PneuMa: Designing Pneumatic Bodily Extensions for Supporting Movement in Everyday Life

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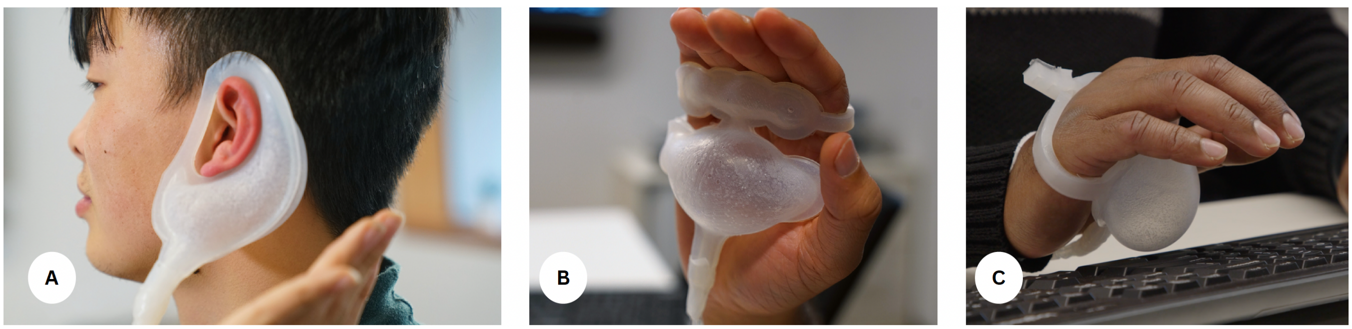

Figure 1: PneuMa Bodily Extensions: A) "Pardon", B) "Greetings", and C) "Take a break".

ABSTRACT

Prior research around the design of interactive systems has highlighted the benefits of supporting embodiment in everyday life. This resulted in the creation of body-centric systems that leverage movement. However, these advances supporting movement in everyday life, aligning with the embodiment theory, so far focused on sensing movement as opposed to facilitating movement. We present PneuMa, a novel wearable system that can facilitate movement in everyday life through pneumatic-based bodily extensions. We showcase the system through three examples: "Pardon?", moving the ear forward; "Greetings", moving a hand towards the "Bye-bye" gesture; "Take a break", moving the hands away from the keyboard, enabling the bodily extensions that support movement in everyday life. From the thematic analysis of a field study with 12 participants, we identified three themes: bodily awareness, Perception of the scenarios, and anticipating movement. We discuss our findings in relation to prior research around bodily extensions and embodied interaction to provide strategies to design bodily extensions that support movement in everyday life. Ultimately, we hope that our work helps more people profit from the benefits of everyday movement support.

CCS CONCEPTS

• **Human-centered computing** → *Human computer interaction (HCI)*; Interaction paradigms;

KEYWORDS

bodily extensions, pneumatics, embodied interactions, embodied experiences

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1 INTRODUCTION

The theory of embodied interaction has been explored extensively by several researchers to offer a wide range of applications [21, 37, 76]. Supporting embodiment in everyday life has been credited with tangible benefits for its users, such as speech production, memory recall, and temporal perception [17, 18, 20, 59]. Owing to these associated contributions, wearables that sense movements for users in everyday life have become prevalent in HCI research [36, 69, 77]. Although these advancements have been primarily focused towards sensing and feedback, there have been some explorations that function as an addition to the human body to facilitate novel experiences [10, 40]. The additions to the human body that physically alter or extend the structure of the body have been called "Bodily Extensions" [13, 49]. Bodily extensions offer a myriad of solutions ranging from accessibility [83], targeted feedback [63], motor functionality [78], or allowing super-normal capability [66].

Along with supporting embodiment, prior work has explored bodily extensions through a variety of lenses. Buruk et al. presented a series of bodily extensions through a phenomenological lens to explore the experiential aspects of using them [13]. Research efforts around both wearables and bodily extensions have been focused towards sensing movements [34, 57, 79]. However, both wearables and bodily extensions that induce movement while also extending the body have been sparingly explored.

Shape-changing wearables and bodily extensions have been proposed in several contexts, including novel interactions [35], virtual reality [71], accessibility [83], and games [70]. However, these systems have been focused on delivering assistance during specific tasks or delivering contextual feedback to the user engaged in a digital experience. Taken together, they miss the opportunity to facilitate an experience where the user moves the body as the eventual interaction, as learned from the embodiment theory. While there has been a recent interest in HCI to create applications that facilitate bodily movement (actuation), the means have been intrusive or have possessed an uncomfortable amount of weight to be wearable (bulky) [38]. Bodily actuation applications, primarily manifested through VR [71], force feedback [43, 44], and games [41, 51, 55, 56, 58] miss out on the opportunity to facilitate an embodied experience which in turn has the potential to increase awareness [37] and various other cognitive abilities [16–18, 54]. As a result, the roles of these technologies have been limited in the scope of everyday life and majorly reduced to short novel interactions owing to their issues with wearability, comfort and body conformity.

As highlighted by prior research, facilitating bodily movement in everyday life scenarios promotes embodiment [23]. Supporting embodiment through movement further leads to improvement in cognitive abilities as it associates sensorimotor feedback with the mind [37, 54]. Therefore, we present PneuMa, a novel wearable system for pneumatic-based bodily extensions to support movement in everyday life. We showcase the system through three examples: "Pardon?", moving the ear forward; "Greetings", moving a hand towards the "Bye-bye" gesture; "Take a break", moving the hands away from the keyboard. As we want to support "everyday life", i.e. enable users to wear the bodily extensions comfortably on their body while not restricting other movements [62], we leverage the soft material feel of silicone to create bodily extensions that support movement in everyday life. We borrow the term "bodily extensions" from Buruk et al.'s work [13], as our wearables, while facilitating bodily movement, also physically alter or extend the structure of the human body. In this paper, we demonstrate our system through two different inputs, speech and an automated timer (user configurable), to support bodily movement. We implemented three unique bodily extensions aiming to support the following scenarios in everyday life:

- Pardon?: Promoting a good-bye gesture by moving the user's hand towards such a gesture if the system senses the words "good-bye" (through a smartphone's microphone).
- Greetings: Moving a user's ear forward and enlarging it whenever the system senses the words "Beg your pardon?"
- Take a break: Moving the user's hands away from the keyboard in order to encourage a break from typing.

