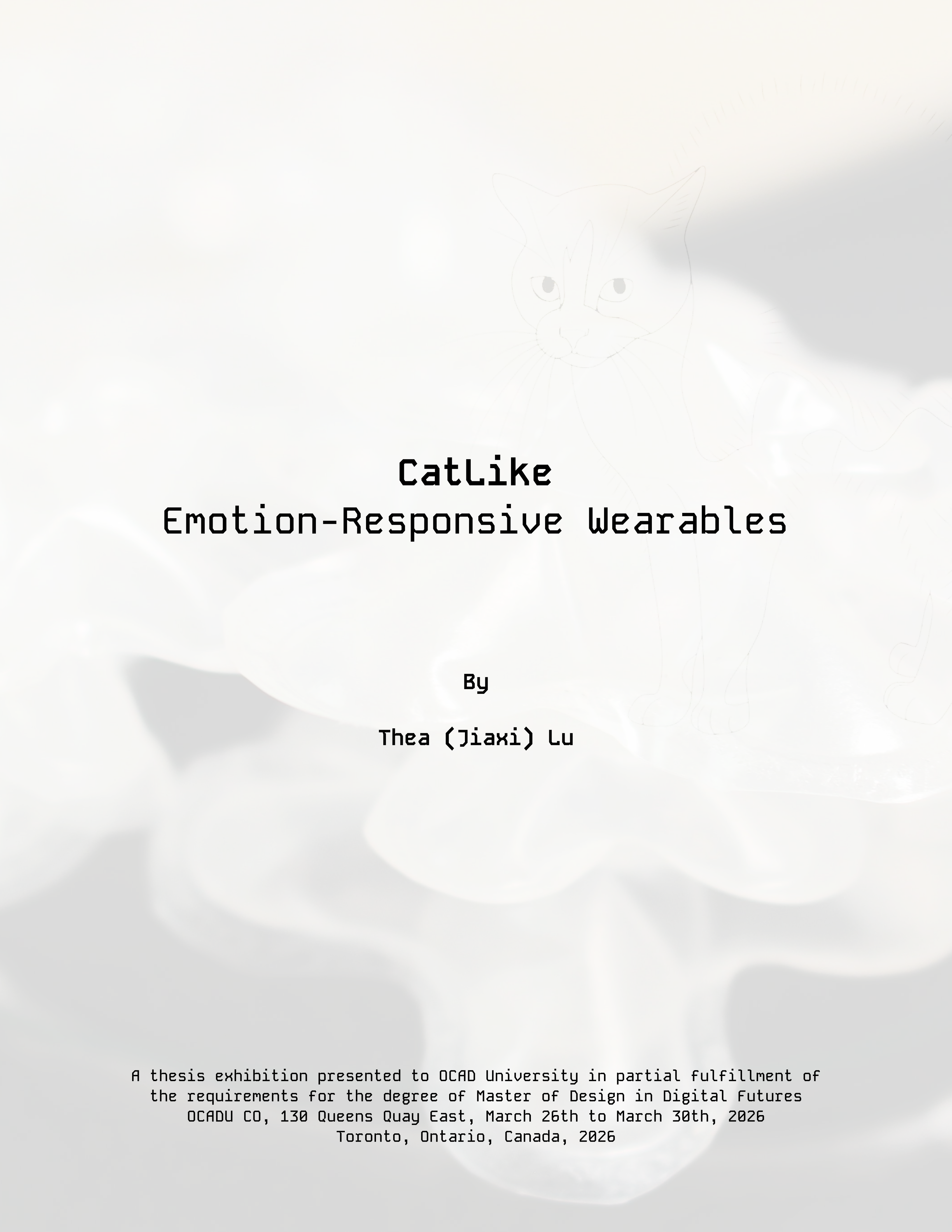
MASTER OF DESIGN · DIGITAL FUTURES



CatLike
Emotion-Responsive Wearables

By

Thea (Jiaxi) Lu

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Abstract

When words are not enough to express how we feel, the body often knows first. A racing heart, gripping toes, or a shift in posture can reveal our true feelings. *Catlike* is a Research through Design project that explores whether wearable technology can make these invisible physiological responses visible through material transformation. This research is inspired by piloerection, the involuntary rising of fur observed in cats during emotional arousal. Based on this biological reflex, the project develops two emotion-responsive wearable prototypes.

The headwear responds to heart rate variability detected at the earlobe, inflating soft robotic units at the center of social gaze. The footwear responds to plantar pressure changes detected by insole sensors, inflating units at the edge of social gaze. Both devices use pneumatic inflation of heat-sealed TPU chambers to create organic, three-dimensional shape change. The fabrication process produced three technical contributions grounded in hybrid craft: a non-destructive heat-sealing method that repurposes an unmodified consumer 3D printer through software-only G-code modification; a variable-size stacking technique for achieving perpendicular inflation movement; and a body-driven sensor layout derived from the wearer's own pressure mapping data. Both prototypes combine traditional haute couture techniques with digital fabrication.

Wearing the prototypes throughout development surfaced an unexpected finding: wearers discovered they could voluntarily activate the footwear by gripping their toes, while the headwear's heart rate signal remained outside their control. This contrast reframed signal voluntariness as a central design variable that shapes how much agency the wearer holds over the body's expression. The headwear's involuntary signal created a feeling of being passively monitored, while the footwear's semi-voluntary signal restored a sense of agency, producing playful, embodied engagement. Unintended sensory outputs, particularly the pump sound in the headwear, became unexpected triggers for emotional self-reflection. Technical failures that made the technology visible immediately redirected attention from emotion to device, confirming that concealment is a functional requirement rather than an aesthetic preference. Peers who encountered the wearables responded to them as fashion objects rather than medical devices, suggesting that fashion framing can reduce the stigma associated with body-monitoring technology.

This research contributes to the fields of wearable design, soft robotics, and fashionable technology by demonstrating that body location, signal voluntariness, and social framing are interconnected design variables that shape not only how emotion-responsive wearables function but how they feel to wear.

Keywords: emotion-responsive wearables, soft robotics, affective computing, Research through Design, biosignal sensing, fashionable technology, hybrid craft, social wearables

Acknowledgment

I am deeply grateful to my principal advisor, Kate Hartman, for her clarity, generosity, and creative trust throughout this research. She tirelessly pulled me out of rabbit holes and brought me back on track. Her willingness to follow this project into its strange corners gave me the courage to take it seriously.

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To my parents, thank you for your unconditional support across distance and time zones. Even when this research did not look like what you imagined, you trusted me to find my own way through it.

To my friends and classmates in the Digital Futures program, thank you for the studio conversations, the late-night problem-solving, and the small acts of care that made this work feel possible. Your willingness to encounter Catlike with curiosity rather than judgment shaped much of what this research became.

Last but not least, to Lu Buhei (卢不黑), my cat, who is the reason this thesis exists. Watching you bristle, stretch, and feel without apology taught me what it means to inhabit a body. This research began with you.

Land Acknowledgment

This work was developed in Tkaronto/Toronto, on the traditional territories of the Mississaugas of the Credit First Nation, and the ancestral lands of the Anishinaabeg, Haudenosaunee, and Huron-Wendat Peoples. Toronto is also home to many First Nations, Inuit, and Métis communities today.

Dedication

This thesis is dedicated to

my nineteen-year-old self,

and to those still learning to feel.

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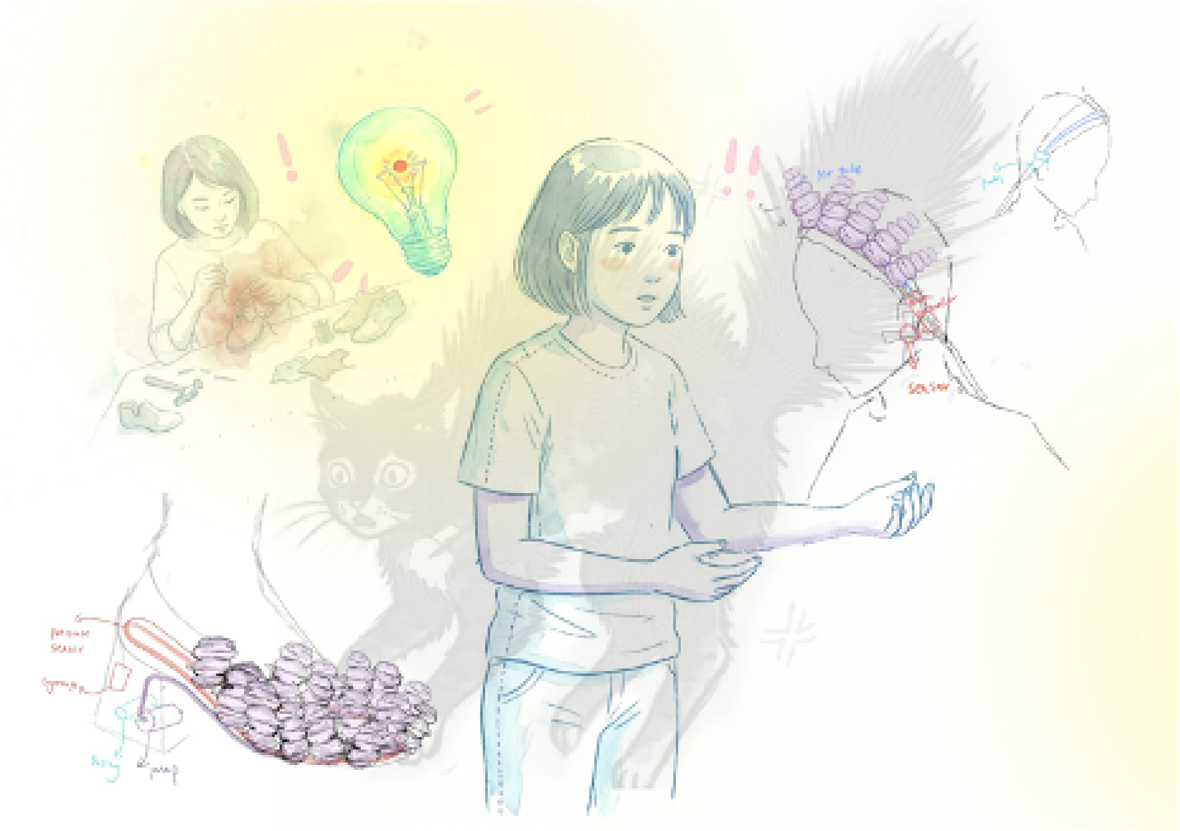
Chapter 1. Introduction

1.1 Research Context and Background



[**Figure 1.1**. The story behind Catlike: a footwear designer's craft (top left), the moment of recognizing piloerection in a startled cat (background) and in one's own body (center), and the two prototypes' sketch that emerged—a plantar pressure-responsive footwear (bottom left) and an HRV-responsive headband (top right).]

[**Figure 1.2**. Catlike on feet and on head.]

The most important lesson I have learned in adulthood is not how to succeed or how to survive, but how to feel. Growing up in an East Asian family where emotions were never the priority, I learned that emotional expression invited judgment and disrupted harmony. The safest response was silence. Learning emotional literacy as an adult meant acquiring vocabulary that others develop naturally through childhood. But even as I learned to name these states internally, articulating them to others remained extraordinarily difficult.

During the COVID-19 lockdown, living with and observing my cat, I noticed I could understand his feelings and needs even though he could not talk. When startled, his fur would stand on end. This involuntary response, known as piloerection, was first documented by Darwin (1872) as a reflexive signal of emotional arousal in mammals. The cat could not choose whether to display it. It happened automatically, making visible an internal state before any conscious decision. This observation crystallized something about my own body: it often knew what I was feeling before my conscious mind did. My heart would race during seemingly calm conversations. My toes would grip when I felt embarrassed. My pace would quicken as anxiety took hold. My body spoke a language I had never learned to hear.

Before observing my cat, before thinking about biosignals or soft robotics, I was already a footwear designer, and I still am. I dedicated nearly my entire undergraduate life to studying footwear design. I learned to make shoes from scratch: measuring the foot, drafting the pattern, lasting the upper, shaping and drying, then removing the last to reveal a finished shoe. Traditional haute couture shoemaking taught me that a shoe is one of the most intimate objects a person wears. Every curve, every material choice, every millimeter of clearance determines how the wearer moves, stands, and feels. After graduation, I worked in the footwear department of a fast fashion company. The experience was clarifying in ways I did not expect. Innovation meant copying runway designs. Creativity was not valued. The wearer's experience was not part of the conversation. When I proposed adding a foam layer to the insoles to improve comfort, the idea was rejected because it would cost fifty cents more per pair. The industry I had trained to join cared only about profit, not about the person who was wearing it. I have always believed that comfort and beauty are not a trade-off. But I also began to wonder: if a shoe already shapes how someone walks and stands, could it also respond to how they feel inside?

These two threads came together in my decision to create Catlike . On one hand, a personal need to find a nonverbal way of recognizing and communicating emotion. On the other hand, my professional belief, shaped by years of making and studying footwear, is that fashion should respond to the wearer's inner life, not just their appearance. What we wear has long been a medium of self-expression, reflecting how we construct and communicate identity through our bodies. This project asks whether that medium can go further: if biosignals like heart rate variability or plantar pressure could trigger visible material transformation in something worn on the body, clothing could become not just expressive but responsive, externalizing emotional states that the wearer may not yet have words for.

Catlike explores pneumatic inflation as "external skin" (McLuhan & Gordon, 2015): soft robotic transformation inspired by biological piloerection. Both wearables sense physiological correlates of emotional arousal through biosignals and externalize them through material transformation, turning invisible bodily changes into visible, kinetic expression. Within wearable design research, where a device is placed on the body shapes both the wearer's experience and how others perceive it (Dagan et al., 2019). The head sits at the center of social attention, where emotional displays are most visible to others. The foot sits at the edge, overlooked in social encounters but closely connected to the wearer's own bodily awareness. By designing parallel wearable devices for both locations using the same inflation mechanism, this project explores how the same outward display of emotion feels and works differently when it happens where everyone can see it and where only the wearer knows.

This project contributes to four areas. First, it extends affective computing from recognizing emotion toward externalizing it, shifting the focus from what the system detects to what the wearer and others can see and feel. Second, it investigates body location as a design variable in emotion-responsive wearables, comparing how the same mechanism produces different experiences at the head versus the foot. Third, it develops a non-destructive heat-sealing fabrication method that repurposes an unmodified consumer 3D printer for precision TPU welding through software-only G-code modification. Fourth, it combines traditional fashion craft with digital fabrication, demonstrating a hybrid approach where haute couture shoemaking techniques and 3D printing each contribute what the other cannot.

1.2 Research Questions

This thesis investigates two interrelated questions:

1. How can soft robotic materials and body-based sensors of emotional arousal be integrated at different body locations to externalize emotional states?
2. How does wearing emotion-responsive displays at different body locations (head versus foot) affect my embodied sense of self-awareness, emotional recognition, and feelings of vulnerability?

Chapter 2. Literature Review

Chapter 1 established the personal and professional motivations for this research: the difficulty of expressing emotion verbally, and the conviction that fashion can respond to the wearer's inner life. This chapter builds the theoretical foundation for that ambition across three interconnected themes. Section 2.1 draws on Merleau-Ponty's phenomenology to establish emotion as embodied experience rather than a detached mental state. Section 2.2 examines fashion theory and the role of clothing as emotional expression and social communication. Section 2.3 traces how McLuhan's concept of clothing as "extended skin" has evolved into the "datafied skin" of contemporary wearable technology.

2.1 Phenomenology of Perception and the Embodied Basis of Emotion

Merleau-Ponty's Phenomenology of Perception (1945) provides the conceptual foundation for this research: to understand emotion as a lived, bodily experience rather than a detached mental state. In his book, perception is not something the body does, but what the body is, a way of being-in-the-world. This theoretical approach is fundamental to the research, treating wearable devices as extensions of body perception. By grounding design in authentic bodily experiences, the project positions emotionally responsive wearables as an integral part of the body's expressive and perceptual field, rather than external attachment.

Merleau-Ponty challenges the Cartesian separation of mind and body by proposing that perception emerges through lived, embodied experience (Merleau-Ponty, 2002). For him, the body is not a neutral vessel or tool of consciousness but, as he writes, "The body is our general medium for having a world" (Merleau-Ponty, 2002, p. 146). Rather than observing the world from a detached standpoint, we engage it through movement, posture, and sensation. The body becomes both subject and object, capable of acting, sensing, and interpreting simultaneously (Merleau-Ponty, 2002). In this sense, emotion is not a cognitive overlay added to bodily states; it is a transformation of the bodily being itself. Fear tightens muscles and narrows spatial awareness, while calmness opens posture and breathing, each altering how the world appears to us (Merleau-Ponty, 2002).

This idea of the "lived body" (le corps propre) reframes design as a practice that begins with embodied perception (Merleau-Ponty, 2002). If the body is the first site of knowing, then wearables become extensions of perceptual experience rather than external instruments of measurement. Emotions are experienced and communicated through these bodily engagements long before they are verbalized (Höök, 2018). Merleau-Ponty's phenomenology also emphasizes intersubjectivity, our ability to perceive and understand others through bodily cues (Merleau-Ponty, 2002, p. 354). Gestures, postures, and micro-movements form a pre-linguistic language of empathy. Phenomenology thus provides a conceptual foundation for understanding how emotion, as a bodily event, might be sensed, interpreted, and externalized through material means, positioning wearable objects as potential mediators between inner experience and the shared social world.

While Merleau-Ponty's phenomenology provides the conceptual foundation, contemporary design researchers have operationalized these ideas within wearable technology contexts. Höök's (2018) Designing with the Body: Somaesthetic Interaction Design explicitly builds upon phenomenological principles to develop a framework positioning the body as both site and resource for design inquiry. Her concept of somaesthetics, drawing from philosopher Richard Shusterman's work, emphasizes the "soma" (the lived body as experienced from within) as central to interaction design. Höök demonstrates how designers can cultivate somatic awareness through first-person engagement with materials and prototypes, creating what she terms "soma-based design." This approach treats bodily knowledge not as secondary to cognitive understanding but as primary data informing the design process. Her Soma Bits project offers interactive components that allow designers to experience bodily engagements through hands-on prototyping, transforming phenomenological awareness into tangible design tools.

This first-person, embodied approach extends to understanding how wearables are experienced over time. Devendorf et al.'s (2016) study "I do not want to wear a screen" explores users' perceptions of dynamic displays on clothing, revealing tensions between technological capability and lived bodily experience. Through probing encounters with e-textile prototypes, they found that wearers expressed concerns about bodily autonomy, self-presentation, and the phenomenological experience of having one's body become a display surface. Participants described feeling that screens on clothing made their bodies into "billboards" or that the technology demanded attention that competed with their sense of embodied presence. These findings show how exploring personal experiences that focus on how people feel and perceive can reveal aspects of wearable interactions that are not obvious through simple technical analysis.

Similarly, Mackey et al. 's (2017) research, "Can I Wear This? Blending Clothing and Digital Expression," examines the lived experience of digitally expressive garments through autobiographical design methods. By wearing their own prototypes in everyday contexts, the researchers documented how digital elements on clothing affected bodily awareness, social interaction, and emotional expression. They found that wearable digital expression created new forms of bodily self-consciousness, sometimes empowering, sometimes constraining, depending on context and the nature of the expression. This work shows how phenomenological attention to wearing reveals that digital clothing is not simply "clothing plus technology" but creates fundamentally new forms of embodied experience.

What Höök, Devendorf et al., and Mackey et al. share is an insistence that wearable technology cannot be understood through technical analysis alone. The felt experience of wearing, the bodily self-consciousness it creates, and the tension between empowerment and constraint all require phenomenological attention. These perspectives inform the theoretical orientation of this thesis: understanding emotion-responsive wearables means attending to what it feels like to wear them, not just whether they function.

2.2 Fashion and Expression

If Merleau-Ponty establishes that emotion is a bodily experience, fashion theory reveals that clothing has long served as the visible medium through which that experience is communicated socially. Fashion has been understood as a system of communication through which individuals construct and express identity (Crane, 2012; Lynch & Strauss, 2023). This section examines how fashion operates as emotional expression and social language, and how contemporary perspectives are expanding that role into the domain of responsive wearable technology.

Crane (2012) situates fashion within a social-communicative framework, arguing that dress functions as "a visible form of identity" that mediates between self-perception and social interpretation (p. 4). Clothing choices are not arbitrary or purely aesthetic but reflect what she calls "a dialogue between individual self-expression and social constraint" (p. 13). Through fashion, individuals signal mood, status, and emotional attitude via color, texture, or silhouette. Emotional self-presentation becomes a key function of fashion, where garments act as mediating objects between internal emotion and external social identity. Crane also emphasizes fashion's relationship to the body, arguing that clothing constructs how individuals experience their own bodies, generating sensations of comfort, constraint, empowerment, or vulnerability. This perspective aligns closely with Merleau-Ponty's phenomenological interpretation of the body as the medium of perception: garments alter posture, movement, and tactile experience, reframing emotional experiences through material interventions.

Lynch and Strauss (2023) extend this understanding to contemporary contexts, demonstrating how fashion meaning-making has evolved through digital mediation, global cultural flows, and heightened awareness of embodied experience. They argue that fashion today operates simultaneously as personal expression, cultural commentary, and emotional communication, increasingly shaped by social media platforms that make fashion choices instantly visible and subject to rapid interpretation. This digital visibility amplifies fashion's emotional stakes, making what we wear increasingly central to how we communicate affective states in both physical and digital social spaces.

Fletcher and Tham's (2019) Earth Logic deepens this perspective by examining how fashion creates emotional relationships between wearers and garments through duration, care, and material engagement. They argue that fashion's emotional dimension emerges not only from aesthetic expression but from the embodied practices of wearing, maintaining, and living with clothing over time. This temporal and material intimacy, the way a well-worn garment conforms to the body, carries memories, or requires attentive care, generates emotional bonds that exceed fashion's communicative function. Fashion becomes not just a medium of expression but a site of emotional experience itself.

