Design and Evaluation of a Clippable and Personalizable Pneumatic-haptic Feedback Device for Breathing Guidance

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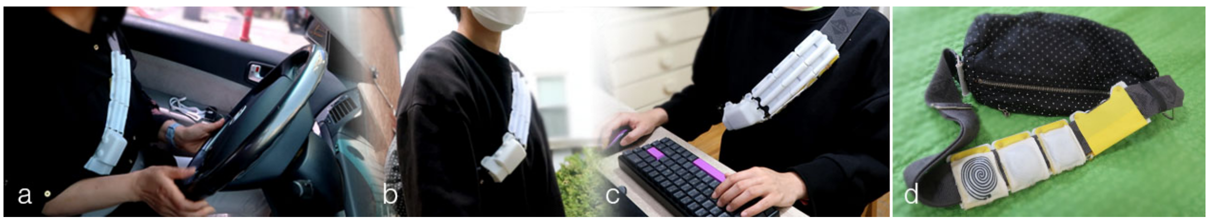

Fig. 1. A pneumatic-haptic device, deployed in (a) on-road driving, (b) outdoor walking, and (c) at the office working environment. (d) The device was clipped on a strap of a cross-body fanny-pack during the user study in the outdoor walking (b) and office working (c) condition.

To assist people in practicing mindful breathing and regulate their perceived workload while not disturbing the ongoing foreground task during daily routines, we developed a mobile and personalizable pneumatic-haptic feedback device that provides programmable subtle tactile feedback. The device consists of three soft inflatable actuators embedded with DIY stretchable sensors. We introduce their simple and cost-effective fabrication method. We conducted a technical and user-based evaluation of the device. The user-based evaluation focused on the personalization of the tactile feedback based on users' experience assessed during three pilot studies. Different personalization parameters have been tested, such as two tactile patterns, different levels of intensity and frequency. We collected the participants' self-reports and physiological data. Our results show that the device has the potential of a breathing guide under certain conditions. We provide the main findings and design insights from each study and suggest recommendations for developing an on-body personalizable pneumatic-haptic feedback interface.

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CCS Concepts: • **Human-centered computing → Mobile devices**; **Haptic devices**; User studies; • **Social and professional topics** → *Assistive technologies.*

Additional Key Words and Phrases: Haptics, Health, Mindfulness, Stress, Affective Haptics, Design, Wearable

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1 INTRODUCTION

For many working people, a typical day is spent performing tasks in an office, commuting in a vehicle, participating in outdoor activities, and/or performing various other types of daily tasks [39, 42, 56]. Despite increasing attention on the well-known health benefits of mindful and controlled breathing, people easily forget to be mindful of breathing and stress levels - especially when occupied with many different activities. Various studies have shown the significant effect of slow breathing guidance techniques and biofeedback systems to improve one's mental and physical health [7, 55, 61]. However, previous works are focused on evaluating their systems during one specific targeted task that lacks the involvement of physical movement, such as relaxing [5], meditation [60, 62, 71] or doing office work [30, 47, 50, 57]. There is a lack of work evaluating effectiveness of such systems in a general outdoor ambulatory setting. Few studies have evaluated their methods in mobile settings such as driving in a car or being a car passenger [13], and of these, most were either conducted in a lab environment with a simulator [4, 43, 48, 58, 81] with few in a real-world, on-road commuting setting [3]. Researchers have also examined different breathing guidance methods for assisting in walking meditation [12, 14, 46, 73], and showed the efficacy of their methods on improving mental health by conducting a user study in a real-world setup. However, these methods were specifically designed only for walking meditation purposes and their evaluation protocol required the participants to fully focus on the guidance/intervention. Hence, it is not clear whether the breathing guidance would work during a routine walking situation not designated for 'walking meditation' purposes.

The above mentioned efforts lack system mobility to allow the user to carry the device with them during their daily routine, or were designated for a specific task rather than for general daily use. Additionally, the studies have not evaluated the effectiveness of their systems to allow various options in customization and receiving of tactile biofeedback. Lastly, it is difficult to find a pneumatic-tactile biofeedback system that provides an ability to adapt its intensity and to adjust to different body shapes and user preferences.

To assist people to breathe slower during different types of ongoing daily tasks and to mitigate their perceived stress level without interrupting their task performance, we developed a mobile pneumatic-haptic device that provides customizable subtle tactile stimulation via the pneumatic inflation/deflation of soft actuators. The pneumatic-haptic intervention provides comfort and a relaxing feeling similar to the breathing movements of the chest or hugging [13]. In this paper, we first describe the process of developing this hardware prototype. The haptic feedback device provides various tactile stimulations that can be personalized on the stimulation intensity, frequency, and pattern. The various tactile stimulation patterns are enabled by an array of pneumatically-driven soft air pouch actuators. The mobile and clippable design allows users to wear the device around their body during their daily routine. To allow for the system to provide an adaptive stimulation intensity based on the user's body shape and preferences, we developed a stretchable pressure sensor with a cost-effective DIY fabrication process. We validated the functionality of the sensor and compared it with an off-the-shelf barometric pressure sensor product.

To evaluate the proposed pneumatic-haptic feedback system we then designed and conducted A series of user-based evaluations. They were conducted to gather users' feedback on some of the device's personalization features: (1) selecting the most promising sequential feedback pattern (Seq). This pilot study collected feedback from 3 participants to tune the parameters to obtain the sequential pattern to be tested with the synchronized one (2) Obtaining users' feedback on the haptic feedback intensity and frequency. This study was a within-subjects design with 5 participants who experienced Sync., Seq. and Control conditions in an office environment. The participants' self-reports and qualitative feedback helped us understand the importance of adjusting the tactile intensity and frequency. (3) Comparison of two distinct tactile patterns (Sync. vs. Seq). We conducted this study with 40 company employees who performed three daily tasks: cognitive task performance in an office environment, on-road car driving, and outdoor walking, in randomized order. (4) Exploring the device's potential as a breathing pacer. One participant tested the device in an office environment set to two different frequencies. Raw breathing data waveform was examined with the device's haptic feedback rhythm, both for Sync. and Seq. feedback.

We also gathered design insights from participants' feedback and shared the main findings from each study and suggested design recommendations for personalizing an on-body pneumatic-haptic feedback interface.

This work makes three main contributions:

- We introduce a novel mobile pneumatic-haptic device and system that produces customizable tactile stimulation patterns, and a novel DIY-fabrication method of a stretchable pressure sensor that enables closed-loop pressure feedback control to provide an adjustable subtle tactile intensity, maintained regardless of body shape.
- We design and carry out technical and user-based evaluation processes that focus on the personalization feature of the pneumatic-haptic feedback device for breathing guidance to discover insights on tuning the tactile feedback intensity, frequency during a office work and on the relationship between different haptic feedback patterns and daily activities.
- We present the results of the user-based evaluation studies we conducted to gather users' feedback and we suggest some recommendations based on the participants objective and subjective data, which shares design insights applicable to develop a design framework for an on-body pneumatic-haptic interface.

2 RELATED WORK

To encourage mindfulness and slow breathing, which helps to regulate negative affective states, researchers have explored how to interact with various biofeedback methods [61]. We first review on-body pneumatic haptic interfaces focusing on those technical contributions. Then, we review the effects of the intervention's personalization for users to their engagement with the intervention. Lastly, we review different breathing guidance methods in various types of daily activities. Table. 1 summarizes the related works of the three categories focusing on the most recent and relevant works found in the ACM Digital Library, and HCI field.

2.1 On-body Pneumatic Haptic Device

PneuSleeve [82] is a forearm sleeve with a pneumatic haptic system for broader application in VR and Augmented Reality (AR). This study shared a closed-loop force feedback control to render 23 feel effects and evaluated its effectiveness. *Flow* [17] is a wrist and forearm wearable that explores a way to convey the movement direction by a pressurized-directional airflow for providing instruction of physical activity learning. *Force Jacket* [19] delivers force and vibrotactile feedback using 26 inflatable airbags arrayed in a jacket for immersive VR experiences. Each airbag contains a force sensitive resistor to measure the force output exerted from the airbag and to produce a range of forces close to a target force. *PneuHaptic* [33] is an arm-band haptic interface that uses a 5-inflatable array. Their study explored a way to convey human touch interactions; tapping, holding, and tracing. However, few studies have explored the potential of a pneumatic haptic interface as a media for biofeedback other than for enhancing VR or AR experiences. Our mobile pneumatic-haptic device we present provides advantages over prior pneumatic haptic devices [17, 19, 33, 82] that require a bulky air compressor, more than two motors to control the actuator array, or are not mobile and do not provide closed-loop control or sensing ability.

Table 1. Related work on different biofeedback methods for breathing regulation.