We present the design and implementation of the PneuMa system along with the three example bodily extensions. We also present the user experiences associated with using the bodily extensions in the form of themes emerging from a thematic analysis of data captured from 12 participants who used the bodily extensions over 7 days. We discovered three user experience themes: bodily awareness, Perception of the scenarios, and anticipating movement. Based on the knowledge of having designed the system and conducted the study, we also present actionable design implications for designers who want to create future bodily extensions for supporting movement in everyday life.

1.1 Contributions

Our paper makes the following contributions:

- First, system contribution in the form of the PneuMa system along with three example bodily extensions. The implementation knowledge could be beneficial for designers interested in creating bodily extensions based on different inputs across a variety of scenarios and product developers seeking inspiration on what bodily extensions can be created to support bodily movement.
- Second, the results from a field study with the PneuMa system with 12 participants consolidated into three user experience themes. These can be useful for user experience researchers aiming to understand how people experience emerging bodily extension systems.
- Third, we present three actionable design strategies emerging from our themes and reflect on similar prior work in HCI. These strategies can help practitioners seeking to design bodily extensions to support movement in everyday life.

Finally, we hope that our work contributes to the theoretical understanding of embodiment facilitated through bodily movement by engaging users in a provocative manner rather than presenting a specific technology solution to support movement in everyday life.

2 RELATED WORK

As our work touches upon embodiment as a result of extending the human body by facilitating movement through a pneumatic system, we now discuss prior work on embodied interaction, bodily extensions, and Pneumatic systems, from which we learned.

2.1 Embodied Interaction

Due to the tangible benefits associated with embodiment in everyday life, embodied interaction has been explored by a plethora of researchers [33, 37, 65]. For example, Kirsh, in his work on embodied cognition, talks about how humans use their bodies to preempt and perceive their actions and the world around them [37], speaking nicely to our approach of conducting a field study that leverages contextual through in the world around our participants to support bodily movements in everyday life. Prior research also suggested how motor movement aids in improving articulation in conversation, aligning with our approach to facilitate movement in "Pardon" and "Greetings" during conversations [16, 18]. Interaction designers have suggested frameworks to understand the implications of building body-centric systems and playful technological augmentations of the human body [24, 48].

The theory of embodied interaction has been adopted for the design of an extensive set of research systems and guidelines by HCI researchers [21, 37, 75]. While previous research indicates that there are various lenses on the application of embodied theory, in our work, we aim to explore the role of promoting movement through technology in an attempt to facilitate embodied experiences of everyday actions. As a result, we talk about interventions and creations primarily centred around leveraging or eliciting bodily movement [8, 77]. Several interactions and systems have been explored in Extended Reality (XR) research that use bodily movement to deliver novel experiences [1, 73, 81]. One such system, "YouMove", offers movement training in augmented reality by providing feedback for the user's movement on a mirror [4]. "Slide2Remember" proposed an interactive photo frame that enables users to view their photos in a multi-modal experience by combining auditory and visual stimulation [36]. Slide2Remember invoked the physical action of sliding a traditional photo frame to view a new photo, thereby eliciting movement within its users. Similarly, the research around tangible interfaces, which has been prevalent in HCI, shares common themes of interaction by invoking physical movement amongst its users [75].

Furthermore, researchers have also proposed a rendition of this theory to create systems that facilitate bodily movement, i.e., employed bodily actuation [15, 56, 64]. However, most of these advancements have been primarily leveraged technologies such as electrical muscle stimulation [44, 71] and exoskeletons [52, 80]. Bodily actuation through electrical muscle stimulation, specifically, has served as a keen interest of HCI researchers in enabling proprioceptive interaction [43], playful experiences [56], user authentication [14] as well as providing force feedback for mobile applications [44]. Bodily augmentation through exoskeletons has also been explored majorly for their assistive applications [64, 78] as well as their ability to facilitate movement [25, 62]. Hence, we also utilize actuation technology (pneumatics) to facilitate bodily movement. However, we find the prior approaches usually focus on specific use cases, situations, or expert tasks, probably due to the nature of the technologies used being considered not very body-conform. Prior work defined body-conform as technology that adapts or conforms to the morphology of the body and informed us that technologies that are more body-conforming are more likely to yield an engaging user experience, especially when the users might want to wear them for extended periods of time [49]. As EMS has been previously described as uncomfortable and sometimes painful [38] along with exoskeletons being criticized for being too heavy to wear outside expert use cases [31], we looked for alternative approaches to facilitate bodily movement. We were guided by prior work on bodily extensions as well as pneumatics, which we further explain in the sections below.

2.2 Bodily Extensions in HCI

In HCI, bodily extensions have been explored in the form of wearables prosthetics [15], and interactive textiles [74] to shape-changing interfaces [28]. Advancements in this area are largely centred around sensing [6, 52] and feedback [9] mechanisms that often leverage the location and movement of the body part to deliver contextual interaction and information. For the scope of our work, we focus on prior work around wearable bodily extensions that are catered towards facilitating novel experiences. We, hence, learned from prior work that alters the perception of one's body (body image), under the influence of a bodily extension that relates to our work and contribution [13].

In particular, researchers have created wearables that leverage physiological input to offer contextualized information to the user [3, 49, 69]. One system, "Wigglears", is a system that wiggles a user's ears based on galvanic skin response to promote playful situations in everyday life [60]. We learned that supporting everyday life using bodily extensions is possible and that not all application scenarios need to be serious. However, as their system used a motor to wiggle the ears, feedback was that the system was not the most comfortable to wear. In response, there seems to be still limited knowledge about how to design body-conform systems that extend our bodies.

Svanæs learned from Merleau-Ponty's phenomenology [45, 67] of the lived body when he created a mechanical tail and ears [66, 68]. Through the design process of creating these prototypes, Svanæs was able to articulate the challenges of creating bodily extensions that serve as a part of the user's body such that they can take advantage of the "bodily-kinesthetic intelligence". We believe that these challenges arrived, at least in part, due to the fact that the author used mechanical actuators that are not very body-conform. In response, we explore the use of pneumatics to create more body-conform wearables that might be able to better take advantage of the "bodily-kinesthetic intelligence".

Umezawa et al. investigated bodily ownership and representation through the addition of an artificial mechanical finger on a user's hand [72]. Their study showed that it is possible to perceive a sense of ownership over bodily extensions that affect a user's self-representation, forming a cognitive association with the mind. However, ownership of an independent artificial limb is difficult from a motor-sensory point-of-view as it requires a prolonged experience with such bodily extensions. As a result, we decided to allow the participants in our study to experience the system for seven days in a row.