Rocamora (2017) analyzes how digital media have fundamentally altered fashion's communicative systems, arguing that mediatization processes have reconFigured the field of fashion by making production, circulation, and consumption increasingly digital and instantaneous. Emotional expression through fashion now extends beyond face-to-face interaction into persistent digital representation, where outfit choices become archived displays of past emotional states and identity performances.

Tomico et al. 's (2017) concept of "a next wave of wearable and fashionable interactions" directly addresses the convergence of fashion expression and responsive technology. They argue that wearable technology has largely failed to integrate with fashion's expressive and emotional dimensions, instead treating the body as merely a convenient location for sensors and devices. They call for a paradigm shift toward wearables that embrace fashion's aesthetic, cultural, and emotional functions, creating "fashionable interactions" that leverage clothing's existing role as identity and affect display while adding technological responsiveness (p. 2). Rather than hiding technology within garments or treating wearables as purely functional, this next wave envisions fashion-technology hybrids where material transformation itself becomes the medium of emotional communication.

Seymour's (2008) *Fashionable Technology* provides one of the earliest comprehensive frameworks for this intersection. Her chapters on "Wearable Explorations" and "Social Fabric" document how designers have treated wearable technology not as engineering problems to solve but as sites of creative experimentation where the body becomes both canvas and interface, and where what we wear can actively shape how people connect and communicate. Among the projects Seymour documents is Philips Design's Bubelle (2006), a dress that responds to the wearer's emotional state through illuminated surface patterns. Philips Design describes the approach as designing technology that is "sensitive rather than intelligent" (Seymour, 2008), using fashion as a medium for emotional research rather than treating wearables as purely functional devices. Projects like Bubelle demonstrate that the integration of sensing technology into fashion is not new, but the question of how body location, material transformation, and wearer experience interact remains largely unexplored.

These perspectives collectively establish fashion as an inherently emotional system, one that materializes, displays, and socially interprets affect through what we wear. They also reveal a trajectory: from fashion as static communication (Crane), through fashion as digitally mediated performance (Rocamora, Lynch & Strauss), toward fashion as responsive, technologically augmented interaction (Tomico et al., Seymour). The design approach described in the following chapters builds on this path.

2.3 "Extended Skin" and "Datafied Skin."

While fashion theory establishes clothing as emotional communication, McLuhan provides a framework for understanding clothing as technology itself. In "Clothing: Our Extended Skin," chapter 12 of *Understanding Media: The Extensions of Man*, McLuhan explores how clothing functions as more than merely a covering but as an extension of the skin, a technology that "amplifies or accelerates the sense of touch and heat control" (McLuhan & Gordon, 2015, p. 129). By extending the body beyond itself, clothing transforms both our relationship with the environment and the way we experience ourselves within it. For McLuhan, each medium reshapes the human sensory system; in the case of clothing, it "extends the full range of touch" (McLuhan & Gordon, 2015, p. 130), creating new boundaries between the self and the world. This transformation is both protective and expressive: clothing simultaneously "reveals the wearer's inner psychological state" while regulating their social being (McLuhan & Gordon, 2015, p. 131). McLuhan's insight positions clothing not as a passive covering but as an active mediator between internal experience and external world, a concept that becomes increasingly literal as technology enters the fabric.

Barile and Sugiyama (2020) revisit McLuhan's concept in the context of digital fashion and wearable technology. In their analysis, the "extended skin" has evolved into what they call the "datafied skin," where "the smartly clothed body produces data as well as wears the data" (Barile & Sugiyama, 2020, p. 223), turning the body into an interface where biological processes, emotions, and information flows meet. This datafied skin not only regulates temperature or texture but also translates emotional states into algorithmic patterns, giving rise to what they term "algorithmic sensibility," a form of perceiving shaped by data collection, analysis, and feedback (Barile & Sugiyama, 2020, p. 224). Within this framework, the body functions as both sensor and display, interpreting emotions through responsive, kinetic, and socially visible digital materials. They emphasize that this shift marks a significant change in how fashion communicates identity and emotion, noting that the integration of sensors, actuators, and technology allows clothing to evolve into "a communicative and relational device" (Barile & Sugiyama, 2020, p. 221) capable of expressing not only aesthetic style but also psychological and affective information. They analyze cases such as Hussein Chalayan's kinetic garments that take on physical transformations in response to narrative cues or environmental triggers, demonstrating what they describe as "the progressive integration between design innovation and increasingly elaborate storytelling techniques" (Barile & Sugiyama, 2020, p. 225), where technology amplifies emotional expression, transforming garments into expressive mediators between inner life and social space.

Together, McLuhan's "extended skin" and Barile and Sugiyama's "datafied skin" trace a conceptual evolution: from clothing as sensory extension, to clothing as data interface, to clothing as emotionally responsive mediator. This trajectory provides the theoretical frame for wearable technology that does not merely collect data about the body but translates bodily states into visible, material transformation, a principle that informs the design approach described in Chapters 4 and 5.

Chapter 3. Contextual Review

While Chapter 2 introduced the theoretical foundations for understanding emotion as embodied experience and fashion as emotional communication, this chapter looks at existing projects that directly influence this project. The works reviewed here are organized around the core design metaphor of piloerection and are evaluated through three questions: how it has been sensed, where it has been located on the body, and how it has been fabricated as a shape-change design. Section 3.1 highlights piloerection as the main inspiration for the design. Section 3.2 examines how body location affects the sharing of emotional expression through wearable devices. Section 3.3 reviews shape-shifting wearables that externalize physiological and emotional states through material transformation. Section 3.4 synthesizes these precedents to position this research within the gaps they collectively reveal.

3.1 Piloerection as Design Inspiration

Piloerection, the involuntary rising of body hair in response to emotional arousal, is the primary design metaphor organizing this project. All subsequent works in this chapter are evaluated through this lens: how closely do they approach the qualities of piloerection as a design goal?

Schoeller et al. (2019) introduce the concept of "extimacy," a framework for understanding technologies that translate internal biosignals into external visual, tactile, or sonic cues. Their research on involuntary chills, the subjective experience closely associated with piloerection, links these responses to openness, meaning-finding, and caring emotions. Importantly, chills are not consciously produced. They happen to the person, not because of them. This involuntary quality is central to the design logic of this thesis: the wearables are designed to respond to physiological correlates of emotional arousal that the wearer does not consciously control, creating externalization that is authentic rather than performed.

Darwin (1872) first documented piloerection as an involuntary emotional reflex in mammals, observing that the erection of body hair served no thermoregulatory purpose in humans but persisted as a vestigial response to states of fear, awe, and excitement. His description established piloerection as a signal that is sudden, visible, involuntary, and body-generated. These four qualities define the design goal for this project: the inflation mechanism should activate quickly, be visible to others, operate without conscious control, and originate from the wearer's own physiological state.

Projects such as Neidlinger et al.'s (2017) AWElectric have already drawn directly on goosebumps as design inspiration, using biosensors to trigger inflatable structures that simulate piloerection on the body's surface(see Figure 3.6). This work, discussed in detail in Section 3.3, confirms that piloerection is not merely a biological curiosity but a viable design goal. The question this chapter asks is what precedents inform how to sense it, where to locate it on the body, and how to fabricate it as a material transformation.

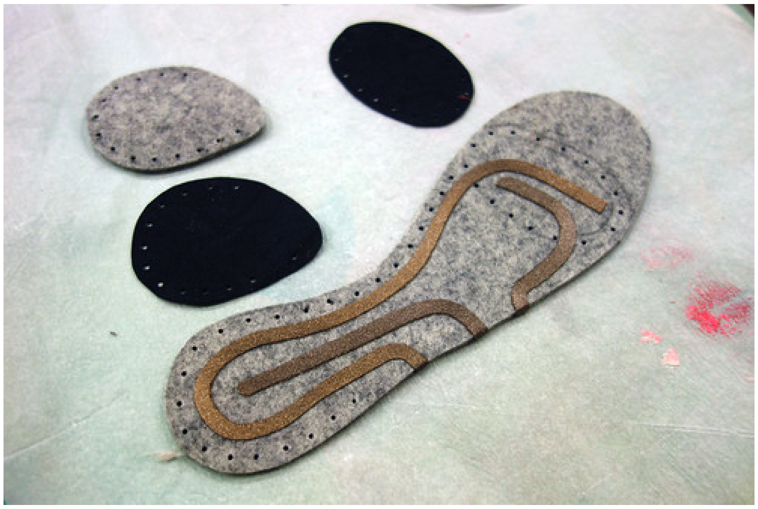
3.2 Body Location and Social Expression

Where on the body an emotion-responsive device is placed fundamentally shapes both the wearer's experience and the social dynamics it creates. This part looks at two main areas: the foot, which is hidden, subconscious, and peripheral to social attention, and the head and upper body, which are visible, performative, and socially central.

3.2.1 The Foot: Hidden Signal, Peripheral Expression

Research has shown that the foot produces physiological responses to emotional arousal that are subconscious and hard to hide or control. Elvitigala et al. (2020) demonstrated that foot pressure, center of pressure shifts, posture changes, and foot tapping can detect acute stress with 87% accuracy, noting that these foot movements are harder to consciously control than facial expressions. Cui et al. (2016) found that ankle-based accelerometry achieved 90.31% emotion recognition accuracy, outperforming wrist-based measurement, suggesting that lower-body movement provides a cleaner signal of affective state. However, existing work treats the foot purely as a diagnostic data source for medical use. Boucharas et al.'s (2022) Smart Insole, for example, uses 16 plantar pressure sensors for Parkinson's gait monitoring but does not attempt to translate that data into expressive output. These studies show that the foot can reliably reflect emotional states, but no one has yet used this information to create outward, body-worn ways of showing feelings.

Two examples of designs start to treat the foot as a way to express social signals. KOBAKANT's Sonic Insoles for Magic Shoes (Perner-Wilson & Satomi, 2017) use DIY electronic textile pressure sensors built into shoe insoles to turn foot pressure into music in real time(see Figure 3.1). This shows that the foot can be more than just a diagnostic tool; it can also be an expressive interface. Their open-source, handmade approach aligns with the idea of accessible, maker-inspired design discussed in this thesis. However, while the Sonic Insoles turn pressure into sound, they don't change the appearance or material of the body itself.



[**Figure 3.1**. Sonic Insoles for Magic Shoes, DIY e-textile pressure sensors embedded in shoe insoles for real-time music control. From "Sonic Insoles for Magic Shoes," by H. Perner-Wilson and M. Satomi, 2017 (https://www.kobakant.at/DIY/?p=6927). Copyright 2017 by KOBAKANT.]

Dagan et al.'s (2020) Flippo, a "robo-shoe-fly" designed to encourage social breaks, takes a different approach (see Figure 3.2). The device nudges the wearer via sound and light when it "needs" social interaction, and two wearers must shake feet facing each other to satisfy it. In user studies, Flippo acted as an icebreaker and conversation piece. But a key limitation emerged: the emotion belonged to the device, not the human. Participants felt a responsibility to care for the creature rather than experiencing it as an extension of themselves. This points to an important design distinction: for a foot-worn wearable to serve emotional externalization, the signal must originate from the wearer's own body, not from the device's programmed personality.

[**Figure 3.2**. Flippo, a shoe-mounted "robo-shoe-fly" designed to encourage social interaction between wearers. From "Flippo the Robo-Shoe-Fly," by E. Dagan et al., 2020, Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems. Copyright 2020 by ACM.]

Neither work uses the foot's own physiological correlates as the content of its expression. KOBAKANT translates foot pressure into sound; Flippo projects device emotion outward. The gap this thesis addresses is a system where the wearer's physiological state, captured at the foot, drives visible transformation on the foot itself.

3.2.2 The Head and Upper Body: Visible Stage, Social Gaze

The head and upper body are the primary stage of social attention, the site where faces are read, gaze is exchanged, and emotional legibility is highest. Design precedents in this zone reveal a consistent pattern: responsive wearables placed here create powerful social effects, but nearly all respond to external stimuli rather than the wearer's own internal state.

Farahi's (2015) Caress of the Gaze is a 3D-printed animatronic cape worn at the shoulder and collar(see Figure 3.3). An embedded camera detects an observer's gaze direction, gender, and age, and quills in the gazed-at area open and respond with lifelike behavior. The work explicitly references goosebumps as the mimicked response and describes the garment as "an extension of our actual skin." Importantly for this thesis, Caress of the Gaze is one of the earliest examples of 3D printing used to fabricate a responsive wearable surface, establishing a precedent for digital fabrication as a method of creating body-responsive second skins. However, its trigger is external: the observer's gaze, not the wearer's internal state.

[**Figure 3.3**. Caress of the Gaze, a 3D-printed animatronic cape with quills that respond to the observer's gaze. From "Caress of the Gaze," by B. Farahi, 2015 (https://behnazfarahi.com/caress-of-the-gaze/). Copyright 2017 by Behnaz Farahi.]

Hartman et al.'s (2015) Monarch, developed at the Social Body Lab, is the most similar prior example to this thesis (see Figure 3.4. Monarch is a shoulder-mounted wearable that uses EMG sensors on the arm to detect muscle activation, triggering pleated textile forms to expand dramatically, framing the wearer's head and amplifying body presence. The work explores how wearable technology can feel like a "visceral extension of self" and was fabricated using 3D-printed servo mounts and laser-cut leather personalized per wearer, demonstrating digital fabrication as an integrated methodology within wearable design research, not merely a production tool. Monarch shares two critical qualities with this thesis: biosignal-driven body extension for emotional expression, and 3D printing as a fabrication methodology. The key difference is that Monarch uses voluntary muscle activation. EMG detects deliberate arm contraction. This thesis extends the approach to involuntary and semi-voluntary biosignals, heart rate variability, and plantar pressure, where the wearer does not consciously choose to trigger the display.

[**Figure 3.4**. Monarch V2, a shoulder-mounted wearable with EMG-driven pleated textile forms that amplify body presence. From "Monarch: Self-Expression Through Wearable Kinetic Textiles," by K. Hartman et al., 2015, Proceedings of TEI '15. Copyright 2015 by ACM.]

McDermott's (2014) Urban Armor #2: The Personal Space Dress investigates the relationship between technology and the body in public space (see Figure 3.5). The Personal Space Dress uses an ultrasonic sensor to detect proximity, triggering servo motors to expand the skirt structure. McDermott describes these works as "extensions of the body in some way, exaggerating your own expression" (McDermott, as cited in Dezeen, 2014). Her practice integrates 3D printing and laser-cutting conductive materials, bridging digital fabrication with body-responsive wearable design. Like Farahi, the trigger is external (others' proximity) rather than the wearer's own biosignals. Together with Monarch, McDermott's work establishes digital fabrication as a legitimate methodology within wearable design research, a principle extended in this thesis's fabrication process, documented in Chapter 5.

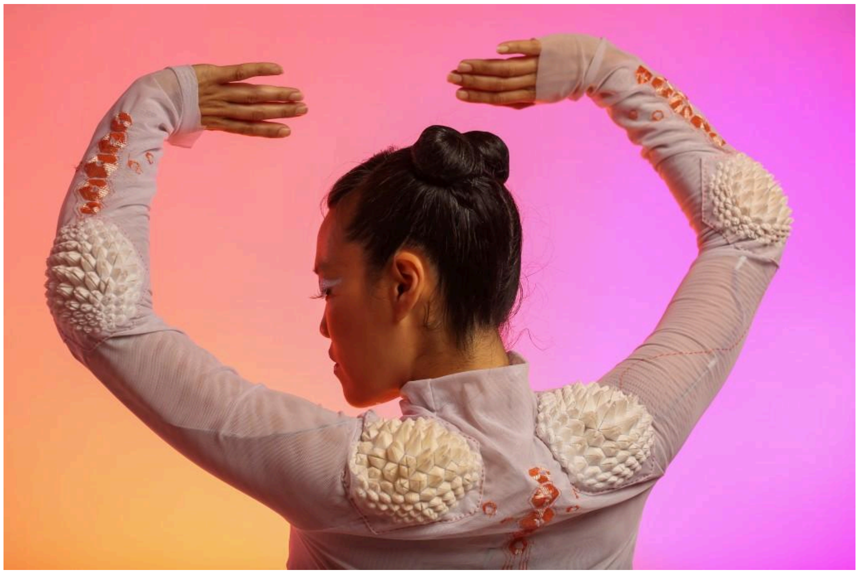
[**Figure 3.5.** Personal Space Dress from the Urban Armor series, using an ultrasonic sensor to expand the skirt structure in response to proximity. From "Urban Armor," by K. McDermott, 2013 (https://www.kthartic.com/index.php/wearables/urban-armor-2/). Copyright 2013 by Kathleen McDermott.]

The works in this section share a critical limitation: they respond to external stimuli or voluntary muscle activation. None capture involuntary or semi-voluntary internal biosignals as the trigger for visible body transformation. This thesis occupies that gap, combining the social visibility of head-located display with the subconscious quality of internally generated signals.

3.3 Shape-Shifting Wearables as Emotional Expression

A growing number of wearable designs explore shape-change as the primary medium for externalizing physiological and emotional states, moving beyond screens and LEDs toward material transformation that echoes biological responses. The works in this section share a common ambition: making the invisible visible through the body's surface.

Neidlinger et al.'s (2017) AWElectric is the most directly parallel precedent to this thesis (see Figure 3.6). Using multi-modal biosensors measuring skin response, breathing, and heartbeat, the system detects physiological correlates of awe and triggers fabric inflatable structures that expand to simulate goosebumps. AWElectric also transmits the sensation to a partner through fabric that produces vibration and sound, creating a dual function: sensing internally and sharing externally through touch. The work demonstrates that biosignal-driven inflation can serve as a medium for emotional expression. The difference from this thesis is that AWElectric does not investigate how body location affects the wearer's subjective experience of this externalization, nor does it compare multiple placement sites.



[**Figure 3.6.** AWElectric inflatable structures simulating goosebumps, activated by multi-modal biosensors detecting physiological correlates of awe. From "AWElectric," by K. Neidlinger / Sensoree, 2017 (https://www.sensoree.com/artifacts/awelectric/). Copyright 2017 by Sensoree.]

Neidlinger's earlier work, the GER Mood Sweater (Sensoree, 2013), takes a different approach to the same goal (see Figure 3.7).. Using galvanic skin response (GSR), a measure of skin conductance that increases with emotional arousal, the sweater translates arousal levels into LED color changes in a tall collar: blue for calm, red for nervousness, purple for excitement. Neidlinger positions the work as a tool that makes the wearer's internal states externally visible, offering the body a form of communication beyond words (Neidlinger, 2013). The project originated in research on Sensory Processing Disorder, a connection that resonates with this thesis's motivation in emotional recognition difficulty.

[**Figure 3.7**. GER Mood Sweater, translating galvanic skin response into LED color changes in a tall collar. From "GER Mood Sweater," by K. Neidlinger / Sensoree, 2013 (https://sensoree.com). Copyright 2013 by Sensoree.]

However, the GER Mood Sweater uses color change rather than material transformation, and its output is a visual display rather than the three-dimensional shape-change that characterizes piloerection. Table 3.1 summarizes how these works compare across sensing, actuation, body location, and expression mode, with Catlike included to highlight where this thesis departs from existing approaches.

Work	**Sensor**	**Actuator**	**Body Location**	**Trigger**	**Expression Mode**
AWElectric	GSR + breath + HR	Inflatable fabric	Torso	Physiological correlates of awe	Inflation + vibration
GER Mood Sweater	GSR (hands)	LED color	Collar/neck	Arousal level	Color change
Catlike (this thesis)	HRV / plantar pressure	TPU pneumatic inflation	Head / Foot	HRV change/pressure change	Pneumatic expansion

[**Table 3.1**: Shape-Shifting Wearables Comparison]

These studies show that shape-change, particularly inflation and surface movement, can be a valid way to express feelings and body states. However, none of them specifically explore how where the device is worn on the body affects how the wearer experiences these changes or how others respond to them socially. Both types of devices are worn on the chest or neck area. Neither looks at what happens when the same shape-changing mechanism is placed where it’s more or less in view of others. This is the design question that this thesis aims to explore.

3.4 Synthesis: Positioning This Research

The works reviewed in this chapter provide context, not conclusions. Together, they establish a design space but leave a specific intersection unoccupied.

What existing works have established: the foot produces subconscious physiological responses to emotional arousal that are difficult to consciously control (Elvitigala et al., 2020; Cui et al., 2016). Body location shapes the social dynamics of wearable expression, with the head operating as the visible stage of social gaze and the foot as its hidden periphery (Farahi, 2015; Dagan et al., 2020). Shape-change, particularly inflation, can externalize physiological states through material transformation that echoes biological responses like piloerection (Neidlinger et al., 2017; Sensoree, 2013).

What hasn't been explored yet: no existing work simultaneously uses involuntary or semi-voluntary internal biosignals, rather than external stimuli or purely voluntary activation, as the trigger for visible body transformation; investigates body location, specifically head versus foot, as a design variable affecting the wearer's experience of emotional externalization; employs a first-person reflective design practice embedded in the making process to generate embodied design knowledge; or develops accessible, non-destructive fabrication methods using unmodified consumer equipment.

Chapter 4. Methodology

The development of Catlike uses Research through Design (RtD) methodology to investigate emotion-responsive wearables across body locations. This project creates two pneumatic soft robotic inflation wearables inspired by the piloerection reaction: Heart Rate Variability (HRV) responsive headwear and pressure-responsive footwear. This chapter is structured as follows: Section 4.1 explains the Research through Design approach, including how first-person reflective practice is embedded in the making process. Section 4.2 describes how Dagan et al.'s (2019) Design Framework for Social Wearables guided the design of both wearables.