Work	Task	Intervention Method	Form Factor	General Mobility	Personalization	Participant (N)	User Study Environment	Pre/during-stressor	User Study Measurement
This work	Driving, Walking, Office work	Pneumatic-tactile	Clippable mobile device	O	Tactile pattern, Frequency, Intensity	40 Company Employees	On-road car, Outdoor walking, Office	(Pre) Modified TSST, (Pre) Position 2-back, (During) Number 2-back	BR, EDA, STAI-X-1, NASA-TLX, Subjective ratings
Just Breathe (2018) [58]	Driving	Vibrotactile, Auditory (Voice)	Car seat mat	X	Frequency	24	Car simulator	--	BR, HR, HRV, Self-reported stress, Driving safety and performance, Subjective ratings
Breath Booster! (2018) [4]	Driving	Vibrotactile	Car seat mat	X	Frequency	8	Car simulator	--	BR, BI, ECG, Subjective ratings
Calm Commute (2020) [3]	Driving	Vibrotactile	Car seat mat	X	Frequency	24	On-road car	(Pre) Modified TSST	BR, HR, HRV, Self-reported stress, Driving safety and performance, Subjective ratings
Zepf et al. (2020) [81]	Driving	Auditory (White noise)	Bluetooth speaker	X	Frequency	24	Car simulator	--	BR, EDA, Driving safety and performance, Subjective ratings
Koch et al. (2021) [40]	Driving	Auditory (Music, Narration)	Smartphone App.	O	Music playlist	10	On-road car	--	PANAS-SF+, Subjective ratings, Driving behavior,
AmbientBreath (2021) [43]	Driving	Auditory (White noise), Tactile (Wind), Visual (Light)	Bluetooth speaker, Fan, LED	X	Frequency	54	Car simulator	--	BR, EDA, Driving safety and performance, Subjective ratings
aSpire (2021) [13]	Passenger	Pneumatic-tactile	Clippable mobile device	O	Tactile Pattern, Frequency, Intensity	15 University Pool	On-road car	--	BR, EDA, Subjective ratings
MoodWings (2013) [48]	Driving	Visual (Butterfly wing)	Butterfly shape Wristband	X	--	11	Car simulator	--	EDA, ECG, Subjective ratings
BrightBeat (2017) [30]	Office work	Visual (Display light), Auditory	Desktop Display, Headset	X	Frequency	32 University pool	Room	(During) Reading tasks (Post)Quizzes	BR, Subjective ratings
PIV (2020) [50]	Office work	Vibrotactile	Two patches on abdomen	X	Frequency, Intensity	97 University pool	Room	(Pre) Reading Text (During) Cognitive Test (Post) Reading Text	BR, EDA, STAI-6, Subjective ratings
Umair et al. (2021) [75]	Office work	Vibrotactile, Thermal	Wrist-worn watch-type products	O	Tactile Pattern, Frequency, Intensity	23 University pool	Room	(During) SCWT*, Modified TSST	HRV, STAI-Y-1, Subjective ratings
Affective Sleeve (2019) [57]	Office work	Tactile (Pressure, Thermal)	Forearm Sleeve	X	Frequency	18 College students	Room	(During) Cognitive test	EDA, BR, BR variability, Subjective ratings
Ambient Walk (2015) [12]	Walking Meditation	Auditory, Visual	Smartphone App.	O	Frequency				
Cochrane et al. (2021) [14]	Walking Meditation	Auditory	EEG headset, headset	X	Volume, Sound composition	6 -8 per workshop	Room	-	Qualitative workbook, Group interview

*SCWT: The Stroop Color and Word Test +PANAS-SF: Positive and Negative Affect Schedule –Short Form

2.2 Effect of the Personalization to Users' Intervention Engagement

Lee et al. [43] reviewed how the user-centered design of human-machine interface (HMI) affects the user interaction with automotive HMI. As they summarized and Robey et al. [64] mentioned, one of the advantages of the user's involvement in HMI design is the user's acceptance of the system. A study by Jin et al. [37] showed the effect of customization on fostering user engagement with a wearable health tracker. Balters et al. [3] recommended to provide a support for personalization, such as varying the tactile patterns and intensity. Also, effects on engagement level from personalizing the feedback and letting the users choose their preferred biofeedback method were shown by Miri et al. [50] and Parades et al. [58]. Miri et al. [50] presented a personalizable and inconspicuous vibrotactile breathing pacer (PIV) which provided a personalization stage to their user study participants. During the personalization stage, the experimenters set an appropriate vibration pace, frequency and amplitude. However, the system lacks a UI to let users adjust the tactile parameters by themselves, and the study did not compare the effect of using different patterns. Based on these prior findings and their limitations, we include a choice of haptic feedback patterns and personalization of intensity level and frequency, which is enabled by a mobile UI.

2.3 Breathing Guidance during Daily Activities

2.3.1 Office Work (Desk Job). *BrightBeat* [30] introduced a set of visual and auditory interventions that helped computer users to effortlessly lower their BR and improve their focus and calmness. *Affective Sleeve* [57] is a sleeve that provides heat and tension created by shape-memory alloy to forearm. Umair et al. [75] explored the personalized vibrotactile and thermal patterns for affect regulation, which provides an option of utilizing the vibrotactile pattern to be personalized to regulate not only the heart rate but also the breathing rate. Their work focused on evaluating the effect of personalized intervention patterns, frequency, and intensity for affect regulation using commercial products rather than exploring a new haptic technology. Miri et al. [50] introduced PIV which uses two vibrotactile motors directly attached on the skin of abdomen to regulate anxiety during cognitive tasks.

2.3.2 Driving and In-Vehicle Environment. Zepf et al. [81] implemented a closed-loop breathing guidance system to provide a personalized auditory feedback to drivers for their stress management. Moving forward, Lee et al. [43] tested the effect of the combination of auditory, tactile feedback by wind, and ambient light on the drivers' BR, stress level and driving performance. MacLean et al. [48] presented a butterfly-shaped wristband wearable, *MoodWings*, which varying the folding angle of its wings in response to the user's electrodermal activity (EDA). It is designed for visual alerts to warning the early stage stress level and for helping users to manipulate their affective state. The result of the study showed that *MoodWings* improved the participants' driving performance, however, also it increased their physiological and perceived stress when the device was activated. All of these evaluated their methods for drivers in a car simulator. *Just Breathe* [58], *Breath Booster!* [4] and *Calm Commute* [3] also focused on delivering vibrotactile guidance for regulating car driver's BR, and they used an array of vibrotactile motors for providing the feedback to the driver's back. While the *Just Breathe* focused on slowing down BR without impairing the drivers' safety, *Breath Booster!* explored a way to increase the BR and heart rate (HR) to increase the car drivers' alertness and focus. Unlike the works mentioned above, which were conducted in a driving simulator, *Calm Commute* evaluated their system in a natural on-road car setting. The result showed that most participants lowered their BR and physiological arousal with no safety-critical incidents. *JustBreathe, Breath Booster!* and *Calm Commute* are subtle yet none of these allow you to adjust the tactile stimulation intensity at the location of the applied feedback or to adjust its contact point to the drivers' body type. These systems might be only best for the car environment due to its hardware implementation on a backrest of car seat or a backrest mat. Also Koch et al. [40] tested the effect of just-in-time auditory interventions in vehicle on affect regulation of drivers in real-world on-road car setting for two-months. They implemented their system on a smartphone so that has a potential of being applicable to other than driving situation, however, the effect of the intervention on the other activities are yet unknown. *aSpire* [13] presented a first study of the pneumatic-haptic device and tested its effectiveness of lowering BR on only on-road car passengers (not drivers or participants engaging in any stressful tasks); that study setup differed from the one in this paper, as it focused only on safety in a real-world passenger commuting setting without inducing extra stress or the normal stressors associated with driving. In this work, we describes the full process of the device fabrication and its control system implementation, and its technical evaluation results, while *aSpire* presented only a single on-road passenger user study result without technical implementation process details and technical evaluation.

2.3.3 Walking and Physical Activities. Researchers have also examined different breathing guidance methods for assisting in walking meditation [46, 73], and showed the efficacy of their methods on improving mental health by conducting a user study in a real-world setup. However, these studies are more about investigating the effect of breathing training before the walking rather than evaluating a new biofeedback technology. Cochrane et al. [14] presented a technology-mediated walking meditation. They studied the effect of rhythmic soundscape modulated by electroencephalogram (EEG). These methods were specifically designed only for walking meditation purposes and their evaluation protocol required the participants to fully focus on the guidance/intervention. Hence, it is not clear whether the breathing guidance would work during a routine walking situation not designated for 'walking meditation' purposes. Ambient Walk [12] presented a smartphone app that provides users with real-time auditory and visual intervention based on the users' walking pace and their breath. However, less information is known regarding its technology implementation and evaluation methods and results.

Strive [76] provided a vibrotactile cue using a single vibration motor placed in a wristband to assist runners in achieving rhythmic breathing for lowering injury risk and improving performance. This work evaluated different vibration patterns to guide different rhythmic breathing techniques. *ExoPranayama* [51] provided breathing guidance via shape-changing of fabric attached to the ceiling of a yoga studio and variation of the light brightness corresponding to the synchronization of breathing among the study participants. Study by Wells et al. [79] tested the effect of slow breathing training via biofeedback on the musicians' performance anxiety and heart rate variability. However, the biofeedback was not provided during the task of performing a musical performance but only before the task.