2.3 Pneumatic Systems

Pneumatic systems have been increasingly explored due to their soft nature, occupying less space, and being lightweight, in applications such as VR [71], accessibility [83] and supporting haptic feedback [29], however, not in regards to bodily extensions (with a few exceptions [28, 69]).There have been several advances in lowering the threshold for the design and fabrication of pneumatic interfaces by creating rapid prototyping techniques [26], toolkits [82] and frameworks [22]. We discuss the learnings from these systems below.

"Menarche Bits" aims to motivate body movement through a shape-changing pneumatic interface [69]. Their work was directed towards facilitating body movements through intimate wearable technology, using physiological input, for young adolescents. We learned that designing shape-changing wearables can help a user reflect on their changing bodies by facilitating movement. While this work focuses on promoting the movement for a specific use case, knowledge about creating pneumatic-based bodily extensions that facilitate bodily movement in everyday life is still limited. With "OmniFiber", the authors presented a fluidic artificial muscle that changes its shape in response to an external stimulus [35]. OmniFiber supported an eclectic set of scenarios; hence we learned that pneumatic systems can be leveraged in everyday life. However, their pneumatic system primarily employed haptic feedback as a response to external input instead of initiating a movement, which we add with our work. Silveira et al. [2] explored a pneumatic system to guide lower limb movement for dancers. Their work helped by informing us how a system that could guide the users to perform specific movements would promote bodily engagement through embodied experiences. While their research investigated the creation of pneumatic wearables for prompting movement in the lower limb, there is limited knowledge on designing pneumatic bodily extensions to support movement of different parts of the body and also outside expert settings such as choreographed dance practice.

2.4 Gap and research question

Prior research has designed systems to support bodily movement through indirect means for invoking movement in daily scenarios. However, there appears to be limited knowledge on designing pneumatic-based bodily extensions that can directly support bodily movement in everyday life. Hence, in this paper, we begin answering the research question: how do we design pneumatic-based bodily extensions to support movement in everyday life?

3 DESIGNING PNEUMA

We primarily leveraged our own past experiences from designing wearables and sought inspiration from the existing literature on pneumatics design (which comes dominantly from the engineering disciplines [27, 50, 53]). We employed research-through-design [84] and iterative prototyping [8, 30, 42] to understand and improve upon the user experience after each iteration. Since PneuMa aims to move a user's body, we thought it was critical to evaluate how a user perceives its use and how they perceive themselves using the system in a social setting. Hence, we began by having the first two authors wear each design iteration in the prototyping stages, which included observing each other to document as well as reflect upon the social (onlooker's) understanding and acceptability of the designs. We now describe the design process, including our rationale and decisions behind the material, location across the body, and input modalities.

3.1 Choice of Material

We wanted a material with soft qualities that is not too heavy and body-conform. We chose silicone instead of polythene [32] as it provides greater rigidity, feels better on the skin, and we believed would be less prone to burst in case of accidental overinflation. Furthermore, we believed that it would lend itself to support fine-motor, not just gross-motor movements, allowing it to cover a larger range of applications in the future.

3.2 Locations across the body

Our design process involved identifying suitable areas for possible movements across the body. We found that in order to facilitate any movement with bodily extensions, it is paramount that the location is accessible for the extension to be inserted or attached in a deflated form and can support enough space for the intended movement when inflated. The location must be enclosed between two surfaces for the inflatable extension to draw a reaction from and result in the intended movement. As the bodily extensions are targeted towards enabling finer bodily movement, the choice relating to the part of the body is critical as well. Only the parts of the body which have at least one degree of freedom for movement can be chosen. Furthermore, as PneuMa leverages the air pressure through a pneumatic system inside silicone-based bodily extensions to facilitate movement, the size of the inflatable bodily extension should be proportional to the part of the body and the extent of the intended movement.

3.3 Input modalities

While ideating over the interaction modalities for the bodily extensions, we decided to create embodied experiences in everyday life without the user's explicit physical input to manifest the movement. We believed that the context of the environment could be a key factor in determining and facilitating the embodied experiences for the user; hence, we employed a keyword-triggered speech-based input along with an assistant app as we aimed to leverage a more natural input, such as speech, instead of relying on typing or touch-based inputs.

3.4 Fabrication Process

We employed a fabrication process that allows us to personalize inflatable bodily extensions based on the appearance, shape, size, and structure of a user's body part. To create silicone-based bodily extensions, we took inspiration from Moradi et al.'s [46] PVA-less molding technique to fabricate our bodily extensions. This technique involves sandwiching a layer of PVA between two layers of silicone during the fabrication process. Once both the silicone

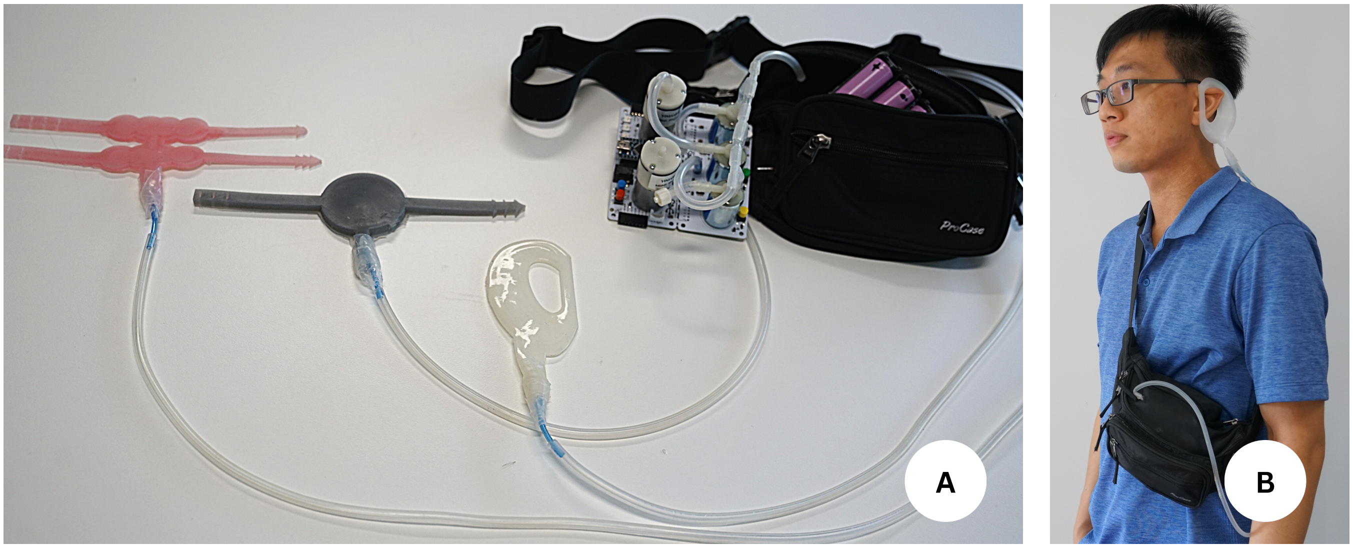

Figure 2: A) The PneuMa System: the pneumatic controller in a waist bag along with the three example bodily extensions; and B) A participant wearing the PneuMa system.

layers are cured, hot water is injected through the air shaft of the extension to dissolve the PVA and create a pocket of space connected to a hole to insert the tubing required to fill the inflatable extension with air. The fabrication process, as such, employs a three-step process.