4.1 Research through Design Framework

RtD offers a different perspective from traditional scientific methods, but it works well alongside them (Zimmerman et al., 2007). Unlike scientific research, which aims to find universal truths through controlled experiments, RtD focuses on tackling what Rittel and Webber (1973) called "wicked problems": complex challenges that are difficult to clearly define. In these cases, understanding the problem and finding a solution develop together during the design process. The question of how to make physiological correlates of emotional arousal visible through wearable technology, for someone who struggles with verbal emotional expression, is precisely this kind of problem. There is no single correct solution, and gaining a better understanding of the issue emerges through trying out different ideas and learning from real experiences with the designed artifacts.

Zimmerman et al. (2007) propose evaluating RtD contributions through four lenses: how they were developed (process), how creative and innovative they are (invention), how useful they are (relevance), and how well they can be expanded or built upon in the future (extensibility). These four lenses are defined here and applied to evaluate the outcomes of this research in Chapter 7.

In order to connect biosignal sensing with soft robotic movement, this research builds on the method of "encoding materials" from Nachtigall et al. (2019). Nachtigall suggests that in digital fabrication, data and physical materials are becoming more connected. Instead of being separate, data can be directly built into how an object behaves physically. Through iterative creation of 3D-printed shoes, Nachtigall et al. demonstrated a "hybrid craft" where the physical material of the shoe was generated based on the wearer's previous movement patterns. The shoe becomes what Odom et al. (2016) call a "research product": an artifact that evolves through use.

This way of working supports the methods used in this project. Instead of viewing soft robotic pneumatic parts as simple mechanisms, this project treats them as materials that carry encoded information. This creates a direct link between data and the physical object. It is important to clarify, however, that the biosignal data (HRV from the ear, pressure patterns from the foot) are physiological correlates of emotional arousal, not direct measurements of specific emotions. HRV rising does not mean "the wearer is anxious"; it means the body is in a state of heightened arousal that may accompany various emotional experiences. This data is encoded into material deformation (pneumatic inflation), transforming physiological changes into a tangible, visible form. Chapter 5 explains how this encoding was developed step-by-step through iterative heat-sealing techniques and hardware development.

Following Gaver's (2012) annotated portfolio approach, this research provides in-depth examples of design knowledge rather than broad generalizations. The central question is not "do these wearables work?" but rather "what is it like to experience piloerection-inspired inflation on your head compared to your feet?" This approach recognizes that emotion-responsive wearables operate in personal and culture-dependent areas, where everyday experience offers important insights that controlled tests cannot fully capture.

4.1.1 Embedded Reflective Practice: Making as Wearing, Wearing as Research

The original research plan included a structured 8-day autoethnographic study across studio and outdoor environments, approved by OCAD University's Research Ethics Board (File No. 102847). Due to time constraints, this formal study was not completed. The full study protocol and REB documentation are provided in Appendix C, and a structured deployment is proposed as future work in Chapter 7.

Instead, experiential knowledge emerged from the entire fabrication process through repeated wearing and testing of prototypes over several months. This approach follows the logic of haute couture fitting: in traditional haute couture, the designer works directly on the body through cycles of fitting, adjusting, and refitting. This project followed the same pattern. As a footwear designer trained in traditional shoemaking methods, this way of working was not adopted as a research strategy but came naturally from my making practice. I am both the designer and the wearer. Each prototype version was worn, evaluated through bodily experience, and revised based on what was felt during wearing. Making and wearing were not separate phases but a single, intertwined process.

This embedded approach aligns with Nachtigall et al.'s (2019) method of wearing shoes while making shoes to inform iterative design. The designer-wearer dual role provides access to insights that external observation cannot capture, including the felt experience of technical decisions and the embodied knowledge derived from repeated fittings. Data sources include process photographs documenting each prototype version, written notes and reflections from and about fitting sessions, and peer feedback from informal demonstrations. Biosignal sensors functioned as real-time triggers only. No biosignal data was stored. The purpose of sensing was to create responsive activation, not to quantify physiological states.

Themes emerged through reflexive interpretation of accumulated wearing experiences, using Dagan et al.'s (2019) framework dimensions as analytical lenses: sensing, actuation, visibility, and personal requirements. Findings are presented in Chapter 6; framework evaluation and RtD lenses are applied in Chapter 7.

This approach has limitations that should be acknowledged. The wearing experience took place primarily in the familiar OCAD University studio, not in public spaces with unfamiliar observers. There were no structured daily sessions and no systematic alternation between devices across environments. As a single person's reflective account, the findings are not generalizable. However, the embedded approach also has strengths: it provided a longer accumulated experience than a single study period would offer; making and wearing were intertwined, producing insights accessible only through the designer-wearer dual role; and every technical decision was experienced firsthand by the same person who made it. These limitations and their implications are discussed further in Chapter 7.

4.2 Design Framework for Social Wearables

The design of both wearables was guided by Dagan et al.'s (2019) Design Framework for Social Wearables, which provided structured questions for making decisions about sensing, actuation, body location, and social interaction. Rather than prescribing specific solutions, the framework helped think through how each design choice would shape the wearing experience and social dynamics.

Both devices were designed to activate automatically based on physiological correlates without requiring conscious input, enhancing existing non-verbal social signals through pneumatic inflation inspired by piloerection. It is important to clarify that biosignals are physiological correlates of emotional arousal, not direct measurements of specific emotions. The devices detect bodily changes associated with emotional states, not the emotions themselves. Automatic activation was a deliberate design choice: if the wearer could consciously control inflation, the display would become performative rather than responsive.

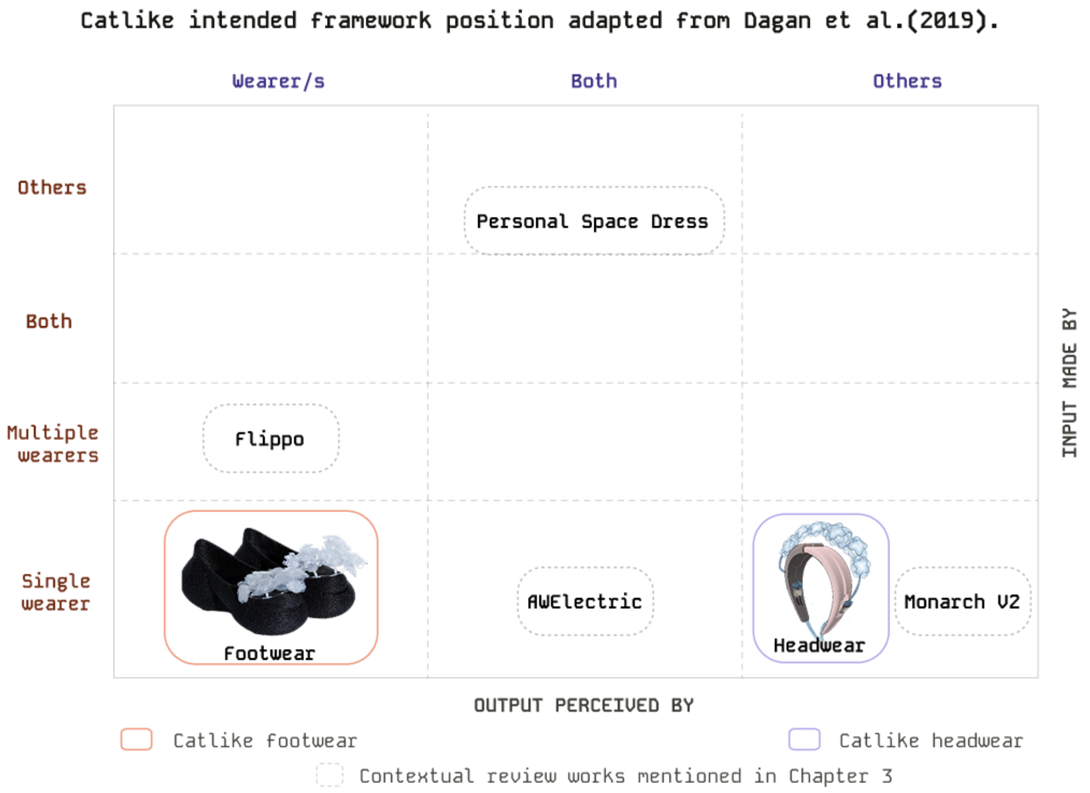
The choice of sensor for each device is determined by what each body location naturally affords. The head does not produce meaningful plantar pressure data; the foot does not offer reliable continuous HRV detection. The headwear responds to HRV changes detected by a pulse sensor on the earlobe, inflating when heart rate rises above the wearer's calibrated average. The footwear responds to plantar pressure changes detected by insole sensors, inflating when forefoot pressure exceeds a running average. This creates a natural comparison: a cardiac signal that is involuntary versus a behavioral signal that is semi-voluntary. The headwear sits at the center of social gaze; the footwear at its edge. Both use the same inflation mechanism to isolate body location as the primary variable. Table 4.1 summarizes these design choices.

Dimension	**HRV Headwear**	**Plantar Pressure Footwear**	**Rationale**
Signal	Heart rate variability	Toe-gripping, pressure shifts	Compare cardiac (involuntary) vs. behavioral (semi-voluntary)
Sensor location	Earlobe	Insole	Each location affords different sensing modalities

Visibility	High (center of social gaze)	Semi-hidden (edge of social gaze)	Compare public vs. private externalization
Communication	Outward (to others before self)	Inward (to self before others)	Contrast social vs. personal awareness
Performative quality	Expressive	Secretive	Explore transparency vs. privacy

[**Table 4.1**: Comparison of HRV-responsive headwear and plantar pressure-responsive footwear across Dagan et al.'s (2019) framework dimensions]

Figure 4.1 maps both devices onto Dagan et al.'s (2019) framework matrix alongside the contextual works reviewed in Chapter 3, showing where each device was intended to sit based on these design choices. The headwear was designed to occupy the Single Wearer / Both (expressive) position, while the footwear was designed for Single Wearer / Wearer (secretive). Whether these intended positions are held during actual wearing is examined in Chapter 6, and the framework is revisited with updated positions in Chapter 7.



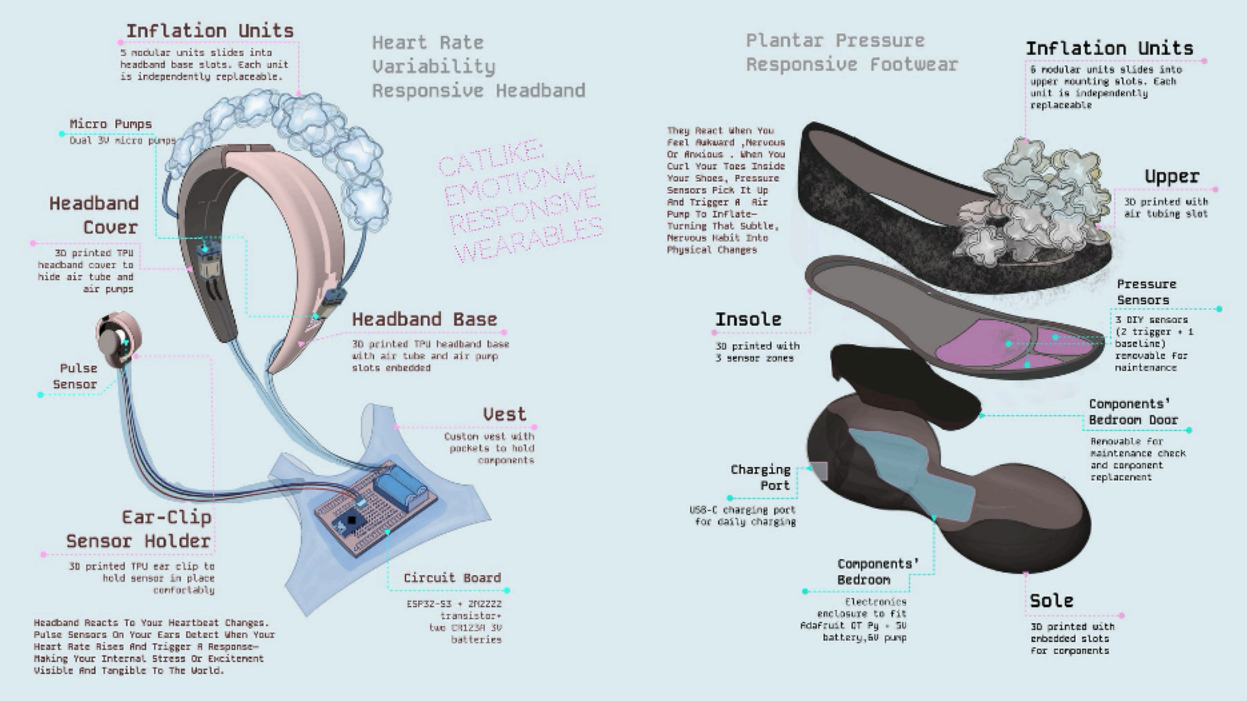
[**Figure 4.1.** Intended framework position of Catlike headwear and footwear before wearing within Dagan et al.'s (2019) Design Framework for Social Wearables, shown alongside contextual works from Chapter 3. Adapted from Dagan et al. (2019).]

These framework-guided design choices directly support the research questions: RQ1 is addressed through the technical integration of different biosignals with inflation at different body locations. RQ2 is addressed through the comparative structure that isolates body location as the primary variable. How these design intentions played out in practice is reported in Chapter 6, and the framework is used as an analytical lens to evaluate the findings in Chapter 7.

Chapter 5. Fabricating the Prototypes

5.1 Overview of Final Prototypes

This chapter documents the fabrication of two emotion-responsive wearabledesigned around a central tension: making invisible body signals visible, while keeping the technology that enables this transformation hidden. Both devices use pneumatic inflation inspired by piloerection, the involuntary rising of hair during emotional shifts, to amplify subtle, unconscious gestures into visible physical change. Figure 5.1 maps every component, sensor, and electronic part across both devices. Figures 5.2 and 5.3 show each piece worn on the body, and Figures 5.4 and 5.5 document how the headwear system connects across the body, including the component-housing vest. The fabrication processes that produced these prototypes are documented in detail in the sections that follow.



[Figure 5.1. An annotated system diagram of the two final Catlike prototypes. Left: HRV-responsive headband, with labeled components including inflation units, micro pumps, headband cover and base, ear-clip pulse sensor holder, and component-housing vest. Right: plantar pressure-responsive footwear, with labeled components including inflation units, pressure sensors, insole, sole, charging port, and electronics enclosure.]

[Figure 5.2. HRV-responsive headband worn, showing inflation units across the crown and the ear-clip pulse sensor.]

[Figure 5.3. Plantar pressure-responsive footwear worn, with inflation units expanded across the upper following toe-gripping activation.]

[Figure 5.4. Rear view of the headband, showing the pulse sensor cable routed from the ear-clip down behind the neck.]

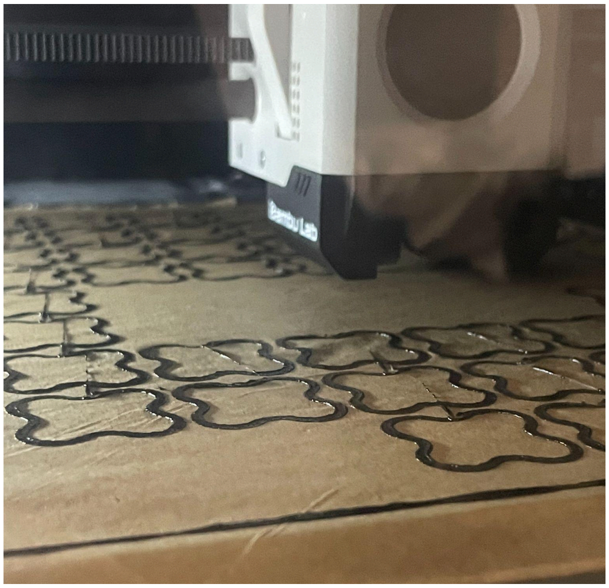
[Figure 5.5. Full headwear system worn from the rear, showing how the headband, ear-clip sensor, and component-housing vest connect across the body.]

The HRV-responsive headwear sits at the center of social gaze, externalizing one of the body's most internal signals through inflatable units that rise from the head, mimicking the bristling of fur. The plantar pressure-responsive footwear operates at the edge of social gaze, making visible the hidden body language of toe-gripping that accompanies feelings of awkwardness, unsettledness, and nervousness. Together, they explore how the location of emotional display, whether impossible to ignore or easy to overlook, shapes the experience of externalizing emotion. As an external skin (McLuhan & Gordon, 2015; Barile & Sugiyama, 2020), these wearables give physical, visible form to feelings that would otherwise remain hidden within the body.

These wearables were developed through hybrid craft (Nachtigall et al., 2019; Devendorf & Ryokai, 2015): a combination of heat-sealed TPU soft robotic fabrication, 3D printing, and traditional Haute Couture techniques, including garment draping and shoemaking. The following sections detail the heat-sealing method used to create the inflatable units (Section 5.2), the development of the headwear (Section 5.3), and the development of the footwear (Section 5.4).

5.2 Heat-Sealing Fabrication

5.2.1 Final Method: Modified 3D Printer as Heat-Sealing Device



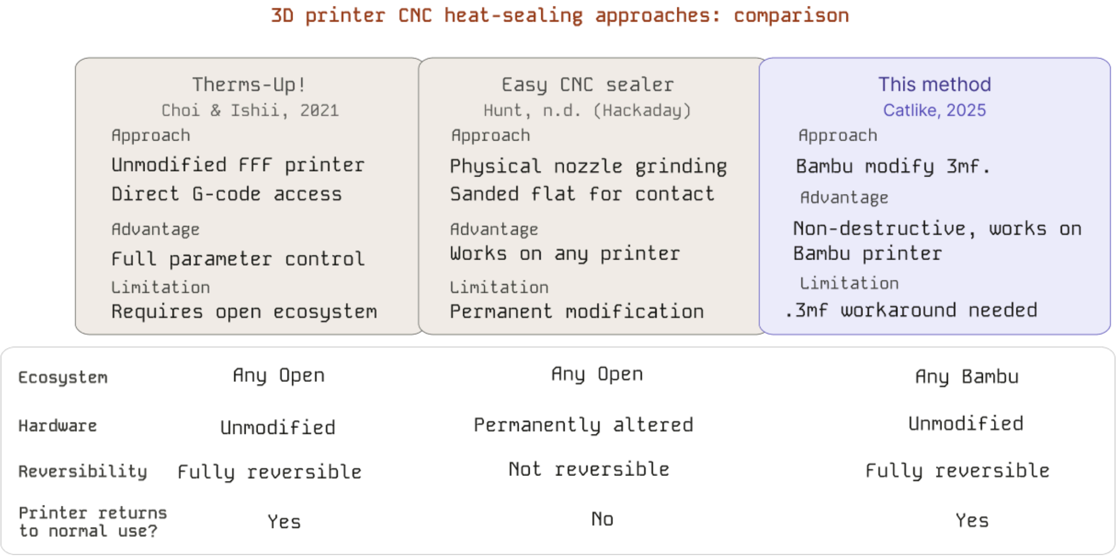
[Figure 5.6: Heat-sealing using Bambu P1S printer]

The final fabrication method repurposes a Bambu 3D printer as a precision CNC heat-sealing machine. The method was primarily developed on a Bambu A1mini and additionally tested on a P1S(see Figure 5.6). Rather than depositing material layer by layer as in conventional 3D printing, the printer's heated nozzle traces vector-designed patterns across layered TPU films, fusing them through controlled temperature and pressure to create airtight pneumatic chambers.

5.2.1.1 Prior Approaches to CNC Heat-Sealing

The concept of repurposing a 3D printer for heat-sealing has been explored in different ways. Choi and Ishii's Therms-Up! Project (2021) demonstrated the approach on printers with open software ecosystems that allow direct G-code editing. The Easy CNC Heat Sealer project (Hunt, n.d.) offered a more accessible version, but required physically sanding down the printer nozzle to create a flat sealing surface(see Figure 5.7). While effective, this modification permanently alters the hardware, turning the printer into a dedicated heat sealer that can no longer function for standard printing.

My approach avoids both limitations. The Bambu A1mini's nozzle remains unmodified, and all adjustments are made at the software level through G-code parameters. This means the printer can switch between heat-sealing and conventional 3D printing at any time, simply by loading different files. For a research context where the same printer is also needed to produce structural components such as shoe lasts, ear clips, and sole enclosures, this reversibility was essential.