2.3.4 Resting. A cushion-like interface, *Relaxushion* [5] used a motorized motion of the expansion and shrinkage of a cushion to provide a sensation similar to breathing. Although the evaluation was conducted under a pilot study with a relatively small sample size (N=5), it showed its potential for leading the users' breathing rhythm to be synchronized with the motion of the device without requiring their full attention. *Respire* [60] and *Attending to Breath* [62] explored the use of visual and auditory modalities to support people's sustained attention to breathing through a virtual environment. They used a VR animation to map the BR of the user and sound directly in real-time. Ståhl et al. [71] presented two different types of interface that assists users to practice a meditative bodily introspection by heat and light. Their user study (N = 22) reported that those interfaces provided them with relaxation feeling and increased their breathing awareness. However, their form factor (ground mat and lamp) limits the users' practicing posture to be a lying-down. Foo et al. [25] presented a haptic garment that provides a compression and warmth to upper body to assist novice meditation practitioners to maintain focused attention.

There also have been mobile app services and smartwatch products to improve one's mindfulness and breathing awareness. Calm [11] provides a breathing practice session that guides calm breathing using bubble animation with auditory cues. Breathwrk [9] also provides a similar session that allows users to customize specific guidance methods such as voice, sound, and vibration from a phone. Smartwatches like Apple Watch [2] and Fitbit [24] provide a function that lets users practice breathing for a few minutes by providing a visual or vibrotactile cue. Apple Watch sends a reminder to breathe at different times of the day, which is closer to notification than guidance. There also have been mobile app services and smartwatch products to improve one's mindfulness and breathing awareness. These studies and products were designed for a dedicated meditation practice or a relaxing break time, which required the participants' full attention to their intervention methods.

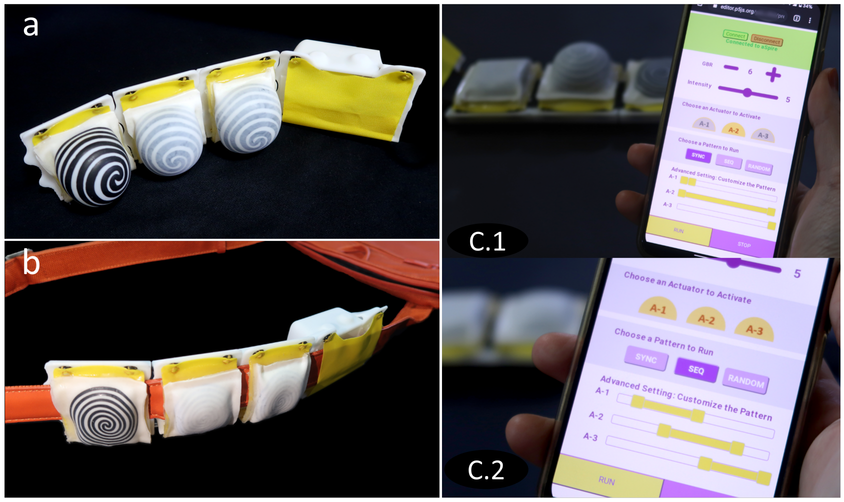
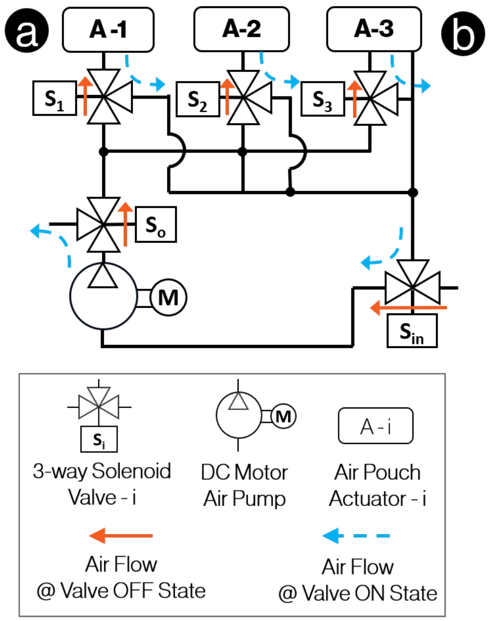


Fig. 2. Working prototype of the clippable pneumatic-haptic feedback device. (a) Bottom view of the device when all the actuators are fully inflated. (b) the device clipped on a cross-bag strap as one of its clippability examples. (c) Control UI; (c.2) Close-up view of the UI.

3 IMPLEMENTATION

Here, we present for the first time the hardware system design and fabrication that achieves the three primary design requirements: personalizable, comfortable, and mobile [13]. To maximize mobility for general use, we made the device to be easily clipped on a belt/strap such as seat-belt, waist-belt, backpack or cross-bag strap, etc. This allows the device to be sandwiched between the user's body and the belt/strap in a way that effectively delivers tactile stimulation with the additional pressure coming from naturally-applied tensions of a belt or weight of backpack on a shoulder. To explore a way to guide different breathing phases such as inhalation, exhalation, and hold, with various rates, we designed the tactile stimulation modules arrayed in a line to deliver various tactile patterns including directional information.

The device consists of three soft air-pouch actuator modules with embedded stretchable pressure sensors and a pneumatic control system module. We wanted to deliver a tactile feedback that mimics the breathing process of human to make the use of our device intuitive. Therefore, we designed a pattern that provides directional information (e.g., stimulation comes from bottom to upward, from top to downward) that could be mapped to indicate inhalation or exhalation. The control module includes three solenoid valves that are connected to each actuator, and a DC motor air pump which is connected to two additional solenoid valves to control the open/close of the outlet and inlet of the pump. Based on these five solenoid valves' ON/OFF state and duration combinations as summarized in the state table (Fig. 3(b)), the system can individually control the deformation speed of the actuator using a single motor. These configurations of solenoid valve states allow the air to flow either between the actuator and 1) the outlet of the motor; 2) the inlet of the motor; 3) the other actuator, or 4) the outside of the system. When the system starts, each actuator runs 2 cycles of full inflation/deflation to initialize and calibrate the sensor. Then, the actuator inflates to maintain 15-20 ml of air inside. To allow users to control and program their own tactile pattern, intensity, **GBR**, we built a mobile UI (Fig. 2 (c)) that runs in web browser on any mobile devices (e.g. laptop, smartphone). The UI and the device is wirelessly connected by Bluetooth communication.



b

State \ Valve	S_o	S_{in}	S_1	S_2	S_3
Inflate All	OFF	OFF	OFF	OFF	OFF
Inflate A-1	OFF	OFF	OFF	ON	ON
Inflate A-2	OFF	OFF	ON	OFF	ON
Inflate A-3	OFF	OFF	ON	ON	OFF
A-1 ← A-2, 3	OFF	ON	OFF	ON	ON
Deflate All	ON	ON	ON	ON	ON
Deflate A-1	ON	ON	ON	OFF	OFF
Deflate A-2	ON	ON	OFF	ON	OFF
Deflate A-3	ON	ON	OFF	OFF	ON
A-1 → A-2, 3	OFF	ON	ON	OFF	OFF
Steady (hold)	ON	OFF	OFF/ON	OFF/ON	OFF/ON

Fig. 3. (a) Pneumatic control system diagram of our device. (b) State table showing different actuation state of air pouch actuators based on the combinations of the five solenoid valves' ON/OFF state. The arrow indicates the air flow direction.

Diverse people have different body shapes, and we wanted to accommodate the diversity in contact area with the device's soft actuator module. We thus developed a system that can deliver uniform intensity of tactile stimulation and maintain it regardless of the actuators' contacting area. Also, to meet the design requirement of personalizability, having an adjustable tactile stimulation intensity regardless of external force applied to the device is required. To do so, we introduce a DIY fabrication technique to produce a stretchable pressure sensor in a cost-effective and simple way in the following section.