In the first step, after identifying the area or body part of possible movement, we measured the area to create a mold in OnShape[1] (a collaborative online 3D CAD software). The mold is primarily used to proffer the shape and size of the inflatable that the user will wear on their bodies. Moreover, although silicone is a soft and stretchable material that can be extended to fit multiple sizes, we added a strap to the design of the inflatable to support different sizes of body parts and maintain the intended functionality, wearability, and comfort. We then proceeded to design the layer of PVA, which is to be sandwiched between the silicone, called the separator. The design of the separator determines the size and shape of the pocket of space inside the inflatable and hence is essential for preserving the intended functionality. We iterated over multiple sizes and shapes of the separator to eventually settle for a size and shape that preserves the structural integrity of the inflatable as well as offers the ability to move. The separator, generally, was in a 2.25mm offset from the inner boundaries of the mold to ensure a strong connection between the two layers of silicone when cured so that it does not burst even when inflated over a set limit.

In the second step, once the mold and separator were 3D printed, a silicone mixture was prepared for an extended working time (30 minutes) that ensured the silicone remained viable throughout the process. However, we used a faster-curing silicone during our iteration process as it resulted in faster prototyping but had a relatively higher chance of defects. After preparing the molds along with the silicone mixture, we deposited an initial layer of silicone halfway into the mold. Once the first layer was cured, we used a pair of tweezers to place the separator in the mold and pour more silicone over it till the brim of the mold. The mold containing the silicone, along with the separator, was then cured inside an oven at 57 °C for 15 minutes.

In the third step, once the silicone was cured and the inflatable was de-molded, an empty syringe was used to inject air into the inflatable through the shaft. Then, warm water was injected to dissolve the PVA-based separator faster along with a binder clip on the shaft to let the PVA dissolve completely. Once the PVA was visibly dissolved, the binder clip was removed, and the water inside was drained.

3.5 Three Scenarios

We identified three example scenarios as we believe they represent key aspects of a user's everyday life in the context of social and private interactions. In order to facilitate the interaction between our system and the study participants, we wanted to ensure that the selected scenarios presented opportunities considering temporal factors, convenience, technical feasibility, cultural considerations, demographic factors, and ambidexterity. We offer a rationale for each of the factors:

- Temporal factor - We selected the scenarios based on the time taken to complete them. By having rather short scenarios, we hoped our participants would interact with them multiple times during the study, giving us more data to analyse.
- Convenience - We selected "everyday" scenarios that we believed could be considered convenient as we wanted to ensure that the participants would engage with them during the study phase without the need for excessive explicit prompting.
- Technical feasibility - We selected our scenarios based on the technical constraints imposed by the design of our system. We had scenarios in mind that our system would not be

[1] https://www.onshape.com/en/

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

able to handle easily as they might break; for example, gross movement or movement during sporting activities. These scenarios might have involved the use of excessive amounts of air pressure and force that would break our prototypical design.

- Cultural consideration - As our past studies taught us [7, 10, 39, 55, 58], study participants in our neighbourhood often come from different cultures and backgrounds. Hence, we selected scenarios we believed could potentially transcend different cultures and backgrounds.
- Demographic factor - We selected the scenarios that we believed would be indifferent to people across different ages, genders, and occupations. Our study participants, irrespective of their demography, would be potentially able to interact with the system across these scenarios.
- Ambidexterity - We selected scenarios that would be applicable to both right and left-handed people and could be worn however the participants preferred during the study phase.

We identified these scenarios as we wanted to show that our approach transcends beyond one scenario and, hence, is more generally applicable. We also chose not more than three scenarios to scope our work and reserve the effort for our study participants to a reasonable level. Taken together, we believe our selection of scenarios is a good starting point. However, of course, we acknowledge that future work can investigate additional scenarios. We hope our work can serve as a scaffold to structure such efforts. Finally, we present the factors above with respect to each scenario that we considered in the form of a table.

We now present the three scenarios: “Greetings”, “Pardon?”, and “Take a break”.

3.5.1 Greetings. “Greetings” features a bodily extension worn inside the user’s palm. If the user or a person they are speaking with says either “bye-bye” or “goodbye”, it is sensed by a custom-made application running on the user’s mobile phone. This smartphone issues a wireless command to the controller to inflate the bodily extension in a way so that it moves the hand from a closed fist position to a straight position, initiating a goodbye gesture. The PneuMa extension consists of two chambers that, when inflated, push against each other as well as the user’s palm and fingers to facilitate the opening movement of the hand to initiate the goodbye gesture.

3.5.2 Pardon? “Pardon?” features a bodily extension attached to the back of the user’s ear. If the mobile phone application detects the keywords “Pardon?”, “Sorry, what was that?” and “Can you repeat?” the PneuMa bodily extension is inflated in a way that not only points the ear forward but also enlarges it through the

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

Table 1: The list of scenarios we considered in our study with their feasibility.

PneuMa extension's shape. This serves multiple purposes: the forward movement might enhance the hearing abilities by directing the ear toward the sound source, while the enlargement might also help with this by funnelling additional sound waves [47]. Furthermore, it also works to inform the speaker that the user is engaged in the conversation by enlarging the size of their ear. Together, they might make any conversation partners more aware that the user is listening but maybe not fully hearing.

3.5.3 Take a break. "Take a break" features a bodily extension attached to the user's palms, similar to "Greetings". The system aims to encourage taking more breaks from prolonged keyboard typing. The use case was inspired by the Pomodoro technique, which promotes focusing on key tasks through breaks and is known to increase productivity [19]. After having worked for 25 minutes (the user can customise the timer in the mobile phone application), the wearable is inflated to push the hands away from the keyboard, encouraging the user to take a break in a bodily way.