3D printer CNC heat-sealing approaches: comparison

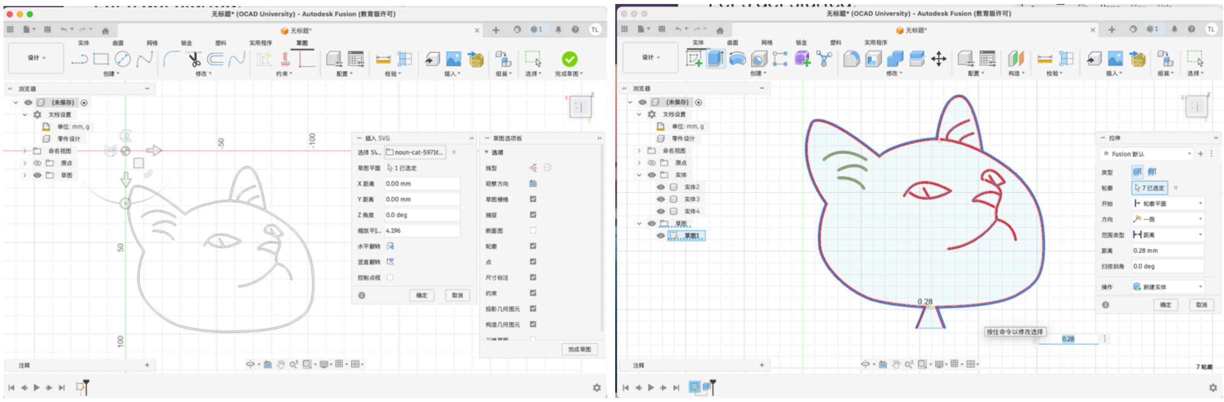
Therms-Up! Choi & Ishii, 2021	Easy CNC sealer Hunt, n.d. (Hackaday)	This method Catlike, 2025
Approach Unmodified FFF printer Direct G-code access	Approach Physical nozzle grinding Sanded flat for contact	Approach Bambu modify 3mf.
Advantage Full parameter control	Advantage Works on any printer	Advantage Non-destructive, works on Bambu printer
Limitation Requires open ecosystem	Limitation Permanent modification	Limitation .3mf workaround needed

Ecosystem	Any Open	Any Open	Any Bambu
Hardware	Unmodified	Permanently altered	Unmodified
Reversibility	Fully reversible	Not reversible	Fully reversible
Printer returns to normal use?	Yes	No	Yes

[Figure 5.7: Comparison diagram showing the three approaches and their trade-offs: Therms-Up! (open ecosystem, direct G-code), Hackaday (physical nozzle modification), this method (Bambu-only, non-destructive)]

5.2.1.2 Digital Design Pipeline

The process begins with designing the seal pattern as a closed vector path in Adobe Illustrator (see Figure 5.8). The SVG file is then imported into Fusion 360, where the path is extruded to a height of exactly 0.28mm with a stroke thickness of 2 to 3mm. The 0.28mm height is critical: it ensures the printer treats the shape as a single-layer trace, preventing the nozzle from making multiple passes that would overheat and damage the film. The resulting STL file is brought into Bambu Studio, conFigured with 0.28mm Extra Draft layer height settings, and exported as a slice file.



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插入 SVG
选择 S\... noun-cat-5971...
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Y 距离 0.00 mm
Z 角度 0.0 deg
缩放平... 4.196

无标题* (OCAD University) - Autodesk Fusion (教育版许可)

拉伸
Fusion 默认
轮廓 7 已选定
开始 轮廓平面
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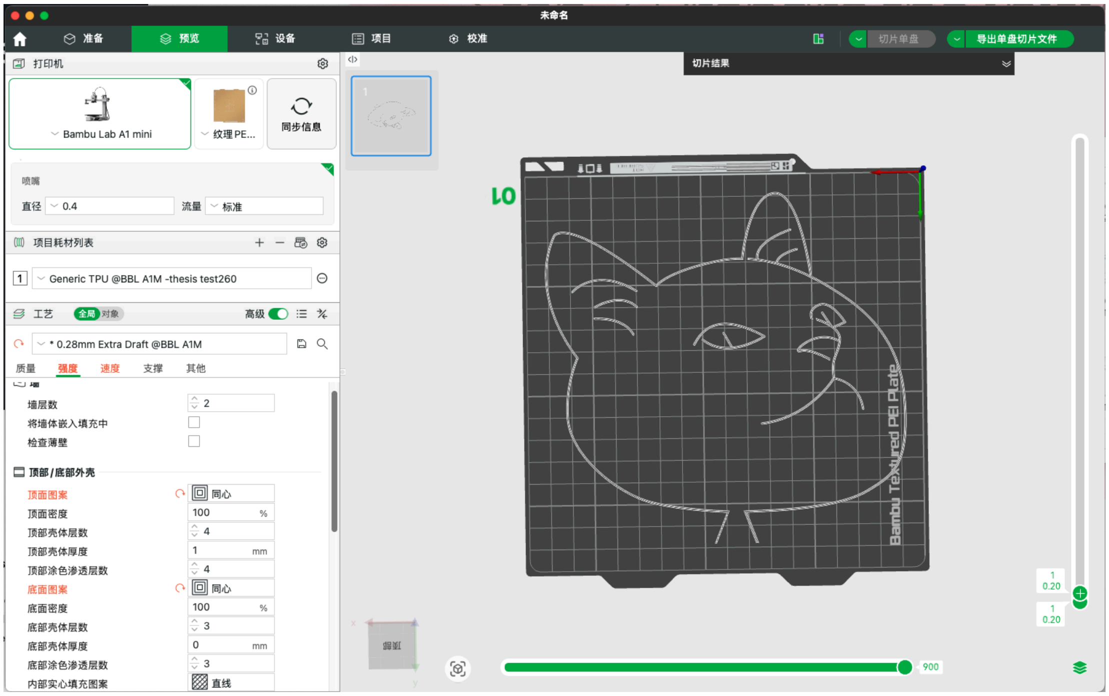
范围类型 距离
距离 0.28 mm
扫掠斜角 0.0 deg
操作 新建实体



Bambu Lab A1 mini
纹理PE...
喷嘴
直径 0.4
流量 标准
1 Generic TPU @BBL A1M -thesis test260
* 0.28mm Extra Draft @BBL A1M

墙层数	2
将墙体嵌入填充中	☐
检查薄壁	☐

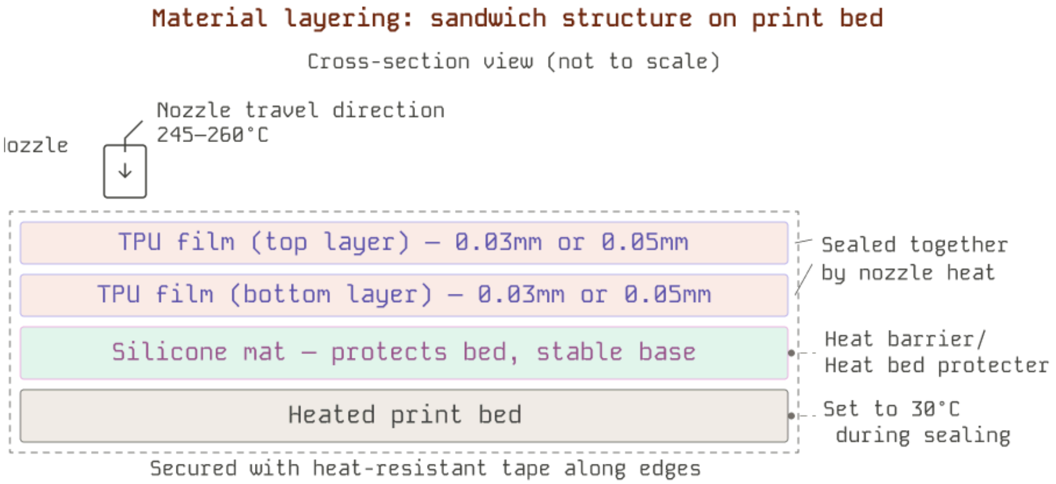
顶部/底部外壳

顶面图案	同心
顶面密度	100 %
顶部壳体层数	4
顶部壳体厚度	1 mm
顶部涂色渗透层数	4
底面图案	同心
底面密度	100 %
底部壳体层数	3
底部壳体厚度	0 mm
底部涂色渗透层数	3
内部实心填充图案	直线

[**Figure 5.8** Digital pipeline from SVG to Fusion 360 extrusion to Bambu Studio slice preview]

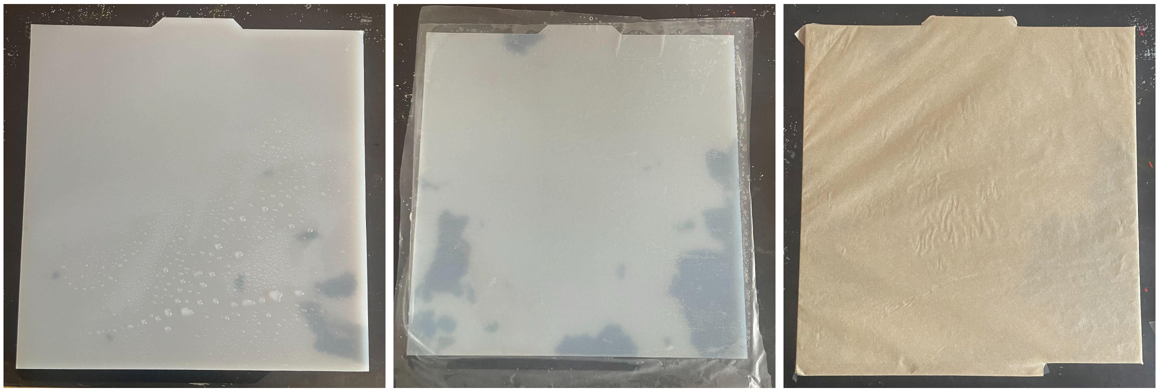
5.2.1.3 Material Layering

This method requires the following tools and materials: a spray bottle, any bambu 3d printer, heat-resistant tape, a 3D printer plate, a 3mm thick silicon mat trimmed to the plate size, TPU film, and parchment paper. The print bed is prepared with a layered sandwich structure(see Figure 5.9), secured with heat-resistant tape along the edges.



[**Figure 5.9** Material layering sandwich structure]

From bottom to top: a silicone mat to protect the heated bed and provide a stable base, the first TPU film layer, the second TPU film layer, and a sheet of parchment paper on top. The silicone mat prevents the films from bonding to the heated bed, while the parchment paper shields the top TPU layer from direct contact with the nozzle. The bed temperature is lowered to 30°C to prevent warping and improve adhesion. As shown in Figure 5.10, the layering must be flat and free of wrinkles, as any trapped air or debris between the TPU layers will create uneven surfaces in the finished seal, compromising its airtightness. The silicone mat can be replaced with thick cardboard, but it needs to be replaced after a few runs.

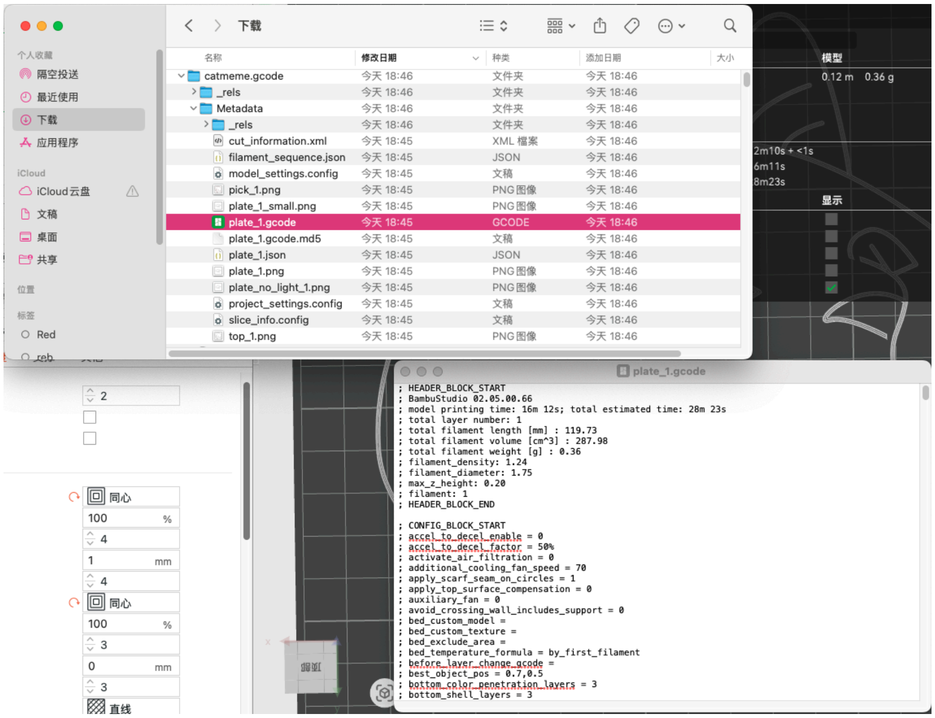


[Figure 5.10: photo of preparing print bed before printing]

5.2.1.4 Overcoming Bambu Studio's Closed Ecosystem

However, achieving software-level control on the Bambu A1mini required overcoming a significant constraint. The same user-friendly design that makes Bambu printers popular also makes them difficult to modify. Bambu Studio operates as a closed ecosystem that does not expose the G-code for direct editing. The software embeds protective routines within its material profiles, including preset extrusion parameters that are difficult to override. More critically, the printer's automatic bed-leveling calibration sequence pre-heats the nozzle to its default printing temperature before the actual job begins. When working with ultra-thin TPU films rather than standard filament, this calibration heat is enough to burn through the material before sealing even starts. Solving this required not only modifying the print job's G-code but also overwriting the temperature commands embedded in the printer's startup routine to prevent premature heating.

After extensive testing, I developed a workaround to access and modify the G-code. Bambu Studio exports slice files in the .3mf format, which is essentially a compressed archive. By renaming the .3mf file extension to .zip and extracting its contents, the embedded G-code file can be located within the metadata folder and edited directly. After making modifications, the files are recompressed into a .zip and renamed back to .3mf for printing (see Figure 5.11). This process, while cumbersome, provides full control over the parameters that determine seal quality without requiring any physical modification to the printer.



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_rels	今天 18:46	文件夹	今天 18:46	
Metadata	今天 18:46	文件夹	今天 18:46	
_rels	今天 18:46	文件夹	今天 18:46	
cut_information.xml	今天 18:45	XML 檔案	今天 18:46	
filament_sequence.json	今天 18:45	JSON	今天 18:46	
model_settings.config	今天 18:45	文稿	今天 18:46	
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plate_1_small.png	今天 18:45	PNG图像	今天 18:46	
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plate_1.gcode.md5	今天 18:45	文稿	今天 18:46	
plate_1.json	今天 18:45	JSON	今天 18:46	
plate_1.png	今天 18:45	PNG图像	今天 18:46	
plate_no_light_1.png	今天 18:45	PNG图像	今天 18:46	
project_settings.config	今天 18:45	文稿	今天 18:46	
slice_info.config	今天 18:45	文稿	今天 18:46	
top_1.png	今天 18:45	PNG图像	今天 18:46	

plate_1.gcode

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; total layer number: 1
; total filament length [mm] : 119.73
; total filament volume [cm^3] : 287.98
; total filament weight [g] : 0.36
; filament_density: 1.24
; filament_diameter: 1.75
; max_z_height: 0.20
; filament: 1
; HEADER_BLOCK_END