3.1 Fabrication Process

3.1.1 Stretchable Pressure Sensor. Fig. 4 illustrates the fabrication process of the customized stretchable pressure sensor. To keep the device compact and mobile, we created a stretchable pressure sensor that can be integrated as a part of the actuator material, instead of introducing an extra barometric pressure sensor tethered to another air channel tube branching from it connecting between actuator and pump, which is commonly used in a pneumatic system. We embedded the sensor system on the air pouch actuator membrane that responds to the volumetric deformation of the actuator by varying its resistance value. Muth et al. [52] introduced a way to utilize a homogenized carbon conductive grease to 3D print the sensor trace loaded in a syringe. We used a raw material directly from a carbon conductive grease (MG Chemicals 846, volume resistivity of 117 Ohm/cm) for creating the sensor trace. This made the fabrication process simple and cost-effective (material cost: $0.27/g) with a high accessibility compared to other conductive material commonly used for creating flexible and stretchable sensors such as a liquid metal (e.g. Eutectic Gallium-Indium [53, 59, 65]), acetylene carbon particle mixed with polydimethylsiloxane (PDMS) [78], silver nanowire (AgNW) ink [16]. The fabrication process starts from vinyl cutting a sensor trace stencil made of a vinyl sheet. We designed a double spiral sensor trace (2 mm width) to make it responsive to the isotropic expansion/retraction characteristic of the silicone membrane with radial and

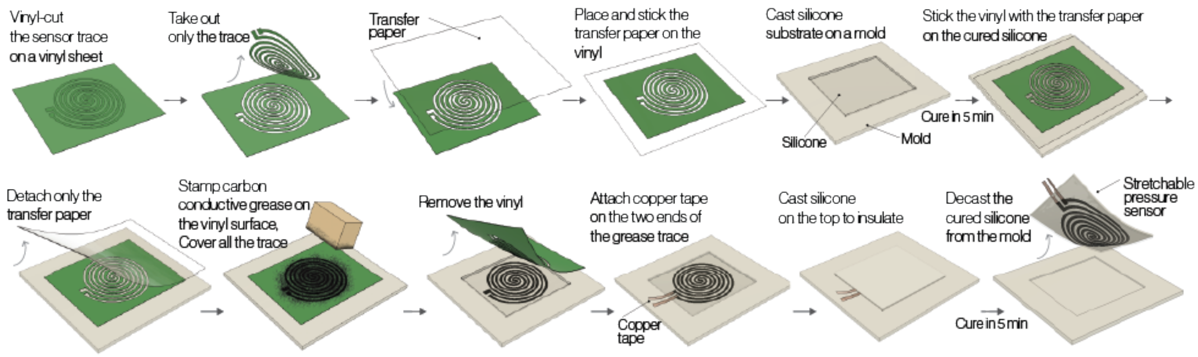


Fig. 4. Fabrication process of the stretchable pressure sensor and the air pouch actuator membrane

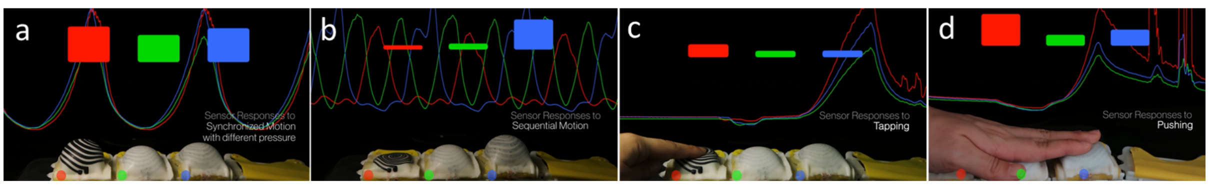


Fig. 5. Real-time sensor response to different tactile stimulation pattern and external force. Sensor response to; (a) the synchronized tactile pattern, (b) the sequential tactile pattern, (c) tapping force by a finger to the first air pouch actuator (red), (d) pushing force by a hand to the all actuators. (Red, green, blue color indicates the each actuator in order starting from the left)

circumferential strains when the air flows in and out. We casted silicone (Ecoflex 00-35, Smooth-On) on a mold to produce a 1 mm thickness silicone membrane substrate of the sensor. After 5 min of full silicone cure, we transferred the vinyl-cut stencil with the transfer paper on the cured silicone substrate and removed the transfer paper. We stamped carbon conductive grease using a sponge on the surface of the vinyl sheet until it fills all the negative part of the stencil pattern. After removing the stencil, we placed two strips of copper tape at the end and the start point of the spiral to make electric connectors. To protect and electrically isolate the sensor trace and to fix the copper tapes, we coated the carbon grease stamped face with the same silicone. We utilized this sensor membrane as a part of the soft actuator by following the process described below.

The introduced fabrication technique could be useful for creating flexible sensors quickly and easily by varying the sensing trace's geometry. This is applicable for creating a silicone-based pneumatic soft actuator and a stretchable sensor specialized for specific measurement purposes. (e.g. strain sensor, pressure sensor, bend/flex sensor). Also, the pneumatic control system (Fig. 3) is applicable to actuate any pneumatic soft actuator array using a single air pump motor simply by replacing A-1/2/3 (Fig. 3 (a)) with any other actuators. Lastly, this system allows the soft actuator modules to have different forms of array configurations other than a line array.

3.1.2 Soft Air Pouch Actuator. We cut the fabric (air-tight thermoplastic polyurethane (TPU) coated Nylon) (yellow part of Fig. 2.(d)) to use it for a clip flap and made the flap inflatable to use as an air pouch actuator. To make the actuator, we coated both sides of the fabric with the silicone, aligned the sensor membrane with the fabric, and sealed all the edges. We made a hole and inserted a elbow connector on the pouch to connect the air channel tube (Black tubes shown in Fig. 2(d)), then attached the pouch on the 3D printed frame.

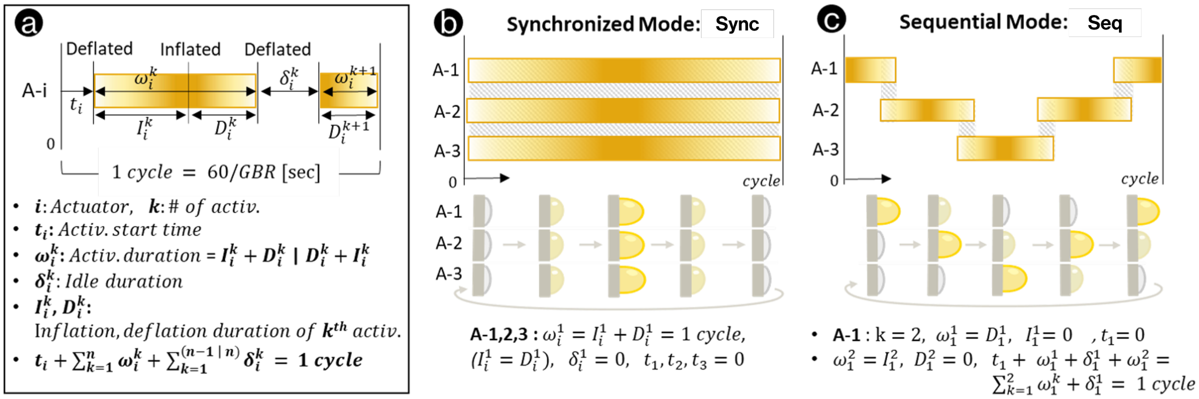


Fig. 6. (a) System diagram of rendering different tactile feedback patterns and frequency. Saturated yellow color indicates the fully inflated state. Examples of tactile patterns and representative model with assigned variables: (b) Synchronized mode. (c) Sequential mode. (GBR = Goal Breathing Rate [per/min])

3.2 Tactile Feedback Personalization: Intensity, Pattern, Frequency

Fig. 6 illustrates the system diagram and control parameters for rendering different tactile patterns and frequency, and two examples with tactile pattern sequence visualizations. One operation cycle of the tactile stimulation is set at $60/\mathbf{GBR}$ [sec]. Once the duration of 1 cycle is obtained, we can individually set the actuator's $(A-i)$ activation start time (t_{i}) and the number of its activation (k) during 1 cycle. The duration of the k_{th} activation of the $A-i$ is denoted as ω_i^k and it is the sum of deflation time (D_i^k) and inflation time (I_i^k), or the other order depending on which one first starts. δ_i^k indicates the idle duration between k_{th} and $(k+1)_{\mathrm{th}}$ activation. Fig. 6.(b, c) shows examples of synchronized activation of 3 actuators and sequential activation. By controlling the $t_{\mathrm{i}}, k, \omega_i^k, \delta_i^k$ values, the flow of the activation of individual actuator can be varies as to be either discrete transition (no overlapping activation time between $A-i$ and $A-(i+1)$) or continuous transition. The control UI offers three sets of pre-defined different tactile patterns for easy and simple usage, and users also can create their own pattern by adjusting the range slider that represents ω_i^k.

From the sensor evaluation process (section 4.1), we found high reliability of the stretchable pressure sensor. We applied a closed-loop pressure feedback PID control (Fig. 7) to provide a uniform contact pressure to different body shapes having different contact points. The contact pressure was calculated by subtracting the calibrated initial value (R_{i}) from the current sensor value (R). If the subtracted value (R_{S}) is positive and reaches the target value (R_{T}) within the designated inflation time of single actuator (I_i^k sec), the controller adjusts the air flow to maintain the R_{T}. If $R_{\mathrm{S}} \leq 0$ from one of the actuators within the I_i^k, the system defines that the actuator does not make any contact with the user's body; subsequently, it can supply more air until it makes $R_{\mathrm{S}} \geq R_{\mathrm{T}}$.