3.6 PneuMa Pneumatic Controller and Smartphone Application

The PneuMa system uses a programmable air[2] as the pneumatic controller, which is controlled via Bluetooth and connects to a Unity-based smartphone application through Bluetooth. The PneuMa system operates at a maximum of 50kPa powered by three 3.7 V Li-ion batteries connected in series and weighs 1.5 kg, including the waist bag. Only one of the bodily extensions can be connected to the pneumatic controller through the air pipe at the time. However, a user can easily swap one extension for the other. For the "Greetings" and "Pardon?" bodily extensions, the smartphone application (Fig: 4) uses the microphone to detect the keywords to trigger the inflation. In "Take a break", the smartphone application allows changing the timer duration.

4 STUDY DESIGN AND ANALYSIS

To gain preliminary knowledge and insights about the user experience associated with the PneuMa bodily extensions, we conducted a pilot study with three participants. The findings from the pilot study were then used to refine the design. As our bodily extensions are designed to support the user across everyday life scenarios, it was crucial to capture their interactions with the bodily extensions in a natural setting. We believed that field studies could yield rich data, allowing the participants to engage with the bodily extensions as per their choice and in an environment they are comfortable in. Moreover, as they are conducted without a researcher being present, the chances of researcher-induced biases are minimised [61]. Therefore, we decided to conduct a field study with 12 participants.

[2]https://www.programmableair.com/

4.1 Onboarding

The onboarding process was structured to gauge the participant's demography and experience with pneumatic-based wearables (if any) and to elicit their initial thoughts about the design of the bodily extensions. The process included - 1. a researcher asking questions such as their age, identifying gender, and their experiences with pneumatic bladders; 2. the participants were instructed about the use case and body location the bodily extensions were intended for along with smartphone application. After the second step of instructing the participants about the usage of our bodily extensions, they were asked to test the bodily extensions functionally along with the smartphone application to gain familiarity. The pre-study ended with the participants trying out each of the bodily extensions at least twice and asking questions about their working to the researcher present with them. Each pre-study lasted around 32 minutes (mean = 32.3 mins, SD = 4.2 mins), followed by the participants being asked to take the three bodily extensions along with the PneuMa kit and use them in their own preferred order whenever it was convenient and appropriate.

The participants were 18-35 years of age, with a mean of 24 and a standard deviation of 5.5. Out of the 12 participants, 5 of them identified as female, 7 as male, and none as non-binary. 2 of the participants had some experience with using exoskeletons, while none of them had encountered pneumatic-based wearables.

4.2 Field Study

Once the participants completed their onboarding, they were asked to use the bodily extensions over a period of 7 days. The participants were informed that they could use only one bodily extension at a time and could easily swap out by plugging them into the air pipe connected to the PneuMa system. Both to serve as a reminder and to encourage the participants to use the bodily extensions and a researcher was tasked to set up Zoom calls every two days as allowed by their schedules. Each Zoom session lasted about 20 mins (mean = 19.2 mins, SD = 2.38 mins), during which the participant interacted with each of the bodily extensions for about 5 minutes.

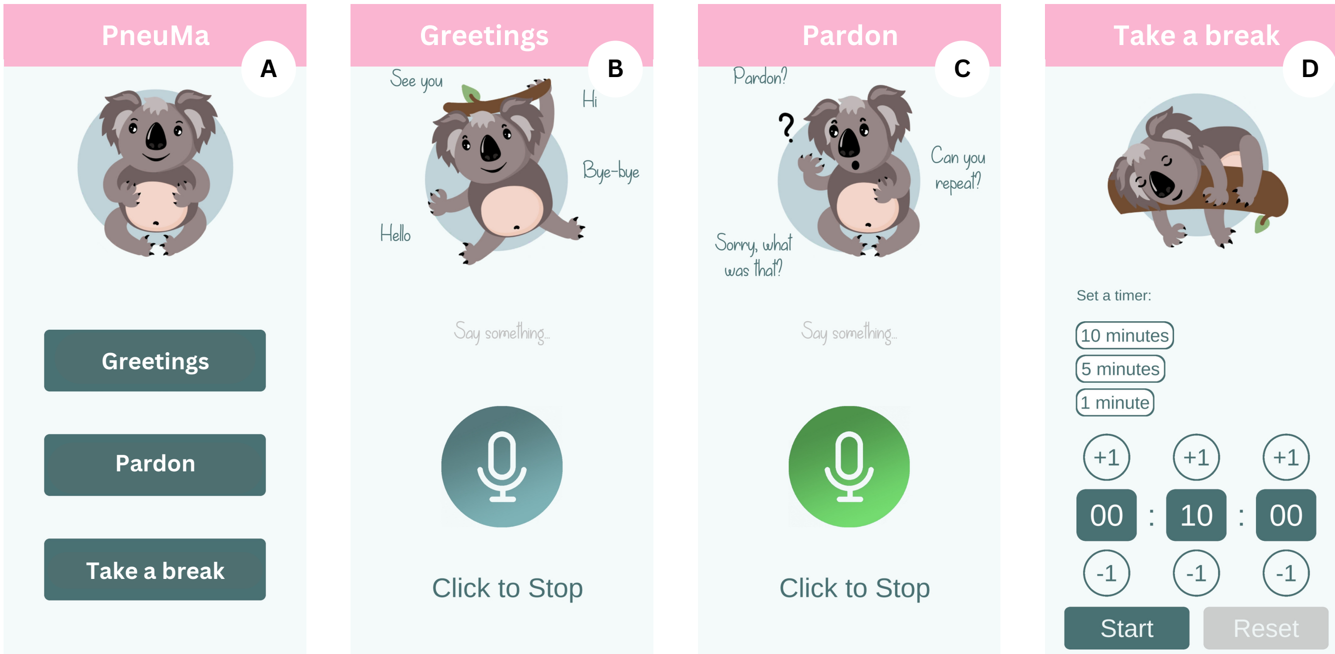

Figure 4: Screenshots from the companion application for the PneuMa system. From left to right, the screenshots are A) The landing screen for the application, B) the "Greetings" tab for voice input containing the activation phrases, C) the "Pardon?" tab for voice input containing the activation phrases, and D) the "Take a break" tab for setting up a custom timer.

These interactions over Zoom were audio and video recorded to gauge the progress of participants' ability to set up the bodily extensions and their interaction with them. Furthermore, the participants were also asked to video-record themselves while interacting with the bodily extensions outside of the Zoom sessions, with a Go-pro given to them in the kit along with the bodily extensions.