; CONFIG_BLOCK_START
; accel_to_decel_enable = 0
; accel_to_decel_factor = 50%
; activate_air_filtration = 0
; additional_cooling_fan_speed = 70
; apply_scarf_seam_on_circles = 1
; apply_top_surface_compensation = 0
; auxiliary_fan = 0
; avoid_crossing_wall_includes_support = 0
; bed_custom_model =
; bed_custom_texture =
; bed_exclude_area =
; bed_temperature_formula = by_first_filament
; before_layer_change_gcode =
; best_object_pos = 0.7,0.5
; bottom_color_penetration_layers = 3
; bottom_shell_layers = 3
```

[**Figure 5.11:** Screenshot of G-code modification process]

The key G-code modifications control four parameters. Nozzle temperature determines how much heat is applied to the TPU layers during sealing. Z-offset pushes the nozzle slightly below the zero point, applying downward pressure onto the film layers to ensure consistent contact. Extrusion multiplier (M221 S120, setting flow to 120%) increases material output to create a more even pressure distribution across the seal line while providing a lubricating effect that protects the nozzle. Movement speed (G1 F180, equivalent to 3mm/s) controls how slowly the nozzle traces the pattern, allowing sufficient heat transfer without burning through the material.

These parameters require adjustment based on TPU film thickness. For 0.03mm film, a nozzle temperature of 245°C and the Z-offset of -0.1mm produce reliable seals. For 0.05mm film, which requires more heat to fully fuse, the temperature increases to 260°C and the Z-offset deepens to -0.15mm with an additional G29.1 Z-0.02 global compensation. A complete parameter reference for both thicknesses is provided in Table 5.1.

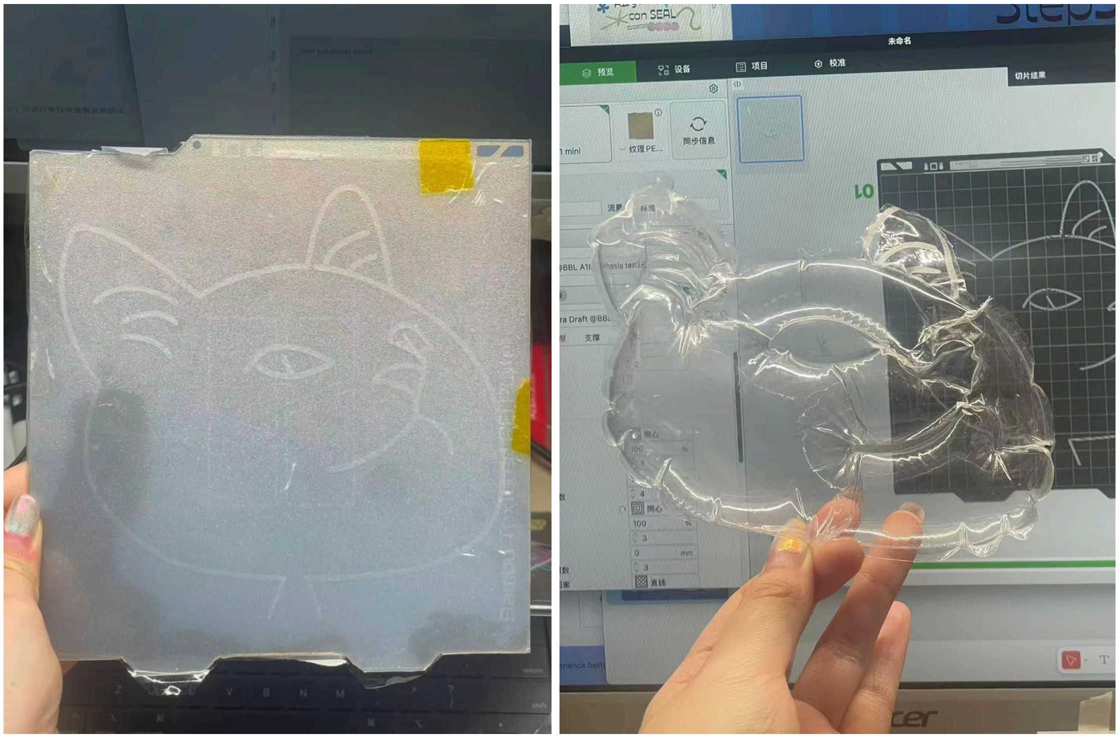
Critical parameters by TPU thickness		
Parameter	***0.03mm TPU***	***0.05mm TPU***
Nozzle temp	250°C	260°C
Z-offset	-0.1mm	-0.15mm
Extrusion	M221 S12 (120%)	M221 S120 (120%)

[**Table 5.1** comparing parameters for 0.03mm vs 0.05mm TPU]

5.2.1.5 Results and Advantages

Figure 5.12 demonstrates the final sealing result using this method on an A1 mini printer. Testing confirmed that units produced with this method retain over 80% of air pressure after 10 minutes and withstand more than 50 inflation cycles without seal failure. Compared to the earlier manual approaches described in Section 5.2.3, this method offers several key advantages. It eliminates the paper template, since the nozzle traces the seal pattern directly onto the TPU layers, removing the most failure-prone step of the manual methods. The digital design pipeline ensures that every unit is dimensionally identical, solving the inconsistency problems of hand-cut templates. The process is fully repeatable through G-code, allowing rapid production of the dozens of units needed for both prototypes. And because no physical modification is made to the printer, it remains available for conventional 3D printing tasks throughout the project.

This method was tested on both the Bambu A1mini and the Bambu P1S, confirming that the same G-code modification approach works across different models in the Bambu ecosystem. Other Bambu printers that use Bambu Studio should be compatible with this workflow, as the closed ecosystem constraint and the .3mf workaround are shared across the platform.



[Figure 5.12: Finished sealed unit on the print bed; the same unit inflated]

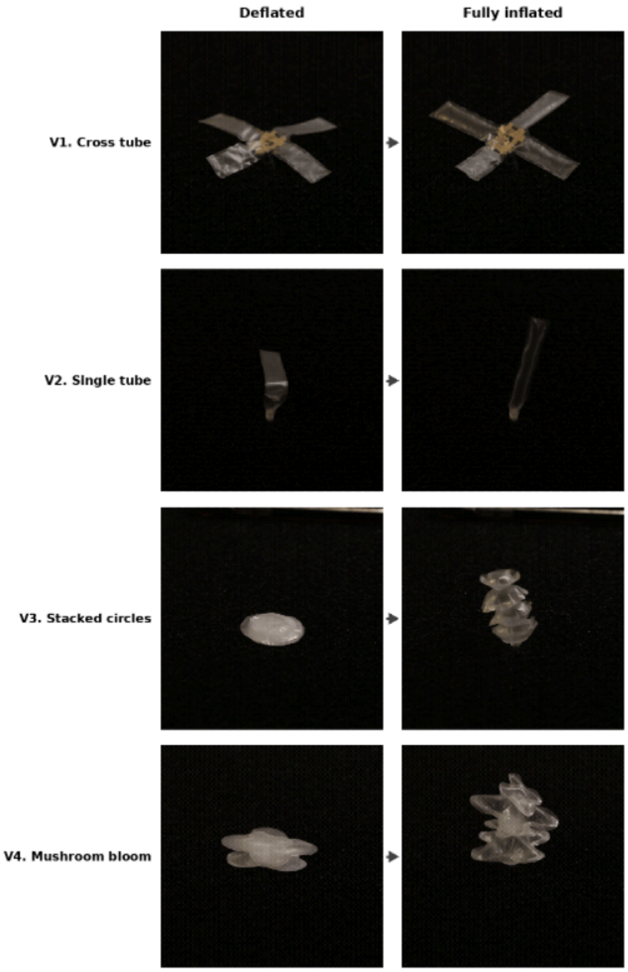
5.2.2 Inflation Unit Design: Achieving Perpendicular Movement

The core design challenge for the inflation units was directional: they needed to rise upward and outward from the body’s surface, perpendicular to the skin, mimicking how hair stands on end during piloerection. Most heat-sealed pneumatic structures simply bulge outward when inflated, creating rounded, pillow-like forms. While visually noticeable, this does not capture the rising quality of bristling fur. The units had to lift, not just swell. Equally important, the inflation needed to read as something growing from the body rather than something attached to it, so that observers would perceive an emotional transformation rather than a mechanical actuation.

5.2.2.1 From Flat Chambers to Stacked Structures

Figure 5.13 demonstrates the development of the soft robotic structures for this thesis. Early versions (V1 and V2) used flat, two-dimensional sealed chambers. V1 was a multi-strip cross pattern with several parallel chambers sealed side by side, used on the first headwear prototype. When inflated, these strips required a large volume of air (a 6V pump running for over 20 seconds) to show any visible change, and the resulting movement was underwhelming: the chambers bulged slightly but lay flat against the headband, unable to stand upright. This was the “sad noodle” stage, where sealed TPU could hold air but could not direct its expansion into meaningful movement.

V2 simplified the design to a single-tube unit, reducing the air volume needed and making inflation faster, but the fundamental problem remained. A single flat chamber, no matter how efficiently sealed, could only expand outward in the plane of its sealed surfaces. Achieving perpendicular movement required a fundamentally different structural approach.



[Figure 5.13: Inflation unit design progression from V1 to V4, showing each version in deflated and fully inflated states. V1 (cross tube) and V2 (single tube) are flat chamber designs that fail to lift perpendicular to the surface. V3 (stacked circles) introduces the stacking method that achieves vertical inflation. V4 (mushroom bloom) refines the stacking with variable-size, four-lobed shapes for organic, blooming movement.]

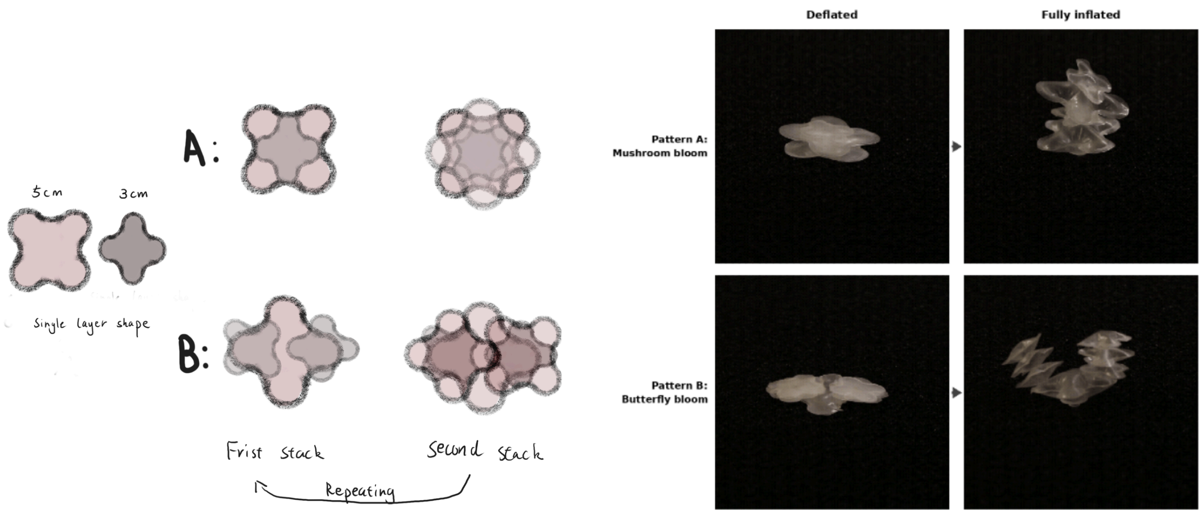
The breakthrough came from studying car seat lumbar massage systems. These systems use stacked layers of small TPU air sacs that inflate in sequence, pushing upward rather than just outward. Each layer acts as a platform for the next, translating horizontal expansion into vertical lift. Adapting this principle, I developed a stacking method: individual sealed chambers are layered on top of each other, with a hole punched through the center of each layer, and bonded together using plastic adhesive. Air enters through the bottom and flows upward through the connected chambers, inflating each layer in sequence.

As shown in Figure 5.14 first stacked units used simple circular chambers of uniform size. While these successfully achieved vertical rising and collapsed into thin, flat profiles when deflated, the uniform circular shape produced a mechanical, cylindrical appearance when inflated. The uniform cylindrical form read as an engineered object rather than a natural growth, drawing attention to the device itself rather than the emotional state it was meant to express.

[Figure 5.14: I inflated stacked circular units on the headwear prototype 3]

5.2.2.2 Organic Geometry: Variable-Size Stacking

The final design replaced uniform circles with organic, four-lobed shapes in two sizes: 5cm and 3cm. These are stacked in alternating layers of 4 to 5 pieces (large-small-large-small), bonded through the same center-hole adhesive method as presented in Figure 5.15. This variable-size stacking transforms the inflation behavior. When air enters, the larger layers expand outward more than the smaller ones, while the smaller layers act as structural nodes that redirect the expansion upward. The result is a blooming effect: rather than rising as a uniform column, the unit opens outward at each large layer while being cinched at each small layer, resembling a mushroom or flower unfurling.This geometry achieves the organic quality that earlier iterations lacked.



[Figure 5.15: Diagram showing the final single-layer shapes (5cm and 3cm four-lobed forms), Pattern A and Pattern B stacking arrangements, and the repeating assembly logic and Comparison of Pattern A (mushroom bloom, top) and Pattern B (butterfly bloom, bottom) in deflated and fully inflated states. Pattern A blooms radially in all directions; Pattern B opens along two opposing axes from a central seam.]

Figure 5.16 shows the final structures deflated and inflated. The uneven, lobed edges and variable expansion rates produce the kind of irregular, asymmetric movement found in biological growth, such as petals opening or fur bristling, rather than the uniform expansion of an inflatable object. When deflated, the entire assembly flattens into a thin stack that sits almost invisibly against the headband or shoe upper. When inflated, it blooms outward and upward, transforming from a barely noticeable surface element into a prominent, three-dimensional form. This transition from hidden to visible reinforces the wearable's conceptual goal: making the invisible visible.

(a) Baseline (HRV stable)
(b) Mid-inflation
(c) Full inflation (HRV elevated)

[Figure 5.16: Final inflation unit sequence on headwear: deflated (flat) to fully inflated (mushroom bloom)]

The units are designed to be fully modular and interchangeable. Different stacking patterns and layer configurations can be swapped onto the headband or shoe upper at any time, allowing the wearer to adjust the visual character of the inflation response. This modularity also means that if a single unit is damaged, it can be replaced independently without affecting the rest of the system. Each layer is produced using the modified 3D printer method described in Section 5.2.1, ensuring dimensional consistency across the dozens of units needed for both prototypes.

5.2.3 Earlier Approaches and Their Limitations

NOTE: Detailed parameter tables and test results for each method are provided in Appendix A.

Before developing the modified 3D printer method, I explored three manual heat-sealing approaches. A summary comparison of all four approaches is presented in Figure 5.13. Each contributed useful knowledge but ultimately revealed limitations that made them unsuitable for producing the quantity and quality of units needed for the final prototypes.

5.2.3.1 Soldering Iron and Household Iron

The most accessible heat sources failed for opposing reasons. The soldering iron concentrated too much heat in too small an area, melting through the ultra-thin TPU film on contact, even at its lowest setting. The 0.015mm film was destroyed by a single touch. The household iron distributed heat across too large an area. Its broad, flat surface trapped air and moisture between the TPU layers, producing clusters of small bubbles that compromised the seal. Progressive temperature testing from the silk to cotton settings revealed a narrow window where bonding occurred, but the results were inconsistent and unreliable.

5.2.3.2 Hair Straightener with Sandwich Structure

The hair straightener proved more promising. Its clamping plates applied steady pressure over a narrow area, and the digital temperature display enabled systematic testing. I developed a sandwich construction with parchment paper protecting the outer layers and a paper template in the center defining the air chamber. The layered assembly was pulled through the heated plates repeatedly to build the seal.

Through extensive parameter testing, I identified an optimal temperature of 285°F for 0.03mm TPU (5 pulls) and 0.05mm TPU (8 pulls), producing seals that survived 10 or more inflation cycles without leakage. However, this method had two fundamental limitations. Each unit had to be made one at a time, making production slow. More critically, the paper template inside the sealed chamber had to be physically extracted through a small opening, which was then resealed by hand. This extraction step had a high failure rate: paper fragments often remained trapped inside, and the hand-resealed openings were inconsistent.

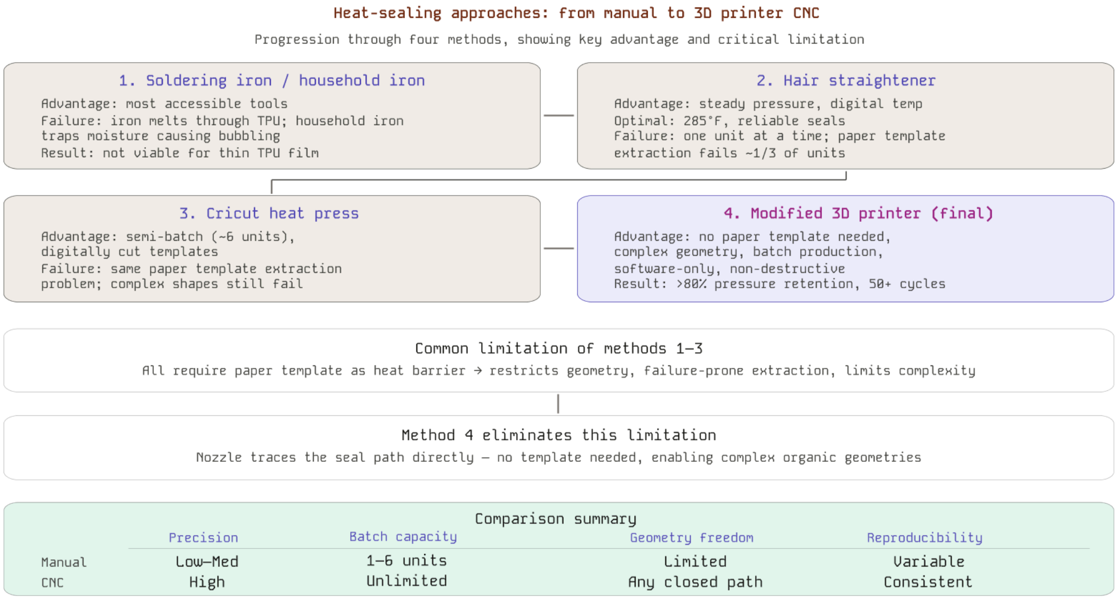
5.2.3.3 Cricut Heat Press for Semi-Batch Production

To scale up production, I combined a Cricut Maker cutting machine for digitally precise paper templates with a Cricut heat press that could process roughly six units at a time. A progressive heating sequence (230°F → 250°F → 280°F → 300°F, 30 seconds each) with a light water mist to prevent film misalignment produced the most reliable results of any manual method.

Even with these improvements, the paper template extraction problem remained. Complex shapes made full removal difficult, and the irregular openings left after extraction were hard to reseal consistently. Of the more than twenty units produced for the second headwear prototype using this method, only about one-third were usable.

5.2.3.4 Common Limitation

All three manual methods depended on a paper template as a heat barrier to define the sealed areas. This dependency created two persistent problems: the template had to be removed after sealing, introducing a failure-prone manual step, and the requirement for removability restricted the geometric complexity of possible designs. The modified 3D printer method (Section 5.2.1) eliminated both problems by tracing the seal pattern directly onto the TPU layers with the heated nozzle, requiring no internal template at all.



Heat-sealing approaches: from manual to 3D printer CNC

Progression through four methods, showing key advantage and critical limitation

1. Soldering iron / household iron
Advantage: most accessible tools
Failure: iron melts through TPU; household iron traps moisture causing bubbling
Result: not viable for thin TPU film

2. Hair straightener
Advantage: steady pressure, digital temp
Optimal: 285°F, reliable seals
Failure: one unit at a time; paper template extraction fails ~1/3 of units

3. Cricut heat press
Advantage: semi-batch (~6 units), digitally cut templates
Failure: same paper template extraction problem; complex shapes still fail

4. Modified 3D printer (final)
Advantage: no paper template needed, complex geometry, batch production, software-only, non-destructive
Result: >80% pressure retention, 50+ cycles

Common limitation of methods 1–3
All require paper template as heat barrier → restricts geometry, failure-prone extraction, limits complexity

Method 4 eliminates this limitation
Nozzle traces the seal path directly — no template needed, enabling complex organic geometries

Comparison summary

	Precision	Batch capacity	Geometry freedom	Reproducibility
Manual	Low–Med	1–6 units	Limited	Variable
CNC	High	Unlimited	Any closed path	Consistent

[Figure 5.17: Summary comparison of all four approaches]

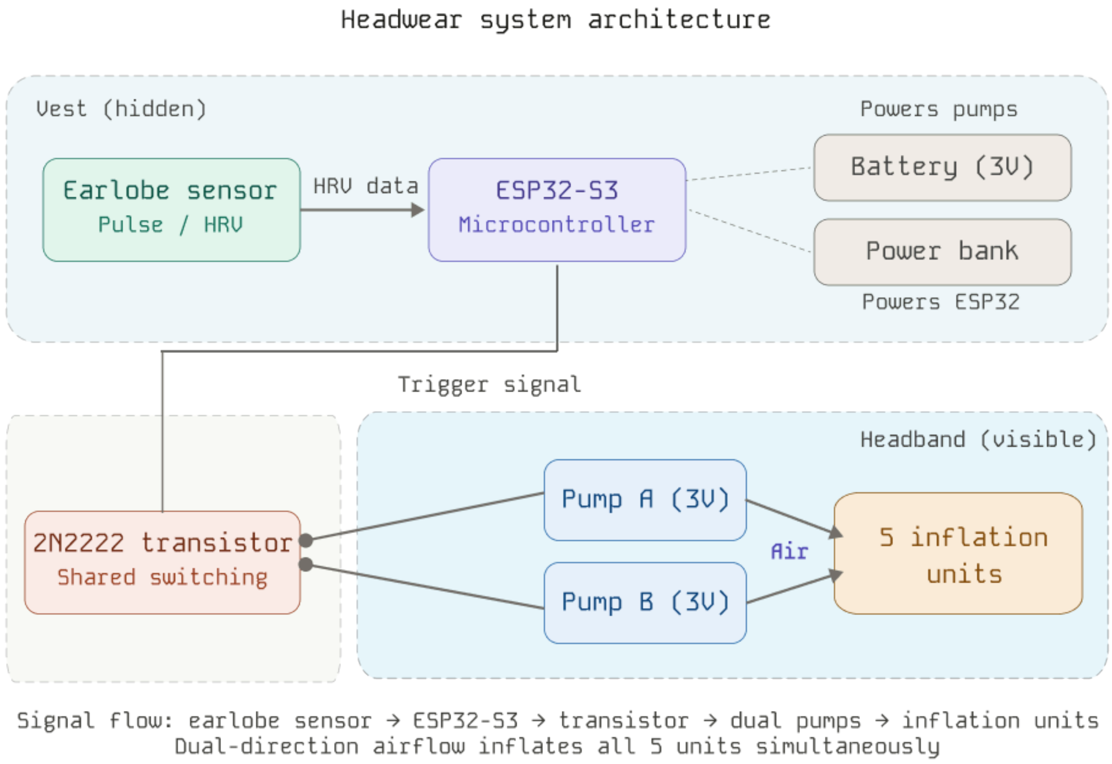
5.3 Headwear: HRV-Responsive Inflatable Headband

5.3.1 Overview of Final Headwear Prototype

The final headwear prototype is a wearable headband that detects the wearer’s heart rate variability and responds by inflating soft robotic units arranged along its surface. When HRV rises above the wearer’s calibrated baseline average, the system activates two micro air pumps that inflate 5 modular units, producing a visible blooming transformation that mimics the bristling of fur during emotional arousal. When HRV returns below the threshold, the units gradually deflate, returning to a nearly flat, unobtrusive profile.

[Figure 5.18: Final headwear prototype on Thea, Inflated and deflated]

The system architecture follows a simple signal flow (See Figure 5.19). An earlobe pulse sensor continuously monitors the wearer's heart rate. The sensor feeds data to an ESP32-S3 microcontroller, housed inside a custom vest worn beneath outer clothing. The microcontroller calculates a running HRV baseline during an initial calibration period, then monitors for deviations above this average. When the threshold is exceeded, the microcontroller triggers two EDZP02-D3 3V micro pumps mounted inside the headband, one on each side, which inflate the units through clear lab-grade tubing. A battery powers the pumps while a compact power bank supplies the ESP32-S3, both housed inside the vest.



[Figure5.19: System architecture diagram showing signal flow from earlobe sensor ⟶ ESP32-S3 (in vest) ⟶ dual micro pumps (in headband) ⟶ inflation units]

The design distributes components across two wearable elements to keep the technology invisible (See Figure 5.20). The headband itself contains only the pumps, tubing, and inflation units, appearing as a simple accessory. All electronics, the microcontroller, battery, power bank, and transistor switching circuit, are concealed inside a custom-made vest worn underneath the wearer’s clothing. Thin wires run from the vest through the collar to the headband. The earlobe sensor is small enough to be hidden beneath the wearer’s hair. When worn, the only visible element is the headband with its inflation units, which appear as subtle surface details when deflated and transform into prominent organic blooms when activated. This prototype evolved through four iterations, each driven by the goal of improving wearability while maintaining the core function of biosignal-driven inflation.

[Figure 5.20: Annotated photo showing what is visible (headband, units) vs. what is hidden (vest with electronics, wiring, earlobe sensor)]

The following subsections discuss the key aspects of this development in detail: the integration of traditional fashion design and digital fabrication in creating the wearable form (Section 5.3.2), the miniaturization and concealment of hardware (Section 5.3.3), and the configuration of inflation units on the headband (Section 5.3.4).

5.3.2 Wearable Form: Integrating Fashion Design and Digital Fabrication

The central challenge of the wearable form was making an electronic device feel like clothing. The headwear system contains a microcontroller, battery, transistor, two air pumps, a pulse sensor, wiring, and tubing. If any of these components are visible or feel foreign against the body, the wearer's attention shifts to the technology rather than to the emotional experience it mediates. The form design had to make all of this disappear.

5.3.2.1 Vest: Traditional Draping with Technical Function

The vest serves as the hidden infrastructure of the system, housing the ESP32-S3, two 3V batteries, a power bank, and a 2N2222 transistor switching circuit. Rather than designing an engineering enclosure, I approached the vest as a fashion garment. Using traditional Haute Couture draping techniques, I shaped muslin fabric directly on a dress form to determine where pockets should sit and how wires should route through the garment (See Figure 5.21). This hands-on process allowed me to find pocket placements that distribute weight evenly across the shoulders while keeping components accessible for maintenance.

The final vest is made from 3M reflective fabric, chosen to give the piece a futuristic aesthetic that complements the transparent TPU inflation units. The pockets are positioned in the back so that the microcontroller and battery sit flat against the torso without creating visible bulges under outer clothing. Wires run from the chest pockets upward through seams to the neckline, where they exit toward the headband. The transition point from vest to headband, where wires are most likely to be exposed, is covered with textile wrapping to minimize the visual presence of the wiring.

[Figure 5.21: Vest pattern development using draping techniques on a dress form. Muslin fabric is shaped directly on the body to determine optimal pocket placement and wire routing]

5.3.2.2 Headband: From Craft Store to Fully 3D Printed

Figure 5.22 shows the development of the headwear form modification based on store bought headband to the final 3d printed headwear.

The earliest prototype used a commercially available headband from a craft store, modified to hold inflation units and tubing. While functional for initial testing, this off-the-shelf form could not accommodate internal pump housing or precise tubing routing. From the second prototype onward, the headband was fully 3D modeled and printed, allowing the form to be designed around the components it needed to conceal.

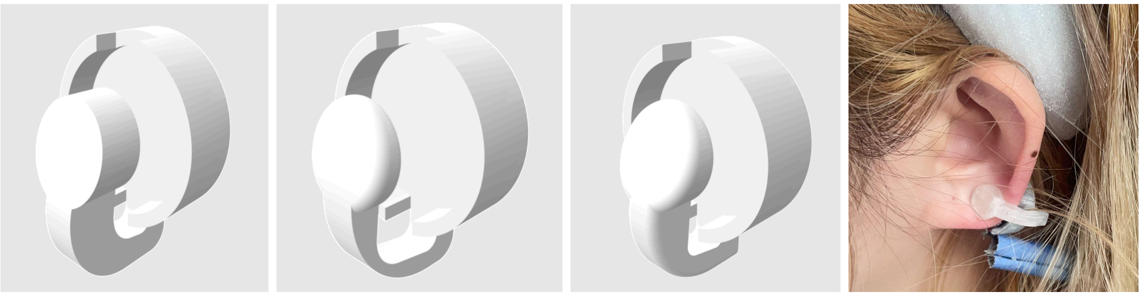
The final headband is entirely 3D printed, designed as an integrated structure that conceals the two EDZP02-D3 micro pumps within its form. Rather than mounting the pumps externally and hiding them with additional covering, the headband was modeled with internal cavities that house the pumps as part of the structure itself. This approach eliminates visible hardware on the head. From the outside, the headband reads as a simple accessory. The air tubing routes from the embedded pumps to the inflation unit mounting points along the top of the headband.

This is where digital fabrication becomes essential. The internal geometry required to house pumps, route tubing, and provide mounting points for the inflation units would be impossible to achieve with traditional craft techniques alone. 3D printing enables precise, complex internal structures while maintaining a clean exterior surface.

[Figure 5.22: Headband evolution: (a) V1 modified craft store headband with externally attached components, (b) V2-V4 3D printed headband with internal cavities for pump housing]

5.3.2.3 Ear Clip: 3D Printed Sensor Holder

In the early stage of the development, I tried the earclip from the pulse sensor kit. I realized two issues with wearing for a period of time: First, Metal ear clips are very stiff and cannot adjust to fit different earlobe thicknesses; wearing them for long periods can be extremely painful. Second, the clip is connected to the sensor by Velcro. It is easily worn down by fiber trapping inside the Velcro, which makes the sensor not steady enough to walk around without falling off. The pulse sensor needs a custom mount that could hold the sensor securely against the skin without pinching during extended wear. I designed a new ear clip sensor holder to solve the problem. This went through three design iterations (See Figure 5.23) before arriving at a clip shape that balanced grip strength with comfort. The small size of the final clip allows it to be hidden beneath the wearer's hair. While printing in soft TPU material ensures stability and comfort during wearing.



[**Figure 5.23:** Three iterations of ear clip design; final version worn on ear]

5.3.3 Hardware Development: Miniaturization and Concealment

Every hardware decision in the headwear prototype was driven by a single question: how can this component become smaller, lighter, or less visible? The system needed to detect heart rate variability, process the data, and trigger pneumatic inflation, all without revealing any of the electronics to an observer. Achieving this required four iterations of progressive miniaturization, with each version reducing the size and visibility of the system until the technology effectively disappeared.