4 TECHNICAL EVALUATION

4.1 Stretchable Pressure Sensor Evaluation

To validate the functionality of the stretchable pressure sensor, we tested and calibrated the sensor by referencing the off-the-shelf barometric pressure sensor product (MPRLS Ported Pressure Sensor, Adafruit). We ran the inflation/deflation cycle of the soft air pouch actuator with 12 bpm speed for 160 min to have it run for 1920 cycles for a durability test and for inspecting hysteresis by the peak-to-peak value variance. After running the 1920 cycles, the barometric pressure sensor's peak-to-peak value root-mean-square error (RMSE) was 8.86% while

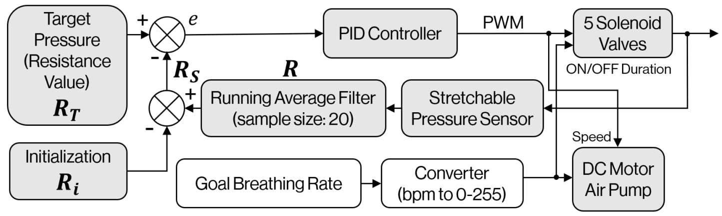


Fig. 7. Closed-loop pressure feedback control and GBR open-loop control block diagram

the stretchable pressure sensor had an RMSE of 7.69%. We used the data acquired from the cycle test for a sensor calibration.

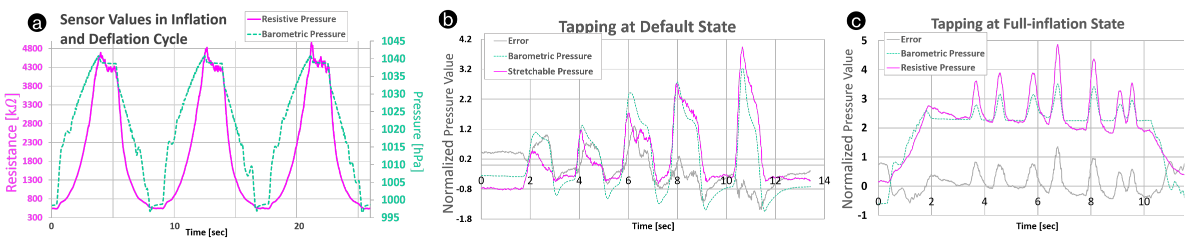


Fig. 8. (a) Part of the duty-cycle (1920 cycles: 12 bpm for 160 min) test result. Variation of the stretchable pressure sensor resistance value [kΩ] and reference value from a barometric pressure sensor [hPa] (dotted-line). Response and the error (b) to tapping when the actuator is at default state (inactive state), (c) to tapping when the actuator is fully inflated

Fig. 8 shows part of the duty-cycle test result with true units (a), and the sensor response test result with error curve compared to the barometric pressure sensor response (b, c). Since we only consider the variance of the sensor value over time, we normalized the acquired data to compare the sensor characteristic in response to the external applied force. When the stretchable sensor was detecting the inflation/deflation, there was a 0.14 sec latency on average. However, it responded 0.1 sec faster on average than the barometric sensor when it was detecting the tapping to the default state actuator (Fig. 8 (b)). The stretchable sensor in response to tapping the fully-inflated actuator (Fig. 8 (c)) produced a higher sensor value variance than the barometric sensor.

4.2 Adaptive Tactile Intensity Corresponding to Different Body Shapes

We evaluated the closed-loop pressure feedback control system in response to a unit step as shown in Fig. 9 (a). We manually tuned the PID controller gains and achieved a desirable step response of the system with the steady state error of ≤ 0.04. Next, we ran the device on a test bed (Fig. 9 (b)) that represents extreme cases of various human body curvatures, and tried the device on a different location of the test bed to make the actuators contact different curved shapes for each run, while obtaining its sensor response. The system inflated all actuators at once and detected the first contact made by any of three actuators, set the sensor value obtained from the first contact as an initialization value (R_i), and repeated the same process for the remaining two actuators. Fig. 9 (c) presents an example from the result. We were able to validate the systems for maintaining and adjusting the uniform pressure stimulation intensity regardless of different physical-body contact shapes.

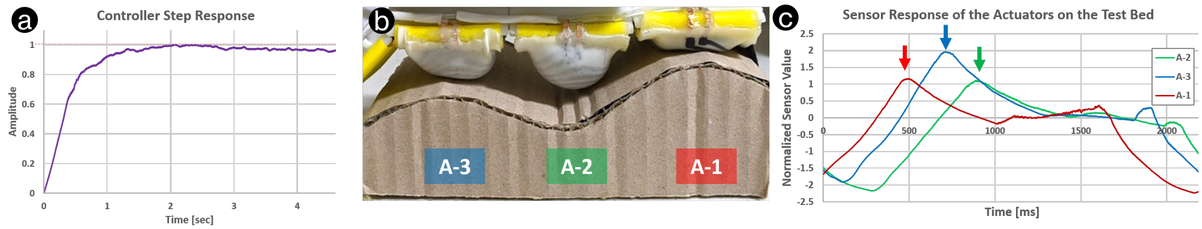


Fig. 9. (a) Closed-loop pressure feedback controller's response to pulse (b) Test bed for validating the adaptive tactile intensity system. The device was clipped on a belt which was fixed on the test bed (c) Example graph of test results, normalized by the target intensity (denoted as 0 in the graph) since only the relative R value from the sensor matters. Arrow indicates the moment of contacting the test bed and generating the peak value. Once the sensor detects the contact, the control system was able to settle the contact pressure to reach the target pressure.

4.3 Hardware Specification of the Device

The maximum speed of the DC motor air pump is 18.5 ml/sec for inflation, and 21.4 ml/sec for deflation. This enables the system to deliver up to 15 bpm with various tactile patterns. When the motor was running at the maximum speed, the noise level was measured as 62 dB from a 1 cm distance, and 38 dB from a 30 cm distance. This maximum noise level is relatively low; for comparison, noise from a conversation in a restaurant or office may be around 60 dB. When the motor was running at the average speed, the noise level was measured as 43 dB from a 1 cm distance and 28 dB from a 30 cm distance (with ambient noise measured as 24 dB). This low noise level was enabled by enclosing the micro air pump motor in a sponge and a case to isolate its mechanical vibration from other contacting materials. Also, the control system of the device allows the motor to operate lower than its maximum operating voltage so that to produce much less noise.

The maximum normal contact force that the actuator can handle was measured as 17.7N. The dimension of the single soft air pouch actuator is 58W x 67L x 15H mm. The dimension of the pneumatic system module is 99W x 67L x 38H mm. The total weight of the device is 252 g. The silicone we used for fabricating the sensor and actuator has a 900% elongation at break, which led us to achieve a maximum z-direction (height) strain of 32 mm, and the maximum volumetric displacement of 40 ml for inflation and 17.5 ml for vacuuming from the default state. At the maximum-inflated state, the pressure inside the actuator goes up to 1054.57 hPa on average (10.6 MΩ) where the average atmospheric pressure was 1010.89 hPa measured from the barometric sensor. When the motor fully vacuums the actuator, the pressure of the actuator drops down to 872.73 hPa (490.8 KΩ). This maximum and minimum pressure values were mapped to the intensity parameter in the discrete range of 1 - 5.

5 USER-BASED EVALUATION: PERSONALIZATION OF THE TACTILE FEEDBACK

We conducted a series of user-based evaluations to gather users' feedback on different aspects of the device's personalization features. The series comprised four separate evaluations: (1) Selection of the most promising sequential feedback pattern (Seq). This study obtained feedback from 3 participants to tune the initial haptic design parameters to obtain a Seq pattern to be tested in comparison with the Sync pattern. (2) Recommendations on haptic feedback intensity and frequency. This study was a within-subject study with 5 participants in an office environment to obtain their feedback for tuning the tactile intensity and frequency parameters. (3) Comparison of two distinct tactile patterns (Sync vs. Seq). This was a between-subject study conducted with 40 participants who each performed three different activities: cognitive tasks in an office environment, on-road driving, and outdoor walking. (4) Exploration of the device's potential as a breathing pacer. This evaluation zoomed into raw data from one participant in an office environment to explore if segments of the breathing data waveform synchronized with the device's haptic feedback rhythm, both for Seq and Sync conditions. Details and results of each of these are described below.