4.3 Post-study

In this phase, the participants were interviewed individually for about 53 minutes (mean = 52.68 mins, SD = 6.24 mins) in a semi-structured interview [11] to understand their experience with the PneuMa system and the bodily extensions with the primary researcher. The researcher employed laddering techniques while conducting the interviews to allow participants to express their experiences with the study with minimal bias. Each interview was then transcribed, followed by an inductive thematic analysis by two coders separately using NVivo Software [12]. In our analysis, a "unit" of data represented a single coded quote, as evident in prior research [5], it offered a means of understanding the frequency and prevalence of codes relating to the given theme occurring throughout interviews. The resulting codes were then examined by the research team along with cross-referencing to identify common themes across participants.

5 RESULTS

In this section, we present the findings and discuss them in the form of quantitative results and three overarching user experience themes: bodily awareness, Perception of the scenarios, and anticipating movement.

5.1 Quantitative Results: Analysing the Usage Patterns of PneuMa bodily extensions

To assess the utility and appeal of our bodily extensions, we conducted an in-depth quantitative analysis of their usage patterns (Fig: 5).

Looking first at the mean (average) usage, "Take a break" led the way, used approximately six times per participant. Meanwhile, "Greetings" and "Pardon" saw slightly less use, with respective means of 3.75 and 3.67. This suggests that "Take a break" was the most frequently used prototype. Furthermore, exploring the distribution of usage, we considered the mode and median values. The mode, the most frequently occurring usage count, was 2 for "Greetings", 3 for "Pardon", and 6 for "Take a break", while the median values were 3.5, 3, and 6, respectively. The alignment of the mean, median, and mode for "Take a break" suggests a symmetric distribution, potentially indicating consistent appeal among the participants.

The measure of variability also provided important insights. The standard deviation was the lowest for "Take a break" (1.809), implying that the usage of this prototype was relatively consistent among participants. The standard error of the mean was also lowest for "Take a break" (0.522), suggesting that the sample mean is likely to be a reliable estimate of the actual population mean. Overall, our analysis reveals that the "Take a break" prototype appears to have the most consistent usage patterns. Nevertheless, the variance of

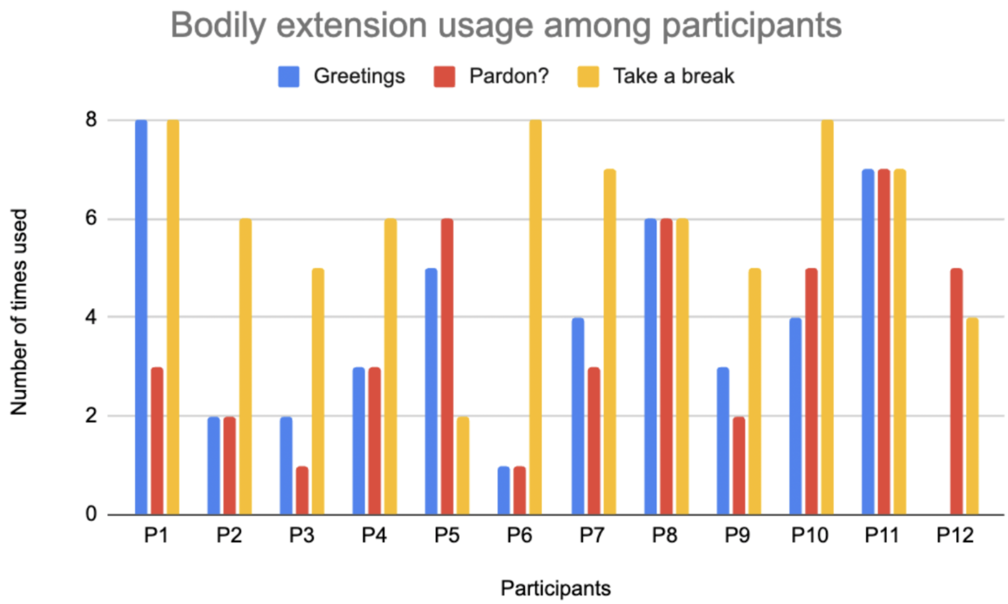

Figure 5: Usage patterns of the bodily extensions across the 12 participants from a field study with the PneuMa system.

usage times for "Greetings" and "Pardon" indicates a wider range of engagement levels, offering the potential for further exploration.

Table 2: Descriptive statistics from the PneuMa field study with 12 participants

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

5.2 Theme 1: Bodily awareness

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

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

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

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

5.2.4 Fusion between bodily extensions and participants' bodies. Participants noted that over time using the system became easier, *"Wearing the extensions sort of seemed natural to me over time, it was similar to wearing an accessory around my body every day"* (P5) and *"At first seemed tricky to navigate, but by the end of the study, I felt way more comfortable with the extensions and was able to get around it quickly around my body"* (P10).

5.2.5 Changes in perception of self over time. Participants' perception of the bodily extension also changed over the period of the study, as two of them noted, *"I can feel I have two hands (talking about the "Greetings" bodily extension) because of the shape, and that made me feel I have two hands attached together like a part of my body"* (P6) and *" I could feel my ears bigger than usual which made me feel wise."* (P1, while talking about the "Pardon" extension). These results suggest that using bodily extensions altered how the participants perceived their own bodies while navigating scenarios in everyday life augmented by the bodily extensions. Participants also mentioned that they became more aware of the morphology of their body, *"I had not observed my hands and the joints this closely before"* (P3) and *"When I reflected upon the design of the extensions, I could understand how my body is constructed"* (P8). These results suggest that although our bodily extensions felt *"unnatural"* and *"weird"* at first, over the duration of the study, the participants' bodily awareness changed.

5.3 Theme 2: Perception of the scenarios

In this theme, we discuss how the participants understood and reflected upon the scenarios supported by the system while navigating everyday life. This theme comprises 67 data units and describes participants' experiences in relation to the scenarios supported by our bodily extensions and their intended functionality.

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

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

5.3.3 Utility of bodily extensions in the scenarios supported by PneuMa. Participants described the experience as *"wholesome"* and *"entertaining"*. The participants also explained how they perceived the bodily extensions in the specific scenarios, stating, *"I think were really accurate, direct and helpful."* (P7) and *"It's something kind of magical in a way on how they keep your body in sync"*.

5.3.4 Contextual movements facilitated by PneuMa. Participants described their experiences with each of the bodily extensions individually. For "Greetings", P6 commented, *"Although I am not used to waving to other people, more of a handshake or a hug person, the inflation served as feedback for me to go in for a hug."* along with P2 stating, *"I don't usually realize when my hands move while waving, the extension helped me kind of kickstart the motion"*.