5.3.3.1 Final Hardware Configuration

The final system uses an ESP32-S3 microcontroller, chosen for its smaller form factor compared to the Arduino Nano 33 IoT used in earlier versions. An earlobe pulse sensor continuously monitors heart rate, replacing the finger-held MAX30105 sensor from the first prototype, which required the wearer to remain stationary. The sensor data feeds to the ESP32-S3, which calculates a running HRV baseline and triggers inflation when heart rate rises above the wearer's calibrated average.

Two EDZP02-D3 3V micro pumps are mounted inside the 3D printed headband, one on each side, and are controlled simultaneously through a single 2N2222 transistor. The dual pump configuration halves the air distance each pump needs to cover, resulting in faster, more even inflation across all units. Clear lab-grade tubing connects the pumps to the inflation units, chosen specifically because it blends visually with the transparent TPU units.

Power is split between two sources: a battery powers the air pumps, while a compact power bank supplies the ESP32-S3. Both are housed inside the custom vest, keeping all power sources off the head entirely.

5.3.3.2 How Each Change Serves Concealment

The progression from V1 to V4 can be read as a systematic removal of visible technology. Each change addressed a specific concealment problem, as shown in Table 5.2.

The original 6V pump required a relay module and four AA batteries. Together, these were heavy enough to fill a small enclosure the size of a book, making the system stationary. Replacing the pump with two 3V EDZP02-D3 micro pumps eliminated the relay, since the low voltage could be switched with a small transistor. This single change removed the two bulkiest components from the system.

Moving the heart rate sensor from a finger clip to an earlobe sensor removed the requirement for the wearer to hold still. It also relocated the sensor to a position that could be hidden beneath hair, making it invisible during normal social interaction.

The most significant change for concealment was redistributing components between the head and the torso. In the second prototype, all electronics sat in a choker at the back of the neck, creating a weight imbalance and visible bulk. The third prototype moved the microcontroller, battery, and switching circuit into a custom vest, leaving only the pumps and tubing in the headband. This split meant the head carried minimal weight while the torso, which naturally supports heavier loads, bore the electronics.

Switching from Arduino Nano 33 IoT to ESP32-S3 in the final version further reduced the footprint of the electronics package inside the vest. The addition of a power bank as a separate power source for the microcontroller simplified the circuit and provided longer operating time for the multi-day study.

	V1	**V2**	**V3**	**V4**
Core problem	Stationary only	Weight imbalance, technology too visible	Inflation units are not organic	—
Key change	First working system: 6V pump, finger sensor, relay, 4×AA batteries	Miniaturized: 3V micro pump, earlobe sensor, CR123A, transistor	Weight redistributed to vest, dual pumps, clear tubing, technology concealed	Mushroom bloom units replace cylindrical stacked units; ESP32-S3 replaces Arduino Nano 33 IoT
Form	Table-mounted installation	Choker-style enclosure at the back of the neck	Vest + headband system	Vest + headband system
Remaining issue	Too heavy and bulky to wear	Exposed wires, weight imbalance, visual clutter	Unit shapes are too mechanical, cylindrical in appearance	Final prototype

[Table 5.2: four-version progression from 5.3.1, with hardware changes at each stage]

5.3.4 Inflation Units: Configuration and Arrangement

[Figure 5.24: Close-up of the Inflation Units]

Five modular inflation units are arranged along the headband, evenly distributed along its arc from the center point. Each unit slots into a 3D printed mounting point integrated into the headband structure, allowing units to be removed and replaced without tools or adhesive. This modularity means different stacking configurations or replacement units can be swapped in at any time, as described in Section 5.2.2.

The pneumatic system uses a single continuous tube that runs along the inside of the headband, connecting all five units in series. Each end of this tube connects to one of the two EDZP02-D3 micro pumps embedded in the headband(see Figure 5.24). When triggered, both pumps activate simultaneously, pushing air from both ends of the tube toward the center. This dual-direction airflow ensures that all five units receive air pressure at roughly the same rate, producing even inflation across the full arc rather than the uneven inflation that occurred in earlier prototypes where units closer to a single pump inflated faster than those further away.

A 3D printed outer shell covers the headband, concealing all tubing, wiring, and pumps from view. From the outside, the headband appears as a clean, continuous surface with only the inflation units visible above it. When deflated, the units sit as flat, minimal forms along the headband. When activated, they bloom upward and outward, creating the piloerection effect while the mechanism driving the transformation remains entirely hidden.

[Figure 5.25: Headband showing unit placement along the arc; cross-section or cutaway view showing internal tubing, pump positions, and outer shell]

The shape, fabrication, and stacking logic of the individual units are detailed in Section 5.2.2. The interaction flow, from HRV calibration through monitoring to inflation trigger, is described in Section 5.3.3.

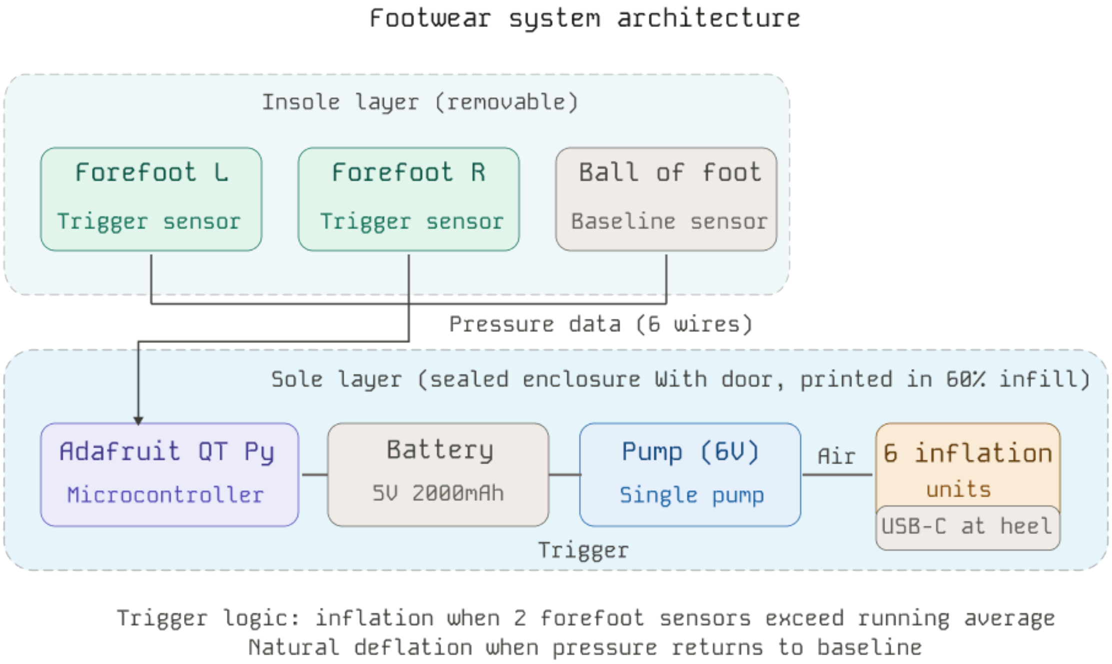
5.4 Footwear: Plantar Pressure Responsive Sneaker Flats

5.4.1 Overview of Final Footwear Prototype

The final footwear prototype is a modular shoe system that detects plantar pressure changes associated with toe-gripping and responds by inflating soft robotic units on the top of the foot. When the wearer experiences awkwardness, unsettledness, or nervousness, the unconscious toe-gripping motion increases pressure at the forefoot. When the two forefoot pressure sensors exceed the wearer's running average, the system triggers a 6V air pump housed inside the sole, inflating five modular units clustered on the dorsal surface of the foot. The units remain inflated as long as the pressure stays above the average, and deflate naturally once the pressure returns to baseline.

[Figure 5.26: Final footwear close-up, worn by Thea]

The system is built as four separable layers, each serving a distinct function. Figure 5.27 shows the System architecture of the footwear. The 3D printed sole acts as an enclosure for all electronics: the Adafruit QT Py microcontroller, a 5V 2000mAh rechargeable lithium battery, and the 6V air pump. A USB charging port is accessible at the heel. The insole sits on top of the sole and houses three DIY pressure sensors positioned at the forefoot. The upper, constructed through digital fabrication based on traditional shoemaking knowledge, contains embedded air tubing that routes from the sole up to the inflation unit mounting points on the dorsal surface. The six inflation units attach to the upper and can be replaced independently.



[Figure 5.27: System architecture diagram**]**

This modular construction means each layer can be iterated, repaired, or replaced independently. A damaged inflation unit does not require disassembling the sole. A sensor issue can be addressed by removing only the insole. The sole went through four iterations, each addressing specific challenges of fit, structural strength, space allocation, charging access, and aesthetics.

The following subsections examine the body-driven sensor design process (Section 5.4.2), the integration of traditional shoemaking and digital fabrication (Section 5.4.3), the 3D printed sole as a hardware enclosure (Section 5.4.4), and the inflation unit configuration (Section 5.4.5).

5.4.2 Body-Driven Design: From Pressure Mapping to Sensor Layout

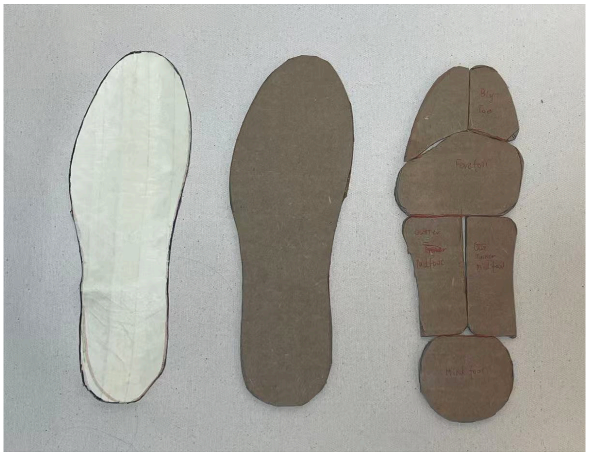
This section describes the process of translating the wearer's own body data into the sensor layout of the footwear. Unlike the headwear, where the sensor (earlobe pulse monitor) is an off-the-shelf component placed on the body, the footwear's sensing system was designed directly from the wearer's pressure behavior. The body itself determines where the sensors should go.

5.4.2.1 Pressure Mapping Process

The starting point was a personal observation: when experiencing awkwardness, unsettledness, or nervousness, I unconsciously grip my toes against the sole of the shoe. This gesture is invisible to others, hidden entirely within the shoe, but it produces a measurable shift in plantar pressure distribution.

To identify exactly where this pressure shift occurs, I developed a two-stage mapping process. First, I stepped onto a large sheet of paper with wet feet and walked normally, leaving footprints that revealed my natural pressure distribution during regular gait. The darkest areas indicate where the foot applies the most force during a normal step. Second, I repeated the process while deliberately performing the toe-gripping motion, pressing my toes down as I do during moments of emotional discomfort. Comparing the two sets of prints revealed the specific zones where pressure changes most significantly during toe-gripping: the forefoot area, particularly beneath the toes, and the ball of the foot.

These wet footprints were then overlaid onto the sole pattern that had been developed through traditional shoemaking techniques (described in Section 5.4.3). By mapping the pressure change zones directly onto the paper pattern of the shoe, I could define precise regions for sensor placement that corresponded to my own foot's specific pressure behavior.



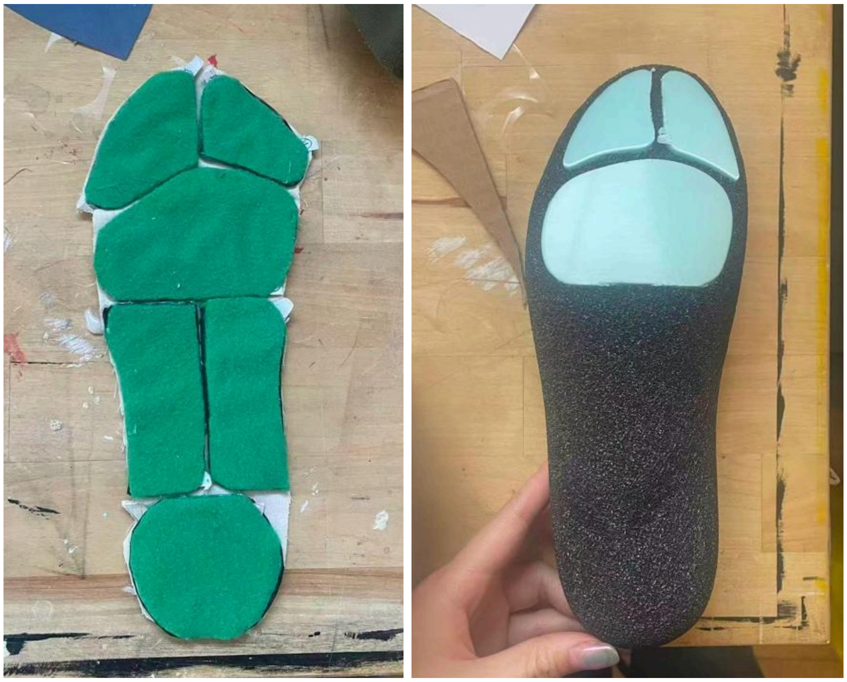
[**Figure 5.28:** Pressure mapping process]

5.4.2.2 From Six Zones to Three

The initial sensor design divided the forefoot into six pressure zones based on the full details of the pressure mapping results(see Figure 5.28). Each zone would have its own sensor, providing a high-resolution picture of pressure distribution across the front of the foot.

However, practical constraints required simplification. Six sensors meant twelve wires (two per sensor) running from the insole down into the sole enclosure, creating a complex wiring challenge within the already tight space of a shoe. Combined with the timeline pressure of producing a working prototype for the study, I simplified the layout to three sensor zones. The three zones still capture the essential information: two sensors at the forefoot (beneath the toes) detect the toe-gripping motion, while a third sensor beneath the ball of the foot provides baseline pressure data. The triggering logic compares the two forefoot sensors against the running average. When both forefoot values exceed the average, the system interprets this as a toe-gripping event and activates the pump.

This simplification was a pragmatic design decision rather than a compromise. The three-zone layout reliably distinguishes toe-gripping from normal walking because the pressure signature of gripping, where the forefoot values spike while the midfoot remains stable, is distinct enough to be captured without finer resolution.



[**Figure 5.29**: Sensor zone comparison: initial 6-zone design vs. final 3-zone layout on insole, with forefoot trigger zones]

5.4.2.3 DIY Pressure Sensors

The three sensors were constructed by hand, following the soft button technique described in Hartman (2025, p. 93). Each sensor is a simple pressure-variable resistor: two layers of conductive material separated by a compressible spacer. When the foot presses down, the layers compress closer together, reducing electrical resistance. The Adafruit QT Py reads this resistance change as an analog signal, converting foot pressure into a numerical value that can be compared against the running average.

The sensors are embedded within the insole, which sits on top of the 3D printed sole as a separate modular layer (See Figure 5.29). This means the sensors can be accessed, adjusted, or replaced by simply lifting out the insole, without disassembling the rest of the shoe.

5.4.2.4 Body Data as Design Driver

This process represents one of the footwear's most distinctive contributions. Rather than selecting sensor positions based on general anatomical knowledge or standard pressure maps, the layout was derived directly from the wearer’s own body in motion. The wet-foot mapping technique translated a subjective emotional experience (toe-gripping during discomfort) into objective spatial data (pressure zones on a paper pattern), which then directly determined the physical design of the sensing system. This approach aligns with Nachtigall et al.’s (2019) emphasis on encoding bodily data into the material design of footwear, though in this case, the data drives sensor placement rather than sole geometry.

5.4.3 Wearable Form: Traditional Shoemaking Meets Digital Fabrication

The footwear prototype required a form that could house electronics invisibly, accommodate pressure sensors, support inflation units, and still function as a wearable shoe comfortable enough for extended daily wear. The design workflow moved between traditional shoemaking knowledge and digital fabrication, using each at the stage where it was most effective.

5.4.3.1 Establishing the Base Form

The process began with 3D modeling a shoe last based on my own foot, which was then 3D printed to produce a physical form. Using this printed last, I applied traditional shoemaking pattern-making techniques to establish the basic shoe silhouette, using a ballet flat as the base style (see Figure 5.26). Working directly on the physical last allowed me to determine the general proportions and identify approximate positions for the five inflation units on the dorsal surface.

However, the traditional approach reached its limit when it came to integrating the pneumatic system. The tubing needed to run from the sole up through the body of the shoe to each inflation unit, and traditional construction methods could not conceal these channels within the shoe’s structure. Sewing or gluing fabric panels together left no practical way to embed hidden tubing paths.

[Figure 5.30: 3D printed shoe last; traditional pattern-making on last to establish base form and unit positions]

5.4.3.2 Shifting to Fully Digital Construction

This limitation led me to move the entire construction into digital fabrication. Based on the sketches and positional decisions made during the pattern-making stage, I modeled the complete shoe digitally, including the upper, sole, and internal tubing channels as a single integrated design.

The first printed version was tested for fit and comfort, and the positions of each inflation unit were confirmed on the physical prototype. These confirmed positions were then brought back into the digital model, where precise channels were cut into the structure to route tubing from the sole to each unit mounting point (see Figure 5.31). This back-and-forth between digital model and physical testing, modeling, printing, wearing, then returning to the model to refine, was essential for resolving issues that could only be discovered through direct body experience.

[Figure 5.31: Design sketch with unit positions marked in prototype 1; 3D model showing integrated tubing channels; printed prototype being tested for fit**]**

5.4.3.3 Hybrid Craft in Footwear

Although the final shoe is entirely 3D printed, the design process was not purely digital. Traditional shoemaking knowledge informed the base form, proportions, and initial unit placement through hands-on interaction with a physical last. Digital fabrication then took over where traditional methods could not follow, enabling the integration of hidden tubing channels, internal electronics compartments, and precise mounting points that would be impossible to achieve through craft alone. This workflow exemplifies hybrid craft (Nachtigall et al., 2019; Devendorf & Ryokai, 2015): neither traditional knowledge nor digital tools were sufficient alone, but together they produced a wearable that functions both as a shoe and as a concealed pneumatic system.

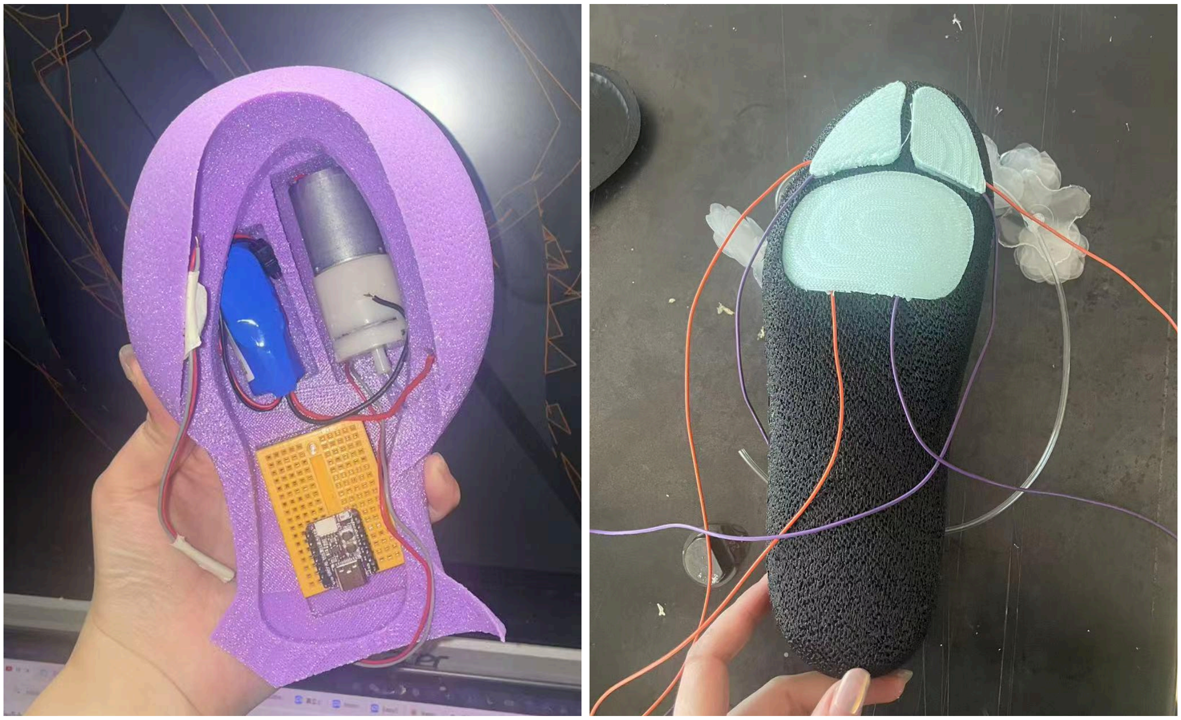
This parallels the headwear's design process, where traditional garment draping informed the vest design while 3D printing enabled the headband's internal pump housing. In both cases, traditional craft established the body-responsive foundation, and digital fabrication resolved the technical integration challenges.

5.4.4 Sole as Enclosure: Hardware Integration Through 3D Printing Iteration

The sole of the footwear serves a role that has no parallel in the headwear. In the headwear system, the vest carries the electronics while the headband carries only the pumps. In footwear, the sole must perform all of these functions simultaneously: it is the structural foundation that bears the wearer's full body weight, the enclosure that houses every electronic component, and the wearable interface in direct contact with the foot. Designing a single 3D printed structure to satisfy all three requirements was the most iteration-intensive challenge of the entire project.

5.4.4.1 Components' bedroom in the Sole

The sole contains the complete electronics system: an Adafruit QT Py microcontroller, a 5V 2000mAh rechargeable lithium battery, a 6V air pump, and all wiring connections to the insole sensors above and the tubing channels in the upper. A USB charging port is positioned at the heel, allowing the battery to be recharged without disassembling the shoe. All of these components must fit within a structure thin enough to function as a shoe sole while remaining accessible for maintenance.



[Figure 5.32: Cutaway of final sole showing internal component layout: QT Py, battery, pump, wiring, and charging port position and modular sensors placed in liner]

5.4.4.2 Four Iterations

The sole went through four versions before arriving at the final design. The progression, summarized in the comparison (See table 5,3), moved from solving basic dimensional problems (components not fitting) through structural challenges (instability and crushing risk under body weight) to integration refinements (wire routing and charging access). Each version was physically printed and worn during walking tests, as many of the problems, particularly the instability and component compression, could only be discovered through direct bodily experience under real walking conditions.

	V1	**V2**	**V3**	**V4**
Core problem	Too small, components do not fit	Unstable when walking, components too tightly packed, risk of crushing	Wire routing issues, no charging port	N/A
Key change	First attempt at housing electronics in sole	Enlarged internal cavities, better space distribution	Reinforced structure, improved component layout	Optimized wire channels, added heel charging port
Remaining issue	Components do not fit	Walking instability, risk of crushing electronics	No charging access, poor wire management	Final prototype

[Table 5.3: four-version footwear progression, with hardware changes at each stage]

5.4.4.3 Modular Layer System

The sole is designed as the bottom layer of a four-part modular system. The insole with embedded pressure sensors sits on top and can be lifted out independently. The upper, with its integrated tubing channels, connects to the sole through a defined interface where tubing and sensor wires pass between layers. The inflation units attach to the upper and can be swapped without affecting any other layer.

This modularity was a deliberate response to the realities of iterative prototyping and extended wearing. If a sensor malfunctioned, only the insole needed attention. If an inflation unit failed, it could be replaced in seconds. If a wire came loose inside the sole, the upper could be detached to access the internals. Without this layered approach, any single failure would require disassembling the entire shoe, a situation that would be impractical during daily wear.

5.4.4.4 Designing for Concealment Under Constraint

Unlike the headwear, where the vest provides ample volume for electronics and the headband only needs to house two small pumps, the footwear must hide everything within the constrained geometry of a shoe sole. Every cubic centimeter matters. The charging port had to be small enough not to compromise structural integrity. The pump had to be oriented to connect efficiently with the tubing in the upper above. The battery had to be positioned where it would not create a pressure point under the foot.

These constraints meant that the core design principle of making technology invisible was harder to achieve in the footwear than in the headwear. The headwear could distribute components across two separate garments (vest and headband). The footwear had to solve everything within a single, compact, weight-bearing structure. The four iterations of the sole represent the progressive resolution of this challenge, arriving at a design where all electronics are fully enclosed and invisible from the outside.

5.4.5 Inflation Units: Configuration on Footwear

Six modular inflation units are clustered on the dorsal surface of the foot, the area most visible when looking down at the shoe. Unlike the headwear, where units are evenly spaced along a linear arc, the footwear units are grouped together in a tight arrangement that blooms outward as a single mass when inflated. This clustering creates a more concentrated visual transformation, appropriate for a body location that is already at the edge of social gaze and needs a bolder change to be noticed.

Each unit slots into a mounting point on the upper and can be removed and replaced independently, using the same modular approach as the headwear. The stacking configurations and fabrication method are identical to those described in Section 5.2.2.

Air tubing is embedded within the 3D printed upper(see Figure 5.34), running from each unit’s mounting point down through integrated channels into the sole, where it connects to the 6V pump. When triggered, the single pump inflates all five units simultaneously. Because the tubing channels are built into the printed structure of the upper itself, no external tubing is visible on the shoe’s surface. When deflated, the units sit as flat, barely noticeable forms on the top of the shoe. When inflated, they bloom upward together, transforming the shoe’s silhouette.