5.1 Selection of the Most Promising Sequential Feedback Pattern

In addition to the synchronized tactile pattern (Fig. 6 (b)), which provides uniform pressure on the body by inflating all actuators together every cycle, we were interested in investigating the effect of sequential tactile patterns, which can render a greater variety of patterns than synchronized actuators. The sequential feedback delivers directional information (flow), which we designed to represent a flow of the air inhaled and exhaled. To select the most promising sequential tactile pattern as a breathing guide, we conducted a pilot study to compare several sequential tactile patterns. First, we compared the following two sequential patterns: *A) flow in round-trip:* inflation of each actuator in sequence with overlapping inflation time and deflating back to where it ends to inflate at last (visualized in Fig. 6 (c)), *B) flow in the same direction:* same as the pattern-A but deflation starts from the actuator that started to inflate at the start of the cycle. We asked 3 participants (2 males and 1 female, Mean age = 47.33, SD= 16.74) to put a cross-bag attached with the device on its strap and to sit on a chair in a room. The device was in contact with their chests. Without disclosing the purpose of the device, we first let them experience the tactile feedback for 2 minutes and asked how they felt. When exposed to the pattern-A, two participants reported the feeling of the circulation of an object around their upper body for massaging. With pattern-B, one participant said that it induced a feeling of a rubbing movement on the chest, as if to help with digestion. Overall, all reported that both types of feedback were relaxing. Next, we asked if the device was designed for regulating BR, which pattern would they prefer to use. All participants preferred pattern-A because they felt that the stimulation flow round-trip reminded them of the direction of breathing in and out through their lungs. They reported that pattern-B was confusing as to how it related to breathing. As a second phase, we compared pattern-C to pattern-A, which is the same as pattern-A but without the overlapping activation time. All participants preferred pattern-A and reported that they felt that pattern-C was annoying, alerting, and something was intermittently poking them, while pattern-A felt more like something was smoothly rolling around. From this feedback, we selected the sequential tactile mode (Seq) with an overlapping activation time set to follow $(t_i + \omega_i^k) - \omega_{i+1}^k = 0.02 \text{ x } 60/GBR$ sec., to be tested in the pilot studies, along with the synchronized tactile pattern (Sync). Other configurations (customizable) with our device may be of interest in future explorations, e.g. to relax in support of digestion.

5.2 Recommendations on the Haptic Feedback Intensity and Frequency

We conducted a pilot study to gather the users' initial feedback and recommendations on setting up haptic feedback intensity and frequency of two distinct haptic stimulation patterns namely: synchronized (Sync) and sequential (Seq) in an office environment.

5.2.1 Procedure and Data Collection. The pilot study is designed to take approximately 1 hour to experience the device in the office environment, including sensor and device equipment, training, and pre- and post-study surveys (Fig. 11). All the survey questionnaires can be found in the Appendix.

After signing the consent form pre-approved by the Institute Review Board (IRB), each participant filled out a pre-survey. The pre-survey included the Perceived Stress Scale [63], the Big-Five Inventory (BFI) [34, 35], and demographics questionnaires. The demographics survey included age, gender, height, weight as well as participant's average time spent on daily activities of driving, riding in a car as a passenger, walking outside, and working at the office. Lastly, the survey questioned the participant's experience of practicing slow breathing and its type of technique.

After the pre-survey, we helped the participant to wear the Zephyr BioHarness chest strap. [1, 36] and the Empatica E4 wristband [20] on their non-dominant hand. As shown in Fig. 10, the BioHarness sensor was worn

Fig. 10. Pilot study setup in an office environment with a BioHarness chest strap (respiration sensor) and a cross-body bag with the device clipped on. Note that this photo was taken during the study described in Sec. 5.4. While the placement of the device and sensor is the same for both studies, the office setup is different: This one used a desktop setting while the other used a tablet PC for completing a cognitive task.

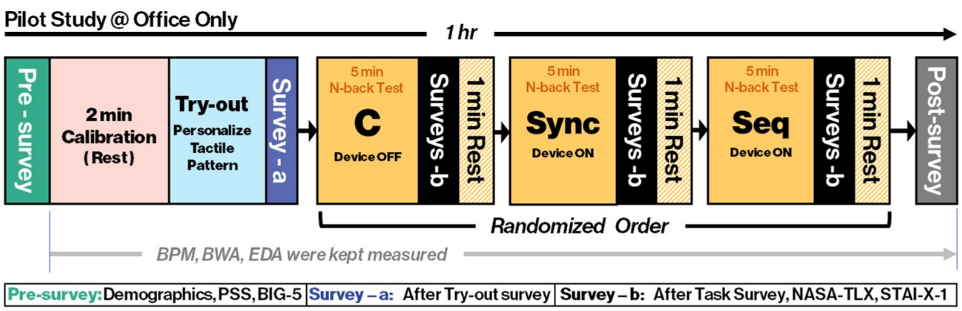


Fig. 11. Pilot study procedure at the office environment only

around the chest area and did not overlap with the device's location. Many previous studies have used this chest strap-type breathing sensor in their user study protocols [30, 43, 58, 81].

Throughout the study, we captured the participant's Breathing Rate (BR) and the Breathing Wave Amplitude (BWA) using the Zephyr sensor. We used the IoTool Android application to log the data from the BioHarness sensor in real-time using the Lenovo Tab M8 HD model. The sampling frequency was 1 Hz and the time window for breathing rate calculation was 45 seconds. The participants' electrodermal activity (EDA) data was captured using the E4 sensor at a sampling frequency of 4Hz. Each participant was asked to wear the wristband on the non-dominant hand to minimize the movement-related noise.

We calibrated the device's breathing guide pace based on each participant's average breathing rate. For this purpose, we asked the participant to close their eyes and relax for two minutes on the seat. Considering the irregular breathing pattern at the beginning of the calibration, we used the measures from the final minute to calculate the mean breathing rate (**MBR**). With an aim to reduce the breathing rate of the participant using the device, we set the breathing guide rate of the device as a goal breathing rate (**GBR**), to be 70% of the individual's **MBR**.

After the calibration, we helped the participant to put on a cross-body small bag ("fanny pack" Fig. 1 (d)) clipped with our device on the bag's strap across the upper body which placed the pouch actuator modules at their chest. Then, we started the try-out session, in which all the participants were introduced to the different combinations of the device settings in order to personalize the tactile feedback that they would like to experience during the whole experiment. First, they were introduced to two different tactile patterns (Fig. 6): synchronized and sequential, each with a fixed stimulation frequency of 10 bpm (range: 6 - 15 bpm) and an intensity level of 1 (range: 1 - 5). We allowed them to experience the two patterns for about one minute each and if they wanted to try a specific pattern again, we let them do so. During this process, if they reported the intensity was too weak or the frequency was too fast/slow, we adjusted the intensity level and frequency and let them try and compare the two tactile patterns again. This process iterated until they found their personalized preferred intensity and frequency setup. After the session, we asked the participant to fill out the survey (denoted as 'Survey - a' in Fig. 11) giving their subjective impression about the device and the two patterns. The device was then set to the preferred intensity selected by each participant.

The three conditions of control (C), synchronized (Sync), and Sequential (Seq) followed the try-out survey. We randomized the order of these conditions for the participants to minimize order effects on our measures. We did not disclose the fact that the device was not working with the control condition (although it was disclosed later, after all study steps and surveys were completed). Instead, we explained to the participants that *"this device provides subtle tactile feedback. Therefore, even when you cannot notice the tactile feedback, it is totally normal and is not the malfunctioning of the device."* We added instructions to prioritize the task: *"Please place the highest priority on performing your given daily life activity. You are always free to engage or disengage your breathing pattern with the device voluntarily based on the priority."* At the end of each condition, we asked the participant to respond to the survey (denoted as 'Survey - b' in Fig. 13) on an Android mobile phone. The survey contained questions about their experience with the intervention and their subjective impression about the device. We included the NASA-TLX [32] with 7-point scale (1:Low, 7:High) and STAI-X-1 [70] with 5-point scale (1:Low, 5:High) in the task survey to measure the participant's perceived workload and anxiety. We also designed customized questions to measure the participant's task experience on a 5-point Likert scale: We asked the participant about their level of perceiving the tactile feedback from the device, awareness of breathing, effort in breathing regulation, and the device's influence on breathing control. Then, the survey questioned the general subjective impression about their activity with the device in terms of pleasantness, energy, stress, comfort, and disturbance.

For each condition, we presented five minutes of the number 2-back test to the participant using a tablet PC in the office. The number 2-back test shifted a random number between 1 to 9 on a screen and required the participant to press "space" in the keyboard when the current number matched the one in the 2-steps previous. After finishing all three conditions, participants completed a post-survey. The post-survey recalled their try-out session about how easy it was for them to follow the training session on a 5-point Likert scale, their preferred pattern of the tactile feedback, and the reason for their preference. The survey asked their awareness of the tactile stimulation during all three different conditions on a 5-point Likert scale. It also asked for other suggestions on using the device in different activities, body parts for tactile stimulation and purposes other than breathing regulation. Then, the survey questioned the participant's willingness to purchase a future commercialized version of the device using a 5-point Likert scale. In the last part of the survey, we asked which activity would be the most suitable for using the device in general and for each tactile feedback pattern. We collected the other extra comments and qualitative feedback.

After filling out the post-survey, we helped the participant take off the Zephyr and E4 sensors and the device. All participants were required to wear a face mask at all times during the study to follow the COVID-19 rules. We thanked them and informed them that they would receive a 20 dollar gift card for a franchise coffee shop in two weeks time by mail as compensation.