5.3.5 The bodily extensions as a social organ. For the pardon extension, P9, initially bemused by the scenario, commented, *"It felt strange at first as to why should I wear something that helps other people speak better; however, as the other person could see the extension inflate, it served as a reminder for the other person that I had some difficulty in either hearing or understanding them"*. P12, in articulating their experience with the pardon extension, described that *"I wasn't sure if I could feel my ear move from the inflation, but hearing the inflation, I improvised by turning my ear towards the speaker hoping they could see the extension."* These comments suggest that although the bodily extensions were designed to prompt movement, the participants sometimes did not explicitly rely on or wait for the extension to facilitate the movement and improvised as they saw convenient. Additionally, four participants felt that wearing these bodily extensions served as a conversation starter, with P1 describing, *"When I was on a video call with my parents, this was the first thing they asked about rather than their usual question of my whereabouts"*. These results suggest that participants' social experiences profited from the presence of the PneuMa system.

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

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

5.4 Theme 3: Anticipating movement

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

5.4.1 Movements facilitated situational awareness. Participants mentioned that the movements helped them understand the context of their situation as they experienced the movement both in an embodied and visual manner. P2 stated, *"I felt more aware of the situation I was in and knew what movements to make in case the*

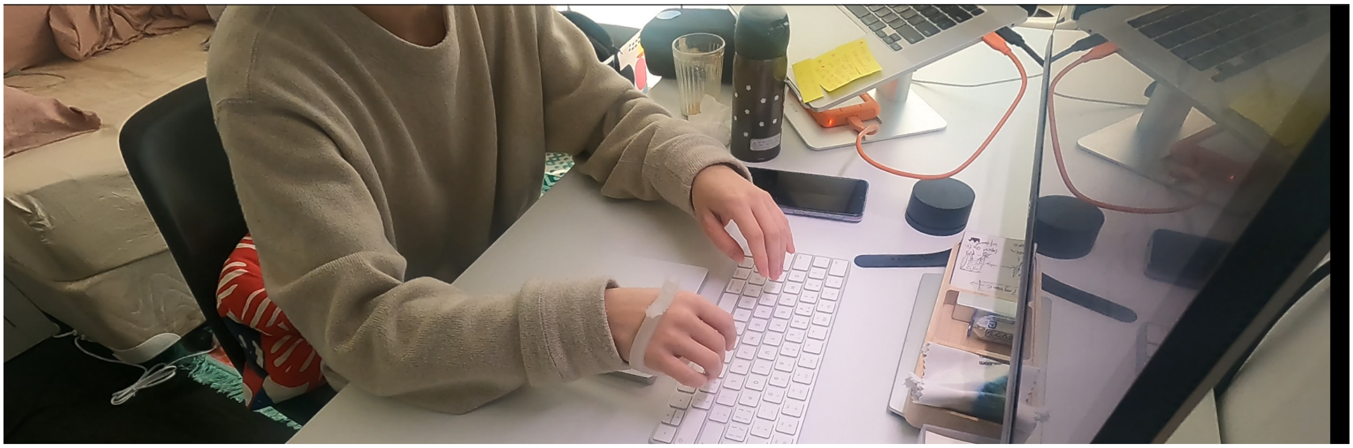

Figure 6: A participant is using the "Take a break" extension.

system failed." with P10 adding, *"I thought the extensions were sort of helping to relearn movements based on context."*

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

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

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

5.4.5 Ability to choose when to activate the movements helped with reliability. P6, articulating their experience in regard to choice and control, said, *"The choice to ignore or just not initiate the movement through the bodily extensions felt reassuring"*.

This suggests that the design (especially the soft material and non-rigidity of the silicone-based bodily extension, along with the ability to regain control over the movement owing to pneumatics) supported participants' movement in a way that suited the variety of the different contexts they find themselves in everyday life.

6 DISCUSSION

We now discuss these results in relation to previous literature to improve our knowledge about designing our bodily extensions to support movement in everyday life.

6.1 Designing for embodied-being in everyday life

The themes extend prior theory around embodiment in everyday life as proposed by the design framework for the embodied-being-in-the-world by van Dijk et al. [75]. We notice that our first two themes describe experiences that confirm the insights put forward by van Dijk et al. in their framework. Specifically, the participants' experiences with bodily extensions described in the first two themes confirm designing for "Transforming the lifeworld" in the framework that relates to an intervention that alters the perception and action in the world.

The first two themes describe the participants' altered awareness of their bodies as well as the perception of the scenarios with respect to movements while engaged in an experience with our bodily extensions, as evident from quotes such as, *"I think because of the extensions, I felt some parts of my body were more active in these situations than others"*. Furthermore, participants mentioned that they felt the bodily extensions served as an augmentation to navigate scenarios in everyday life. These experiences speak to the insight about transforming the lifeworld generated in van Dijk et al.'s work. As the PneuMa system works towards supporting embodiment in everyday life, it helps the users gain more awareness about their

Figure 7: A participant is using the "Pardon?" extension.

bodies by allowing them to try out, improvise, and decide when to activate the bodily extensions. Our work also confirms van Dijk et al.'s insight about designing for embodiment to reflect in- and on-action. The participants reported that they gained familiarity with their movements as a result of being prompted by the bodily extensions and often found themselves observing the movements more closely than before. We believe that van Dijk et al. would refer to this insight by describing an intervention that promotes rational thought based on the context, i.e., thinking, taking appropriate action, and reflection. This reflective practice was observed amongst our participants as they learned to navigate daily scenarios with our bodily extensions. Taken together, as the case studies for developing the framework by van Dijk et al. were in the area of accessibility, our work extends this prior theory by expanding it to the design of bodily extensions in everyday life.