[Figure 5.33: Top view of footwear showing unit placement on dorsal surface; deflated (relexed) vs. inflated states(nervous/awkward)]

[Figure 5.34: Cross-section of upper showing embedded tubing channels routing from units down to sole]

The inflation units required minimal iteration for the footwear, as the shape design and stacking method had already been refined during the headwear development. The main adaptation was adjusting the mounting interface to work with the 3D printed upper rather than the headwear's headband slots.

5.5 Chapter Summary

This chapter documented the fabrication of two emotion-responsive wearables: HRV-responsive headwear and plantar pressure-responsive footwear. The key technical contributions include the modified 3D printer heat-sealing method, which enables production of airtight TPU chambers through software-only G-code modification without altering the printer hardware; the variable-size stacking technique that transforms flat sealed chambers into organic three-dimensional inflation units; and the body-driven sensor layout derived from the wearer's own pressure mapping data. Both wearables were developed through hybrid craft (Nachtigall et al., 2019; Devendorf & Ryokai, 2015), combining heat-sealed TPU fabrication, 3D printing, and traditional fashion techniques. The following chapter presents what it was like to wear them.

Chapter 6: Findings

6.1 Introduction

This chapter shares what I learned from making, testing, and wearing the two emotion-responsive prototypes described in Chapter 5. These observations did not come from a single structured study period. Instead, they built up over months of development: trying on prototypes in the studio, testing them during walks around campus, showing them to friends, and going through repeated cycles of building, wearing, fixing, and rebuilding. The findings draw on my own embodied experience and self-reflection as both the designer and the wearer of these devices.

Rather than organizing by device or by timeline, this chapter is structured around four themes that surfaced through the wearing experience: how the wearables prompted me to notice my own emotions (Section 6.2), how the type of body signal shaped what it felt like to wear each device (Section 6.3), how technical problems revealed why the design philosophy matters (Section 6.4), and how the people around me and the setting I was in affected the experience (Section 6.5). Chapter 7 reflects on these findings through the lenses of Research through Design and the Design Framework for Social Wearables.

6.2 Emotional Self-Awareness Through Wearing

I started this project because I have difficulty recognizing my own emotions. The wearables were meant to make invisible body signals visible through inflation, turning internal states into something I and others could see. What I did not expect was that the act of wearing them would itself become a way of tuning into my emotions, even when the technology was not working perfectly.

The headwear showed this most clearly through sound. Even though I chose the smallest, quietest pumps I could find, the inflation was not completely silent. Each time the pumps kicked in, I could hear a faint whir. That sound became a kind of tap on the shoulder. It made me stop and ask myself: What am I feeling right now? What just happened that might have shifted my heart rate? The sound interrupted whatever I was doing and opened a small window for self-reflection, one that would not have existed without the device.

The footwear created a different kind of awareness. The pump inside the sole was nearly inaudible, but I could feel a gentle vibration through my foot when it turned on. This was subtler and more private than the headwear's sound. Where the headwear pulled me out of the moment to ask "what's going on?", the footwear gave me a quiet nudge, a physical hint that my body was reacting to something before my conscious mind had caught up.

In both cases, the wearables created what I think of as moments of bodily listening. The original goal was to make emotions visible to other people. But the first person who benefited was me. The devices did not just display my emotions outward; they reflected them back to me, giving me access to information about myself that I usually miss. For someone who struggles to read their own emotional states, this turned out to be the most personally meaningful part of the project.

6.3 Control and Agency: Voluntary vs. Involuntary Signals

One of the biggest surprises was how differently the two wearables felt to wear, based on whether I could control the signal that triggers them.

The headwear responds to heart rate variability, something I have no conscious control over. Wearing it felt like being watched by my own device. When the pumps activated, I could never be sure whether the inflation meant I was actually experiencing an emotional shift or whether the sensor had simply glitched. The pulse sensor was unstable during extended wear, sometimes losing contact with my earlobe and producing erratic readings. This made the uncertainty worse: was the system picking up on my emotions, or just malfunctioning? I ended up in a strange loop where my anxiety about whether the device was working correctly became itself a source of the very arousal the device was meant to detect.

The footwear was a completely different experience. It responds to plantar pressure, a signal that can be both unconscious and deliberate. Toe-gripping happens naturally during moments of discomfort, but I can also do it on purpose. This changed everything. Instead of feeling monitored, I felt like I was having a conversation with the device. I caught myself deliberately gripping my toes just to watch the inflation units bloom on the top of my foot. The experience became playful. I was not worried about whether the system was working because I could test it any time I wanted.

This contrast pointed to something I had not thought about during the design process: the type of body signal does not just affect the technical design; it shapes the entire feeling of wearing the device. When the signal is involuntary, the wearer is passive, receiving information about themselves but with no control over the display. When the signal is voluntary (or can be), the wearer becomes an active participant who can engage with the device on their own terms. The same core concept, inflation driven by a body signal, created two fundamentally different experiences.

6.4 When Technology Fails to Disappear

Throughout fabrication, the guiding principle was to make the technology invisible so the emotional display could be the focus. Wearing the prototypes put this principle to the test, and the moments when it failed made its importance very clear.

The headwear was the bigger challenge. The ESP32-S3 needed a manual restart every time it was powered on before it would run the code. So each wearing session started with a technical routine: power on, restart, wait, check that it was running. Before I could experience the wearable as an emotional device, I had to manage it as a piece of technology. Battery life added another layer of worry.

With two separate power sources (one for the pumps, one for the microcontroller), I was always tracking charge levels in the back of my mind. If either ran out mid-session, the whole experience would simply stop.

The footwear did better at hiding itself in some ways. The pump sound was nearly imperceptible, and all the electronics were sealed inside the sole. But the weight was hard to ignore. The sole was printed at 60% infill to protect the components inside, which made the shoe noticeably heavy, similar to a chunky platform shoe. It was stable enough to walk in, but the heaviness was a constant reminder that I was not wearing an ordinary shoe. I also worried about the sole separating from the upper during walking, which led me to design a strap that binds the foot, sole, and upper together. The strap helped a lot with my sense of security, but the fact that I needed it at all showed that my attention was still partly on the technology instead of on my emotional experience.

All of these moments shared something in common: they pulled my focus away from what I was feeling and toward whether the device was working. Instead of noticing my emotions, I was thinking about sensors, batteries, and structural integrity. This was not just an inconvenience. It directly got in the way of what the wearable was supposed to do. If the point is to make internal emotions visible, the wearer needs to be thinking about their feelings, not about the machine.

At the same time, these failures made me more certain that the design philosophy is right. The moments when the technology truly was invisible were the moments the wearable worked best. The footwear's quiet vibration, the headwear's visual bloom caught in a mirror: these worked because the mechanism was not asking for attention. Making technology disappear is not just about aesthetics. It is a functional requirement. Without it, the emotional purpose of the wearable gets lost.

6.5 Social Perception and Context

Most of my wearing happened in the school's studio, where my classmates knew about my project. This made the experience feel relatively normal. People understood what the devices were, asked thoughtful questions, and treated them as design objects rather than something strange. Being in a familiar environment with an informed audience made it much easier to wear the prototypes without feeling self-conscious.

When I showed the wearables to friends outside the studio, their reactions were positive and, more importantly, went in the direction I had hoped for. Nobody connected the devices to medical equipment or mental health issues. The typical reaction was curiosity and excitement. People were drawn to the visual transformation, the organic quality of the blooming inflation, and the idea that clothing could respond to what is happening inside the body. The conversations that followed were about fashion, technology, and self-expression, never about illness.

This response touched on something that has motivated this project from the start. By placing sensing technology inside objects that look and feel like fashion, the wearables avoid the implicit message that medical devices carry: that wearing one means something is wrong. The emotional data is still being captured and made visible, but the social meaning of the object is different. It reads as expressive rather than clinical.

Despite my initial plan, I have not yet been able to test these wearable devices in public. I have not worn either prototype in a fully public space where strangers have no idea what the devices are. The studio and friend demonstrations were done in a supportive, informed settings. Whether the fashion framing holds when unfamiliar people encounter the wearables, whether they see them as interesting accessories or odd attachments, is still an open question discussed in Chapter 7.

Chapter 7. Discussion and Future Work

7.1 Reflection on Findings

The findings from Chapter 6 show that wearing emotion-responsive wearables is shaped by factors I did not fully expect during the design process.

The most surprising discovery was the difference between voluntary and involuntary signals. I had thought of the headwear and footwear as two versions of the same idea: take an invisible signal and make it visible through inflation. They produced completely different relationships between me and the device. This highlighted that when designing future biosignal-driven wearables, designers need to think carefully about not just what to detect, but how much control the wearer has over the signal. This control directly determines whether wearing the device feels like being monitored or like engaging in a conversation. Furthermore, the enhancement of self-awareness was an unexpected outcome. The self-awareness aspect was also unexpected. I designed these wearables to show emotions to others, but the most consistent observer was myself. For someone who struggles to read their own emotions, this reflective quality may actually matter more than the social display. The wearables worked as a kind of emotional mirror, turning body signals I usually ignore into something I could notice and think about.

The findings about technology visibility confirmed the design philosophy but also showed how fragile it is. When concealment works, the wearable feels like an extension of the body. When it breaks, even briefly through a sound, a restart, or a heavy sole, attention immediately shifts from emotion to device. For this type of wearable, the tolerance for technical visibility is much lower than for devices where function matters more than experiential flow.

As someone trained in footwear design, the hybrid craft approach also changed something fundamental about how I relate to the making process. In traditional shoemaking, the shoe must be shaped and dried on the last over extended periods before it can be removed and worn. There is no fitting during construction, no chance to adjust mid-process. Every measurement and decision must be right from the start. This is fundamentally different from garment-making, where a designer can cut a muslin, fit it on the body, adjust, and refit within hours. Traditional shoemaking has never had that iterative flexibility. 3D printing gave it that flexibility for the first time in my experience. The four versions of the sole were each printed, worn, evaluated, and reprinted within days. Problems like the weight, the instability, and the missing charging port only became apparent through wearing, and could only be resolved because the next version could be produced quickly enough to test again. Without this rapid cycle, the footwear prototype would not have reached a wearable state within the timeline of this project. Hybrid craft did not just combine traditional and digital methods; it gave shoemaking the same capacity for continuous refinement that garment-making has always had.

The social perception finding, while based on limited testing, hints at a genuinely different path for body-monitoring technology. If devices that track emotional and physiological states can exist as fashion objects rather than medical tools, they may reach people who would never accept something clinical. This is not about hiding medical technology inside clothing. It is about understanding that the social meaning of an object affects whether people are willing to wear it, and that fashion offers a space where responsiveness to the body can be celebrated rather than treated as a sign of something wrong.

7.2 Evaluating Through the Lenses of Research through Design

Chapter 4.1 defined four lenses proposed by Zimmerman et al. (2007) for evaluating Research through Design contributions. This section applies them to the outcomes of this project.

Process. The development of both wearables followed an iterative cycle of making, wearing, evaluating, and remaking, documented in Chapter 5. The headwear progressed through four versions, the footwear sole through four iterations, and the heat-sealing method through four approaches before arriving at the modified 3D printer. Following the logic of haute couture fitting, each version was worn and evaluated on my own body, with the felt experience of wearing directly informing the next design decision. Dagan et al.'s (2019) framework functioned as a design tool throughout this process, prompting structured questions about sensing, actuation, and commitment at each stage, not only as an analytical lens applied after the fact.

Invention. Three original technical contributions emerged: the software-only modified 3D printer heat-sealing method (Section 5.2.1), the variable-size stacking technique for organic perpendicular inflation (Section 5.2.2), and the body-driven sensor layout derived from the wearer's own pressure mapping (Section 5.4.2). Beyond fabrication, the comparative design structure itself is a methodological contribution: placing the same inflation mechanism at two body locations with different social visibility produced the voluntary versus involuntary finding (Section 6.3), which was not predicted by the framework and extends existing understanding of how biosignal type shapes wearing experience.

Relevance. The project addresses nonverbal emotional expression for people who struggle to recognize and articulate emotions verbally. The fashion framing finding (Section 6.5) demonstrates that body-monitoring technology can exist as empowerment rather than diagnosis, because the social meaning of the object directly affects whether people are willing to wear it.

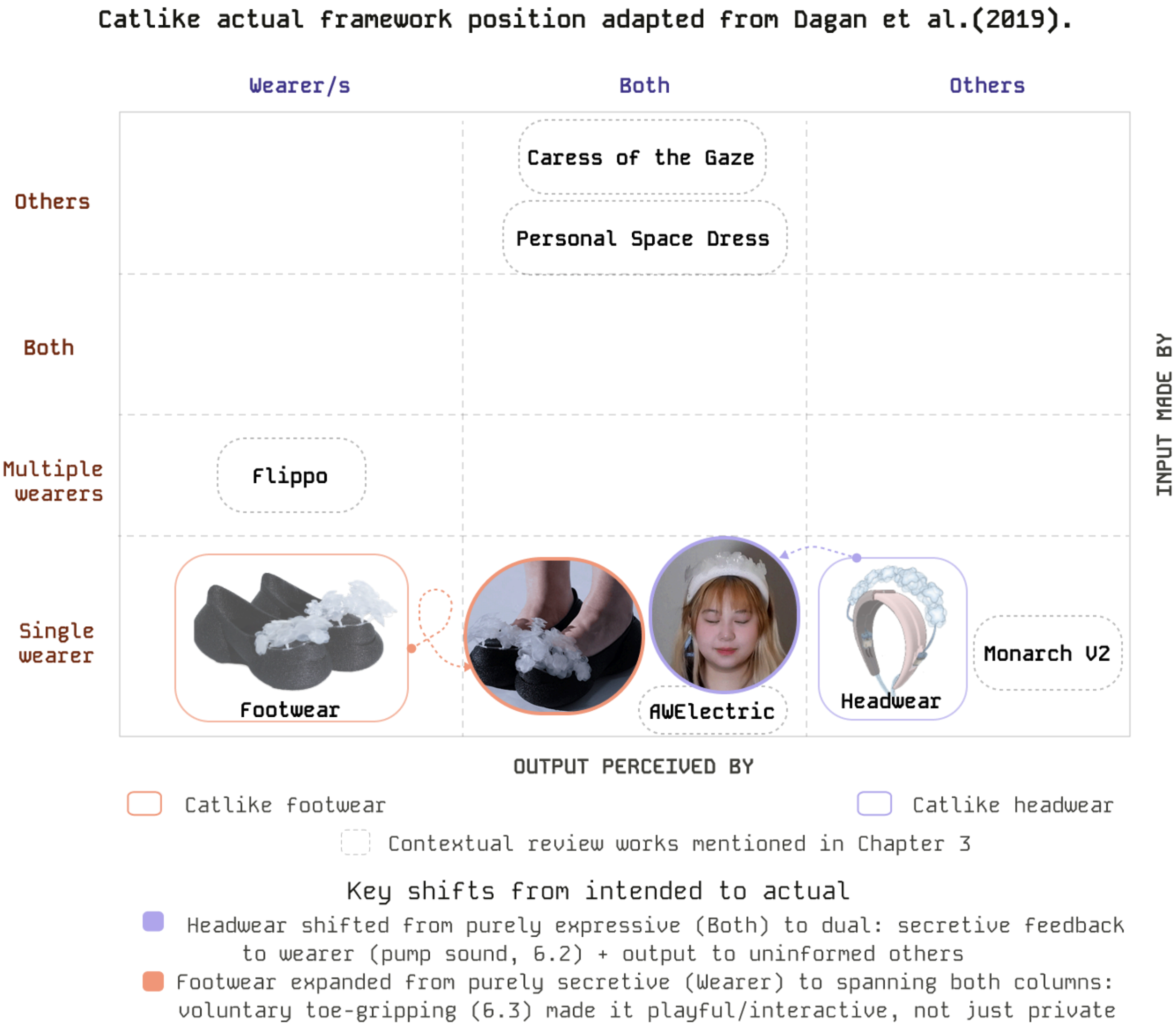
Extensibility. The heat-sealing method is reproducible by other makers using consumer equipment, already validated through a workshop. The voluntary versus involuntary finding offers a design guideline: wearer control over the triggering signal should be treated as a primary design variable. The framework extensions discussed in Section 7.3 provide conceptual tools applicable to other social wearable designs.

7.3 Situating Within the Design Framework for Social Wearables

Mapping the two wearables onto Dagan et al.'s (2019) Design Framework for Social Wearables helps situate these findings within a broader design vocabulary. The framework asks designers to consider sensing, actuating, their interplay, personal and social requirements, and social acceptability.

The input for both wearables is made by by the wearer alone, with outputs that are secretive to the wearer (pump sound, vibration) and magical to uninformed others (visible inflation with no apparent trigger). However, the experience of wearing them diverged in ways the framework's categories alone do not fully capture.

Figure 4.1 shows where both devices were intended to sit within the framework. Figure 7.1 updates these positions based on the wearing experience. Both devices expanded beyond their intended single-cell positions: the headwear acquired an unexpected secretive dimension through pump sound as self-reflection (Section 6.2), while the footwear's voluntary activation potential (Section 6.3) shifted it from purely secretive toward interactive and expressive.



Key shifts from intended to actual

- Headwear shifted from purely expressive (Both) to dual: secretive feedback to wearer (pump sound, 6.2) + output to uninformed others
- Footwear expanded from purely secretive (Wearer) to spanning both columns: voluntary toe-gripping (6.3) made it playful/interactive, not just private

[Figure 7.1. Actual framework position of Catlike headwear and footwear after wearing, compared to intended positions from Figure 4.1. Adapted from Dagan et al. (2019)**.]**

The most significant extension concerns the framework's sensing dimension, specifically the question of intentionality. Dagan et al. ask whether device activation is intentional or automatic, and whether it is triggered by the wearer or by others. My findings suggest that this dimension has experiential consequences beyond what the framework currently articulates. The headwear sits firmly in the wearer-triggered, not-intentional zone: HRV is automatic and outside conscious control. The footwear spans both intentional and non-intentional activation: toe-gripping happens unconsciously during emotional discomfort but can also be performed deliberately. This dual positioning is not just a technical distinction. It fundamentally determines the quality of the wearer's relationship with the device, whether that relationship feels like passive monitoring or active dialogue. Future iterations of the framework might benefit from treating signal voluntariness not as a binary classification but as a spectrum that directly predicts wearer agency and experiential quality.

The framework's actuating dimension categorizes output by sensory channel and noticeability. My experience revealed that unintended outputs can serve functions not anticipated in the design. The pump sound was designed to be minimized, yet it became the primary trigger for emotional self-reflection. The footwear's vibration, similarly unintended as a feedback channel, provided a private bodily nudge. These accidental feedback loops suggest that designers of social wearables should consider not only the intended actuation but also the secondary sensory effects of the mechanism itself, as these may shape the wearer's experience as much as the primary output.

The framework treats personal and social requirements (the commitment level demanded from the wearer) as a relatively stable design property. My findings show that this level is dynamic rather than fixed. Both wearables were designed for low commitment: the wearer should be able to go about daily activities without attending to the device. But technical failures (sensor instability, required restarts, battery anxiety, sole weight) involuntarily raised the commitment level, pulling attention from emotional experience toward device management. This suggests that for emotion-responsive wearables, technical reliability is not merely a quality-of-life improvement but a direct determinant of whether the device achieves its intended commitment level and, by extension, its social purpose.

Finally, the framework's social acceptability dimension is confirmed and extended by the fashion framing finding. Dagan et al. note that what is considered socially acceptable changes over time and across contexts. My wearables add that the framing of the object itself, whether it reads as fashion or as a medical device, fundamentally shapes social acceptability independent of its technical function. The same sensing and actuating capabilities, embedded in a clinical-looking device, would likely produce very different social responses than they do when embedded in objects that read as expressive accessories.

7.4 Limitations