5.2.2 Cohort Description and Main Results. Five male participants were recruited for the study from the Hyundai Kia Namyang R&D Center located in South Korea. Their ages ranged from 32 to 48 (AV = 41.8 and SD = 5.31). All

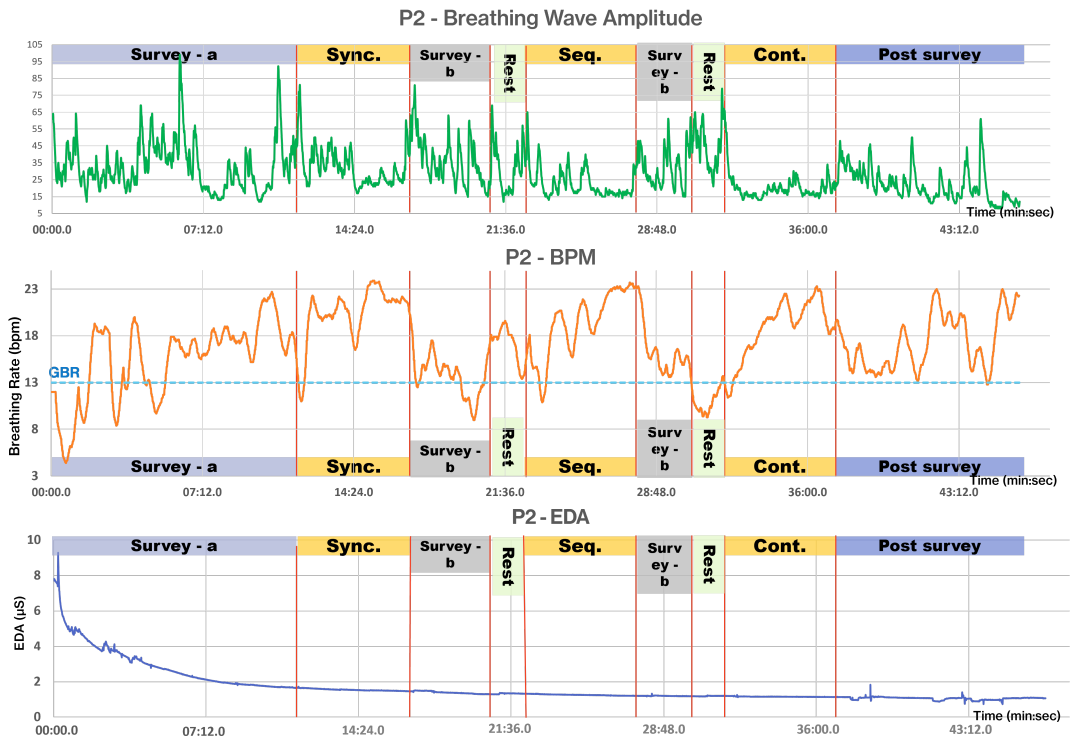


Fig. 12. Breathing wave amplitude (a), breathing rate (b), and EDA (c) of participant-2 of the pilot study.

of them reported that they never practiced slow breathing, yoga, or meditation. Regarding the amount of time spent sitting in the office per week, their responses ranged from 25 - 40 (AV = 35 and SD = 6.32) hours.
Based on the findings reported in Miri et. al. [49], active breathing resulted in a larger breathing wave amplitude when compared to passive breathing. In addition, it has been shown that higher workload reduces Breathing Wave Amplitude (BWA) [28]. Based on those earlier findings, we anticipated that 1) If the device is helpful in reducing the workload and stress, then the BWA will be higher and the BR lower during the sync and seq feedback compared to the control condition and 2) Whenever the participant is aware of their breathing, then active breathing is more likely to be performed and a larger BWA will be observed. We plot in Fig. 12 the raw breathing signals (Breathing Wave Amplitude and Breathing Rate) and the electrodermal activity (EDA) of participant P2 who participated in this pilot study, to showcase some of the objective data gathered.

For P2, we observe significant peaks in the BWA signal at the beginning of each experiment segment. The BWA values are higher during the first half of the Sync. and Seq. interventions. Overall, the values are higher during the intervention compared to the control condition. Participant P2 reported that he felt more comfortable during the interventions (Sync.:3 and Seq.:2) compared to the control condition (Control:1). The interventions were pleasant (Sync.:5 and Seq.:3) compared to the control (Control:3). However, he found the interventions not too noticeable (Sync.:1 and Seq.:2), more stressful (Sync.:2 and Seq.:3), and disturbing (Sync.:4 and Seq.:3) compared to the control (both ratings of stress and disturbance are equal to 1). Regarding his STAI-X class, his anxiety level was high under all three conditions. His perceived total workload score (5 - 35) based on the NASA-TLX survey result, Control: 30, Sync: 30, Seq: 32.

Three participants responded that they preferred the synchronized tactile pattern. They reported that it felt stronger compared to the sequential one. Two of the participants recommended the Sync. pattern for office work while one thought that it might be proper for walking activity. The remaining two participants who preferred the Seq. pattern reported that it felt like soft massaging or a cat kneading. One of them recommended the Seq pattern for the office and driving environment, while the other recommended it for use with walking. All 5 participants responded that they would like to use the device in general for an activity related to sleep or meditation. Regarding the perceived comfortableness (a scale from 1 to 5), P1 and P3 marked 3 for all three conditions, P2 reported a higher level for Seq.:3 compared to the Control:1 and the Sync.:2, P3 reported higher levels for both Control and Sync. (rating:3) compared to the Seq. feedback: 2. Lastly, P4 reported a low comfort level for Control (score:1) and a higher rating for the interventions (3 for both Sync. and Seq.). Overall, the perceived comfort during the Sync. pattern was consistent between the participants (rating of 3 from all them).

Users feedback-based findings and recommendations:

- Findings:
  - The feedback intensity and the modulation frequency are among the most critical design parameters.
  - Even though the tactile intensity was tuned at the level that each individual found high enough during the' Try-out' session, the participants' perception of the intensity changed once they were given the main foreground task.
- Recommendations:
  - Include higher levels of intensity in the settings suggested to the users to make the tactile feedback more noticeable, particularly the synchronized one.
  - Since the device comes with a UI, offering the user the choice to select the preferred haptic pattern might increase the efficacy of the device as a breathing guide.
  - Explore the usage of the device during different daily activities like walking and driving other than office work, and compare haptic patterns' effects on different activity.

5.3 Tactile Patterns: Synchronized vs. Sequential

The pilot study presented in Section 5.2 allowed the participants to experience the two different haptic stimulation patterns only in an office environment. Their qualitative feedback suggesting the use of the device during different activities led us to investigate the device's effect during different daily activities. Reflecting on the findings and users' recommendations from the pilot study, we designed the following study illustrated in Fig. 13.

This study aims to evaluate the effect of giving the choice of selection of the preferred tactile pattern on the effectiveness of the device while the wearer is performing daily stressful tasks. We are particularly interested in whether the subtle breathing guidance of our system disturbs the primary daily task performance: office working and driving. We also want to examine if the device efficacy and user preference are different between the two tactile patterns: synchronized (Sync) and sequential (Seq).

We conducted an exploratory user study with a mixed experimental design considering a between-subjects factor (device ON and OFF) and a within-subjects factor (activity type: working in the office and driving).

5.3.1 Procedure. This study was conducted using our device in three different daily life scenarios: driving, walking and working at an office. Before starting the user study, participants gave informed consent in a study pre-approved by the IRB. The study procedure is almost the same as the first pilot study, described in Section 5.2.1, except that here we gave subjects the choice to personalize their tactile feedback by selecting either the synchronized or sequential, whichever they preferred after experiencing both of them. Specifically, participants were asked to choose a pattern that feels more intuitive to follow with their breathing without feeling disturbed. The device was then set to the preferred intensity selected by each participant when they chose either the

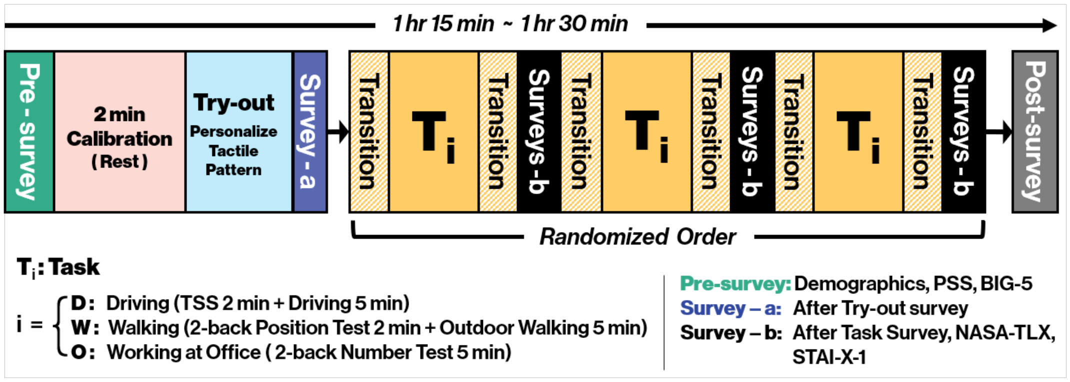


Fig. 13. The user study procedure

synchronized or the sequential pattern to use in the rest of the study. As summarized in Fig. 13, the user study is designed to take from 1 hour 15 minutes to 1 hour 30 minutes to experience the device in three daily life scenarios. The performance of the cognitive activity in an office environment was the same as described in Sec 5.2.1. All the participants were rewarded with a 20 dollar gift card for their participation.