6.2 Perceived control over bodily extensions

The themes emerging from our study closely speak to the design implications offered by Buruk et al. in their exploration of playful bodily extensions [13]. Buruk et al. focus towards exploring the design of bodily extensions from a playful lens [48]. Specifically, their proposed design implications around creating bodily extensions suggest instilling *"user control over the extensions as a critical element in incorporating them into the body"*. Considering the results of our study, our bodily extensions appeared to have facilitated a relatively high level of control over the interactions. According to the participants, this was achieved majorly due to two factors: first, the choice of activation and second, the fabrication material. As the bodily extensions were designed to be activated on explicit user input, such as voice (Greetings and Pardon) and timer (Take a break), users had a temporal choice (when to activate) of interacting with the bodily extensions. Additionally, as the voice interactions were activated using phrases in the English language, users could either choose different phrases or navigate the scenario using a second language. This appeared to instil a sense of control amongst the participants, as evident from their quotes such as, *"I felt I had a choice to use or ignore the extension whenever I wanted to"*. These results extend the design implication proposed by Buruk et al. (who investigated mostly bodily extensions with limited control, such as afforded by physiological sensors) by highlighting the opportunity to design bodily extensions with a relatively higher level of control by the user. We propose that this can be facilitated by giving users more choice about what activates the bodily extensions, but also through the choice of material, which we further discuss. Since our bodily extensions were created using silicone as fabrication material, the participants credited the ability to exercise control to the soft structure of the bodily extensions. The material of the bodily extensions, along with the pneumatic system, allowed the participants to suppress the inflations whenever their support was inappropriate, thereby presenting them with a choice, which ultimately aided in inducing confidence among participants that the support was well-intended and helpful in their everyday lives. Taken together, our work extends prior theory by proposing that bodily extensions could benefit from offering a relatively high sense of control through utilizing explicit input and choice of material, thereby extending the existing design knowledge around the field of bodily extensions.

6.3 Design Strategies

Considering the analysis of our results in lieu of prior work, and the design and fabrication knowledge gained through the creation of the PneuMa system and our bodily extensions, we now present a set of design strategies to help designers of bodily extensions that aim to support movement in everyday life.

Consider soft materials for designing bodily extensions. Prior research around bodily extensions has primarily leveraged mechanical sensors and actuators to facilitate embodied experiences [3, 62]. The results of our field study with bodily extensions indicated that participants found the silicone-based designs comfortable and expressed that their stretchable and shape-changing nature allowed them to exercise more control over the intended movements in everyday life. With this considered, we recommend designers consider silicone-based pneumatic bodily extensions to allow the users a more body conform user experience. Silicone as a base material allowed us to create bodily extensions that were lighter in weight as compared to other systems that promote movement. The process of creating the bodily extensions also supported us to customise the design of the bodily extensions, which can ultimately be leveraged to design for a specific part of the human body. Finally, designers can also consider pneumatic systems in order to facilitate the movements across everyday life as the participants in our study found the prompted movements, although explicit, were not immediate, which allowed them enough time to exercise control over their movements.

Consider augmenting explicit movements for increased awareness. The results of our study indicated that the participants appreciated the explicit movements promoted by the PneuMa extensions. As the bodily extensions initiated movements that were easily understood in regard to the part of the body as well as the range of the movement, participants felt more aware of their body and could perceive the everyday life scenario as an embodied experience. Owing to these results, we suggest designers hoping to create interfaces that engage a user in an embodied experience, consider designing to elicit movements that involve a lower cognitive load to understand in order to facilitate higher awareness of the user's body along with the existence of their body in the embodied scenario. Augmenting embodied scenarios with implicit input may lead to a higher cognitive effort from the user, which might lead their focus towards understanding the movement rather than the position and movement of their bodies.

Consider explicit input and modular design for higher bodily control. Learning from the analysis of our study, the design of the PneuMa system resulted in the participants feeling in control of both their bodies and the everyday scenario they were engaged in. Prior research centred around supporting embodiment through initiated movement has relied upon physiological sensors, which elicit a lower sense of bodily control among their users [30, 60]. These experiences have been credited to the implicit nature of physiological input that is difficult to be influenced or altered in the moment directly by the user. Hence, designers and researchers hoping to support the embodiment of everyday life scenarios through prompting movement can learn from our work by considering initiating movements through explicit input directly accessible to the user. In the PneuMa system, as the movements were initiated through speech-based cues, the participants in our study reported having a higher sense of control over the movements and the everyday life scenarios they encountered. Furthermore, designers can also consider a modular design similar to PneuMa that involves initiating movement through a variety of inputs (keywords and a custom timer, in our case) in order to facilitate a higher sense of control among the users.

7 LIMITATIONS AND FUTURE WORK

Our work had some limitations, which we acknowledge in this section. To begin with, the fabrication of the pneumatic extensions in our work could be improved as the strategy employed, although it enabled custom designs, had a mediocre success rate. In particular, the PVA-less technique resulted in air bubbles being trapped inside the silicone, which eventually resulted in defective bodily extensions. Although we identified two key techniques to improve the success rate during the fabrication of the bodily extensions: creating a silicone press to squeeze out the bubbles before curing each layer, and pouring extra silicone over the holes and curing it again, this process could benefit from automated fabrication to reduce human intervention errors.

We had 12 participants in the study, which resulted in novel findings; however, some participants noted that prolonged use of the PneuMa system might have resulted in enhanced engagement with the bodily extensions. Hence, a longitudinal study would offer an improved understanding for designers hoping to utilize the implications of our work. Furthermore, during the field study, participants commented on the wearability of the system as they experienced some situations with the pneumatic pipe obstructing their movement in general. This issue primarily resulted from using the programmable air pneumatic controller repurposed into a wearable form to fit inside a waist bag. These issues could be mitigated by building a customised printed circuit board to house a wearable pneumatic system to create a smaller system. The participants also noted that while using the phone companion for the "Greetings" and "Pardon" bodily extensions, the voice recognition did not always detect their cues to initiate the embodiment. This limitation largely stemmed from using a speech recognition library with limited training data and compatibility with different English accents across the participants. As a result, future work could include speech recognition libraries that support a wider range of auditory cues.

Furthermore, our bodily extensions were majorly designed to support smaller movements across the body. Future work could investigate the effect of bodily extensions on gross-motor movements across the body owing to the promising results of the current bodily extensions. Finally, the context of using the bodily extensions can be designed around specific social or private activities by leveraging interaction nuances on offer in everyday life.

8 CONCLUSION

In this paper, we presented PneuMa, a pneumatic-based wearable system for silicone-based bodily extensions to support movement in everyday life. We presented our fabrication pipelines for creating three bodily extensions, showing the versatility of our approach. We also presented the associated user experience of using our bodily extensions through a field study with 12 participants. We identified three themes: bodily awareness, perception of the scenarios, and anticipating movement. These themes suggest that our system appeared to support movement in everyday life while preserving participants' perceived sense of control in moving their bodies owing to the pneumatic-based approach. Furthermore, using our system helped the users become more aware of their bodies and highlighted for them the importance of bodily movement in certain scenarios. We also discussed the implications of our design in light of prior research. Finally, we presented a set of design strategies that researchers can utilize to create bodily extensions. We hope that our work extends and creates knowledge for exploring the area of bodily extensions for embodiment. We hope that our work helps people profit from the benefits of embodiment support.

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