The original research plan included a structured 8-day autoethnographic study conducted in campus studios and outdoor streets. Due to the time commitment and complexity of iteratively designing and fabricating two categories of fashionable technology devices, the intended formal study was ultimately determined to be out of scope. The findings presented in Chapter 6 are drawn instead from the accumulated brief but frequent experiences of casually wearing the prototypes throughout the development process, including studio testing, campus walks, and demonstrations to peers. While these experiences provided substantial first-person insight into the lived reality of wearing emotion-responsive devices, they are more limited in scope than a structured deployment would have been.

Several specific limitations should be acknowledged. The wearing experience took place almost entirely in the school's studio, a familiar and supportive environment where my peers understood the project. I have not yet worn the prototypes in fully public settings where strangers would encounter them without context. The social perception findings (Section 6.5) are therefore based on informed, sympathetic audiences and may not reflect how the wearables would be received by unfamiliar observers.

The technical instability of the headwear's pulse sensor made it difficult to separate findings about the emotional wearing experience from frustration with the technology. A more reliable sensor would likely produce a different experiential quality, and some of the anxiety I attributed to the involuntary nature of HRV may have been amplified by uncertainty about whether the system was functioning correctly.

The footwear's weight and structural concerns, while addressed through iterative design, remained noticeable during wearing. A lighter, more refined prototype might shift the wearing experience further toward the emotional and away from the physical awareness of the device.

Finally, as a single person's reflective account, these findings reflect one wearer's experience. Different wearers with different bodies, emotional patterns, and relationships to technology would likely report different experiences. The findings should be read as a detailed first-person account that generates insights and questions, rather than as generalizable conclusions.

7.5 Future Work

Several directions for future work emerge from this project.

Structured wearing study. The most immediate next step is conducting the originally planned comparative wearing study. The study would follow an 8-day structure, wearing the headwear and footwear across two environments. Studio sessions (Days 1-4) would test both devices in the familiar OCAD University studio for one to two hours each day, beginning with the headwear (Days 1-2) and shifting to the footwear (Days 3-4) to maintain location consistency while changing body location. Outdoor sessions (Days 5-8) would extend testing to quiet streets near campus, introducing real-world variety and unfamiliar social encounters. This step-by-step approach, beginning in familiar surroundings before progressing to the more unpredictable outdoor environment, would reduce initial anxiety while building continuity of experience. Shifting between devices rather than wearing both simultaneously would allow focused attention on each body location's distinct experiential qualities. Detailed data collection methods and analytical approach for this study are provided in Appendix C.

Beyond the single wearer. This project was developed and tested on a single body, my own. But the original motivation was never purely personal. Approximately 10% of the general population experiences alexithymia, difficulty recognizing and expressing emotions (Ricciardi et al., 2015). For these individuals, emotion-responsive wearables could serve as tools for developing emotional awareness, making invisible physiological states visible in a way that supports self-recognition over time. Equally important, caregivers and people around those with emotional difficulties often struggle to understand what the person is feeling. A wearable that externalizes physiological correlates of emotional arousal could offer a nonverbal channel of communication, giving caregivers a way to notice emotional shifts without requiring the wearer to articulate them verbally. Future work should test these wearables with a broader range of wearers, including individuals with alexithymia and their caregivers, to understand how the wearing experience differs across bodies, emotional patterns, and social contexts. The voluntary versus involuntary finding from this project (Section 6.3) suggests that the footwear's semi-voluntary activation may be particularly suited to this population, as it offers the wearer a sense of agency over when and how their emotions become visible.

Heat-sealing toolkit. The modified 3D printer heat-sealing method has potential beyond this project. The technique could be developed into a more accessible toolkit or workshop format, building on the workshop I already conducted. Making the G-code modification process more streamlined, perhaps through a dedicated software tool that automates the .3mf extraction and parameter adjustment, would lower the barrier for other makers and researchers working with TPU pneumatics.

Biosignal refinement for headwear. The current HRV-based sensing proved unstable during extended wear, with the earlobe pulse sensor frequently losing contact and producing erratic readings (Section 6.4). This instability made it difficult to separate genuine emotional responses from sensor malfunction, and contributed to the anxiety loop described in Section 6.3. Future iterations should explore electroencephalography (EEG) as an alternative biosignal source for the headwear. EEG measures electrical activity in the brain and can detect emotional arousal states with greater reliability than peripheral pulse sensing. The head is also the natural location for EEG sensors, eliminating the need for remote sensing from the earlobe. This would address two problems simultaneously: improving signal reliability and reducing the technical anxiety that undermined the emotional purpose of the device. However, EEG introduces its own challenges, including sensor comfort for extended wear and the complexity of interpreting brainwave data as emotional triggers, which would require further research.

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Appendix A: Heat-Sealing Parameter Reference

This appendix documents the systematic testing of four heat-sealing approaches explored during the fabrication of TPU pneumatic chambers. The first three methods (A.1–A.3) are manual approaches that informed the development of the modified 3D printer method described in Section 5.2. The fourth (A.4) documents the final G-code parameters used in production.

A.1 Material Selection: TPU Film Thickness

TPU films were sourced from a fashion fabric supplier in three thicknesses: 0.015mm, 0.03mm, and 0.05mm. Thinner films create units with minimal material presence, allowing the inflation movement itself to read as an organic transformation rather than an obvious mechanical actuation. The 0.015mm film proved too fragile for any sealing method and was abandoned early. The 0.03mm and 0.05mm films were used throughout subsequent testing.

A.2 Attempt 1: Soldering Iron and Household Iron

The soldering iron failed immediately. Even at the lowest temperature setting, direct contact melted completely through the TPU, leaving holes while the surrounding areas deformed from radiant heat. The 0.015mm film was especially vulnerable. A single touch destroyed the material. The tool could not provide the controlled, distributed heat necessary for sealing.

The household iron offered more gradual temperature control through fabric-type settings. A technique was developed using parchment paper cut to the desired pattern shape, positioned between stacked TPU layers as a heat barrier.

Setting	Temperature	Result
Silk	Lowest	No bonding, insufficient heat
Wool	Medium	Sealing began, but scattered bubbles appeared
Cotton	Higher	Dense clusters of small holes, similar to soldering iron damage

[Table A.1. Household iron temperature testing with 0.03mm TPU film.]

The bubbling at the wool setting was not caused by trapped air from the initial layering, but by many tiny bubbles spread across the sealed areas. Two likely causes were identified: the wide, flat surface of the iron caused uneven pressure and inconsistent heat transfer, and residual moisture inside the iron turned to vapor when contacting the waterproof TPU, disrupting the bonding process. Different techniques to reduce the bubbles did not help. The iron's large, flat surface trapped air and moisture with no escape path. Neither the soldering iron (focused point heat) nor the household iron (distributed surface heat) could apply heat in a controlled, even way.

A.3 Attempt 2: Hair Straightener with Sandwich Structure

The hair straightener (digital temperature control) proved more promising. Its clamp created steady pressure over a small area, and the digital temperature display enabled systematic testing. The straight, flat plates suggested a pull-through approach: instead of pressing down, the layered material was pulled through closed heated plates, heating along the direction of movement.

A sandwich construction was developed: parchment paper on the outside layers for protection, with two TPU film layers surrounding a paper pattern template in the center. The paper template defined the sealed region, since areas covered by paper would not receive direct heat and would remain unsealed, creating the air chamber.

Temp (°F)	Pulls	TPU (mm)	Airtight	Result	Observations
250	5	0.03	Y	Fail	Leaked after 3rd inflation test
250	8	0.03	Y	Fail	Leaked after 5th inflation test
250	10	0.03	N	Fail	Bubbles along pattern edge
265	5	0.03	Y	Fail	Leaked after 5th inflation test
265	8	0.03	N	Fail	Bubbles along pattern edge
265	5	0.05	N	Fail	Only partial points sealed
265	8	0.05	N	Fail	Only small portions sealed
265	10	0.05	N	Fail	Leaked after 2nd inflation test
285	5	0.03	Y	Success	10+ tests, no leakage
285	5	0.05	N	Fail	Leaked after 3rd inflation test
285	8	0.05	Y	Success	10+ tests, no leakage
300	5	0.03	Y	Fail	Bubbles along pattern edge
300	5	0.05	Y	Success	10+ tests, no leakage

[Table A.2. Hair straightener parameter testing across temperature, pull count, and TPU thickness]

The data revealed a narrow optimal temperature range. At 250°F and 265°F, seals initially appeared sound but failed after repeated inflation because the TPU layers bonded only at the surface without fully fusing. At 300°F, excessive heat created edge bubbles. The optimal temperature was 285°F: 0.03mm TPU required 5 pulls for a durable airtight seal, while 0.05mm TPU required 8 pulls.

Once reliable sealing parameters were established, a new issue emerged: inconsistent unit sizes. All paper templates were hand-drawn and hand-cut, producing small variations between pieces. Since the final structures required many identical units assembled together, these variations caused alignment problems. A sturdy pattern template was designed and 3D printed for tracing, which improved consistency, but some variation remained because cutting was still manual.

A.4 Attempt 3: Cricut Heat Press for Semi-Batch Production

The hair straightener produced reliable seals but could not be scaled. Making one unit at a time was too slow for prototype production. Switching to a Cricut heat press with a Cricut Maker cutting machine improved the process in two ways: digital cutting ensured accurate template shapes, and the larger press surface allowed processing approximately six units per batch.

The workflow proceeded as follows: (1) Design shapes in Adobe Illustrator as vector lines. (2) Upload to Cricut Design Space and conFigure for paper cutting. (3) Cut paper templates with Cricut Maker. (4) Prepare heat press layers (bottom to top): 3mm silicone mat, first TPU layer misted with water, paper templates with 1cm spacing, second TPU layer misted with water, parchment paper cover. (5) Apply progressive heat: 230°F for 30s, 250°F for 30s, 280°F for 30s, 300°F for 30s. (6) Remove assembly and trim sealed units, leaving 2–3mm margin from pattern edge. (7) Extract paper templates using tweezers. (8) Re-seal openings with hair straightener.

Several aspects required calibration. The water mist temporarily adhered the ultra-thin TPU films to the surface, preventing misalignment and wrinkles that would trap air during pressing. The gradual temperature increase proved most reliable for removing bubbles by allowing trapped air to escape incrementally as the TPU softened. The 2–3mm trimming margin prevented accidentally cutting through the paper template inside.

The template extraction step remained the critical failure point. The paper had to be physically removed from the sealed chamber before use, since its thickness would affect inflation. This required cutting a small opening, inserting tweezers to grip and pull out the paper, and resealing the opening with a hair straightener. Complex pattern shapes made full paper removal difficult, with fragments often remaining trapped inside. The irregular opening made consistent resealing unreliable. During production of the second prototype, over twenty units were made using this method. The overall failure rate was high, with approximately one-third of units usable.

More importantly, this method still depended on the paper template that limited all previous approaches. The paper acted as a heat barrier defining sealed areas, but it also prevented complex geometries. Any pattern with internal features or tight curves needed the paper to be removable, which was not possible for many of the intended designs.

A.5 Method 4: Modified 3D Printer G-code Parameters

The modified Bambu A1mini method eliminated the paper template entirely, resolving the fundamental limitation shared by all manual methods. Two TPU thickness configurations were tested and validated:

Parameter	0.03mm TPU	0.05mm TPU
Nozzle temperature	M104 S245	M104 S260
Bed temperature	M140 S0 (off)	M140 S0 (off)
Z-offset	-0.1mm	-0.15mm + G29.1 Z-0.02
Extrusion multiplier	M221 S120 (120%)	M221 S120 (120%)
Travel speed	G1 F180 (3mm/s)	G1 F180 (3mm/s)
Fan	M106 S0 (off)	M106 S0 (off)
Retraction	Disabled	Disabled
Layer count	1	1

[Table A.3. Modified 3D printer G-code parameters by TPU thickness.]

Command	Function
G28	Home all axes
G29	Auto bed leveling
G29.1 Z-0.02	Fine Z-offset adjustment (0.05mm TPU only)
M104 S245/S260	Set nozzle temperature
M140 S0	Disable bed heater
M106 S0	Disable cooling fan
M221 S120	Set extrusion flow to 120%
G1 F180	Set movement speed to 3mm/s

[Table A.4. G-code command reference.]

The full fabrication method, design rationale, and comparison with prior approaches are documented in Section 5.2.

Appendix B: Bambu G-code Modification Guide

B.1 Workflow: .3mf to Modified G-code

The Bambu A1mini uses a proprietary .3mf file format that does not allow direct G-code input. The following workaround extracts, modifies, and repacks the G-code within the .3mf container.

- Step 1. Design the seal path in any CAD or vector software and export as a single-layer 3D model (0.2mm height).
- Step 2. Import the model into Bambu Studio. Set layer height to 0.2mm, single layer, no infill, no top/bottom layers. Slice and export as .3mf file.
- Step 3. Rename the .3mf file extension to .zip.
- Step 4. Extract the .zip archive. Navigate to the Metadata folder and locate the plate_1.gcode file (or equivalent).
- Step 5. Open the .gcode file in a text editor. Locate the movement commands (G1 lines) that define the seal path.
- Step 6. Insert the following parameter modifications before the movement commands: *M104 S245 (nozzle temp, adjust for TPU thickness); M140 S0 (bed heater off); M106 S0 (fan off); M221 S120 (extrusion 120%); G1 F180 (speed 3mm/s).*
- Step 7. Save the modified .gcode file.
- Step 8. Repack the extracted folder into a .zip archive and rename back to .3mf.
- Step 9. Transfer the modified .3mf to the printer via SD card or Bambu Studio network transfer.

B.2 Bambu Studio Slicer Settings

Setting	Value
Layer height	0.2mm
Number of layers	1
Infill	0%
Top/bottom layers	0
Wall count	1
Filament	Generic PLA (placeholder, not extruded)
Support	None
Brim	None

These settings generate the minimal toolpath needed. The actual sealing is performed by the heated nozzle pressing against the TPU layers, not by filament extrusion.

B.3 Troubleshooting

Issue	Cause	Solution
TPU not sealed	Temperature too low	Increase nozzle temp by 5°C increments
TPU melted through	Temp too high or speed too slow	Decrease temp or increase speed (F200)
Uneven seal	Z-offset too high	Decrease Z-offset by 0.01mm increments
Seal breaks under pressure	Incomplete contact	Add G29.1 fine adjustment, increase extrusion
.3mf rejected by printer	Incorrect repack	Ensure folder structure matches original exactly

B.4 File Process Script

Modify Bambu Lab 3D printers into a TPU heat-sealing tool by patching G-code through: https://github.com/Thearetically-speaking/All-you-can-seal

This is a small Python utility that rewrites the G-code inside Bambu Studio's .gcode and .gcode.3mf files to repurpose any Bambu printer (tested on A1 mini and P1S) as a heat-sealing machine. Instead of extruding filament to build a 3D object, the modified printer traces a 2D path with the nozzle hovering just above the bed — fusing two layers of TPU film into a custom-shaped inflatable pouch.

Appendix C: Research Ethics and Study Protocol

C.1 Ethics Approval

This research received approval from OCAD University's Research Ethics Board (REB File No. 102847) under Principal Investigator Kate Hartman and Co-Supervisor Nicholas Puckett. The original approval covered a structured 8-day wearing study. The actual scope narrowed to self-only wearing during the development process, reducing associated risks. The approved protocol is preserved below as the basis for future work described in Section 7.5.

C.2 Original 8-Day Study Protocol

The following study was designed but not completed within the timeline of this research. It is included here as a reference for the future work described in Section 7.5.

The study follows an 8-day comparative structure wearing the headwear and footwear across two environments. Studio sessions (Days 1–4) test both devices in the OCAD University studio for one to two hours each day, beginning with the headwear (Days 1–2) and shifting to the footwear (Days 3–4) to maintain location consistency while changing body location. Outdoor sessions (Days 5–8) extend testing to quiet streets near campus, introducing real-world variety and unfamiliar social encounters.

Day	Device	Environment	Duration
1	Headwear	Studio	1–2 hours
2	Headwear	Studio	1–2 hours
3	Footwear	Studio	1–2 hours
4	Footwear	Studio	1–2 hours
5	Headwear	Outdoor (quiet streets)	1–2 hours
6	Headwear	Outdoor (quiet streets)	1–2 hours
7	Footwear	Outdoor (quiet streets)	1–2 hours
8	Footwear	Outdoor (quiet streets)	1–2 hours

[Table C.1. Planned 8-day study schedule.]

This step-by-step approach begins in familiar surroundings before progressing to the more unpredictable outdoor environment. Shifting between devices rather than wearing both simultaneously allows focused attention on each body location's distinct experiential qualities.

C.3 Planned Data Collection Methods

Video recording. Each wearing session would be recorded using a body-mounted camera (chest or shoulder level) to capture the wearer's perspective and a stationary camera to capture the overall scene. Video serves two purposes: documenting visible inflation events and their timing, and recording social interactions with observers.

Field notes. Structured written reflections would be completed within 15–20 minutes of each session, documenting the felt experience of wearing, notable moments of device activation, social encounters, technical issues, and emotional observations. A consistent template would ensure comparability across sessions.

Voice memos. Brief audio recordings would capture immediate observations during wearing when written notes are impractical, particularly during outdoor sessions.

Process photos. Still images would document the physical state of the devices before and after each session.

Biosignal data. Consistent with the approach described in Chapter 4, biosignal sensors would function as real-time triggers only. No physiological data would be stored or recorded for later analysis.

C.4 Planned Analytical Approach

Analysis would follow three phases:

During-session reflection. Awareness of device activation, emotional state, social context, and technical performance noted in real time through voice memos.

Post-session documentation. Structured field notes completed immediately after each session, organized by Dagan et al.'s (2019) framework dimensions: sensing (when and how activation was perceived), actuation (how inflation felt and appeared), visibility (how being observed affected experience), and personal requirements (how much attention the device demanded).

Cross-session thematic synthesis. After all eight sessions, themes would be identified across sessions through reflexive interpretation (Ellis et al., 2011; Gamboa et al., 2024), comparing headwear versus footwear experiences, studio versus outdoor environments, and changes across consecutive days of wearing.

C.5 Ethical Considerations and Risk Management

Participant safety. The sole participant is the researcher. Pre-testing of all electrical components ensures no risk of shock or burn. All wearable components are adjustable and can be removed immediately if discomfort occurs.

Psychological risk. Extended self-observation of emotional states may produce discomfort. Session duration is flexible and can be shortened or terminated at any time. Support resources include the OCAD University Student Wellness Centre, faculty supervisors (Kate Hartman, Nicholas Puckett), and the researcher’s personal therapist.

Environmental safety. Outdoor sessions are conducted on quiet streets near campus during daylight hours. The researcher carries a mobile phone and has informed a contact person of the session schedule.

Privacy of others. Informational posters are displayed in the studio to notify other space users that recording may occur. No other individuals are included as participants. If bystanders appear in outdoor recordings, their faces would be obscured in any published materials.

Data storage. Process photos, field notes, and video recordings are stored on encrypted drives and password-protected cloud storage accessible only to the researcher and supervisory committee. No biosignal data is stored at any point.