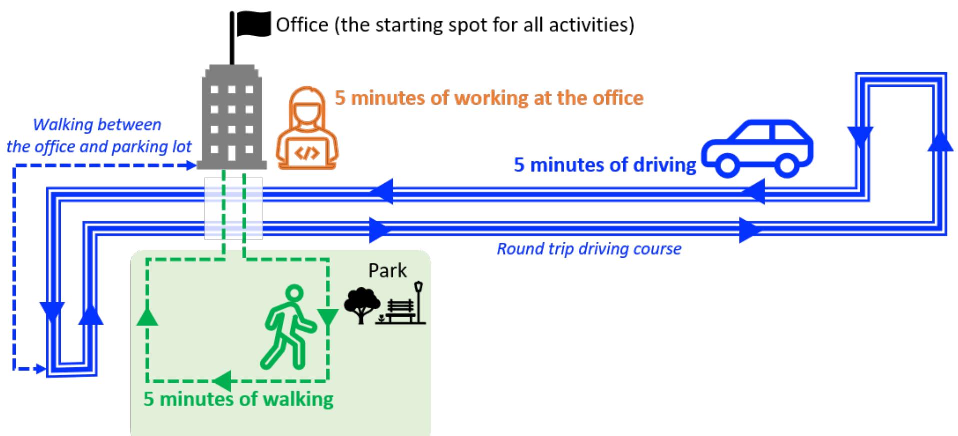


Fig. 14. Route description for three daily activities: driving, walking, and office working

For the driving activity, we used the same vehicle for all the participants, a 2019 Hyundai KONA EV, to provide a consistent driving environment. The participants walked to the parking lot, located 5 minutes walking distance from the office, to start the activity. We prepared another of the same device, which we installed on the driver's seat-belt in advance and calibrated to their stated preferences. Once the participant arrived at the car, we helped the participant take off the fanny-pack clipped with the device, so that they could use the one built-into the car. They then sat in the driver's seat, and fastened the seat-belt which has the same device already pre-installed (to minimize the duration of the user study). Before starting the drive, we presented a short math quiz to the participant, adapted from the Trier Social Stress Test (TSST) [38], to increase their stress from the base level. We gave a random number between three-thousand to four-thousand, and the participant was asked to subtract 13 from the given number and speak out the answer, and to keep subtracting 13 from their own answer. We let them know that the instructor kept checking whether the answer was correct or not, but did not correct their answer even if they calculated the number wrong. This method of introducing the stressor was used in prior work testing a real-world driving setup by Balters et al. [3]. We explained the driving course to the participant and asked them not to interact with the instructors in the car, but to imagine that they were alone in the car, and to drive safely.

Before the walking activity, we conducted the position 2-back test to increase the participant's stress level. The participant took the test in the office using a tablet PC. The proposed 2-back test asked the participant to memorize the randomly shifting position of the square box in a three-by-three grid space and press the "a" key in the keyboard when the current position of the square box matches that seen from two previous steps. For the walking activity, we described the course at the park to the participant, where there was a one minute walk across from the office building. We explained to them to walk for five minutes without a designated route in place. We asked them to not engage with other extra activities beyond walking and interacting with the device, such as using a smartphone or talking to people around them. In addition to putting on the bag clipped with the device, we gave the participant a tote bag which contained the Android tablet for collecting sensor streaming data, operating the device, and sounding an alarm after the five minutes of walking was completed. At the end of the walking activity, the participant returned to the office and filled out the surveys. All the survey forms can be found in the Appendix.

5.3.2 Cohort Description and Participants' Feedback. Forty participants were recruited for the study from the same company. All of them are employees of the company. Only 8 of the participants were women (20%), while 32 were men. They ranged in age from 27 to 54 (AV=36.6 and SD=6.4) years old. Fifteen participants (37.5%) reported that they practiced slow breathing, yoga, or meditation exercises at least once, while 35 (62.5%) reported that they never practiced them at all. We asked the participants about the amount of time spent driving per week. Their responses ranged from 1 to 20 (AV=6.13 and SD=5) hours/week. The average time spent by the participants walking was 4.98 (SD=4.23) hours per week (min=1 and max=7). When asked about the time spent per week sitting in the office, the participants reported values between 2 and 45 (AV=28.8 and SD=12.18) hours a week. We randomly assigned the participants to one of the two groups: control and intervention so that we have 20 participants per group, making sure the randomization maintained the gender ratio (4 females per group).

Most participants selected the highest intensity of 5 when asked to adjust the strength of the pressure during the try-out session. For both control and intervention groups, 8 participants selected the synchronized pattern while 12 selected the sequential one.

The questionnaire given after the try-out session helps reveal how the participants perceived the personalized tactile feedback and the synchronized and sequential patterns.

Fig. 15 summarizes the average and the standard deviation of the participants' ratings to each of the 7 questions, on a 5-point Likert scale (1:Low, 5: High), asked after experiencing the Sync and the Seq tactile feedback, each for about a minute. Participants reported that the intensity of the pressure is perceived as stronger when experienced with the sequential pattern compared to the synchronized one. The sequential feedback was reported to be more intuitive, made the participants feel more active and was anticipated to interfere slightly more with the main task compared to the synchronized one. Both types of tactile feedback were perceived as low stress and both were comfortable.

Of the twenty receiving active feedback, 8 selected the synchronized pattern while 12 participants selected the sequential one. For self-reported workload, the overall score was higher for the control group than the intervention group.

For the office environment, the participants who selected the Seq reported higher mental, physical and temporal demand and effort. However, their frustration ratings tend to be lower overall compared to the ones reported by

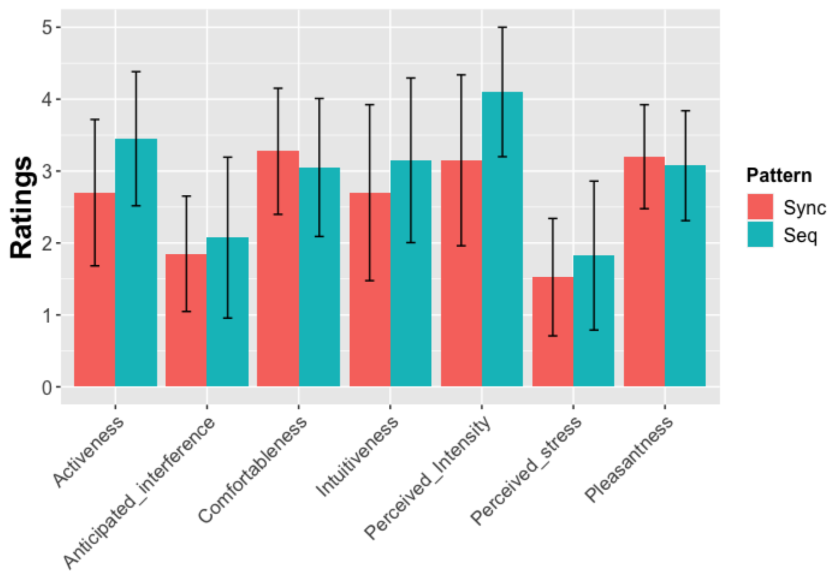


Fig. 15. Average and standard deviation of the self-reports (Survey-a) provided by the participants after the try-out session.

the synchronized group. For the driving environment, in terms of their reported subjective workload, the ratings of the participants who selected the Sync tended to be lower compared to the participants who selected Seq for all dimensions. For the walking activity, in terms of subjective workload, the mental and physical demand, effort, and frustration have almost the same level on average for both Seq and Sync.

Fig 16 depicts the after-task survey average ratings reported by the intervention group, including the participants who selected the synchronized pattern and those who selected the sequential one. There were 8 questions, on a 5-point Likert scale (1:Low, 5:High), for the after-task survey. We asked how much they notice the level of haptic stimulation (Notice), how much effort they expended to recognize and control their breathing (Effort_for_BR_Control), how much the device was helpful for increasing breathing awareness (BR_awareness) and how much the tactile feedback was disturbing (Disturbance). Other dimensions (Activeness, Comfortableness, Perceived_stress, Pleasantness) were the same as for the Survey-a.

For the office task, those who chose the Seq condition reported higher activeness, pleasantness, comfortableness and less stress than those who chose the Sync condition. For the driving task, the participants who selected Seq reported higher pleasantness, comfortableness and less disturbance compared to the participants who selected the Sync. For the walking task, the Seq condition was reported as inducing higher activeness and lowering stress compared to the Sync condition.

Overall, participants enjoyed the tactile feedback delivered by the device. They reported that they would use it on a daily basis. On average, they responded that they would use it for 2.14 hours per day. Fig.17 and Fig. 18 summarize the post-survey results. We asked the participants why they selected either Sequential or Synchronized pattern as their preference. It was an open question so the participants provided their own answers, and we categorized them based on the key points of their answers. For the selection of the Sequential pattern, most of the participants chose it because they felt it more clearly (34%) compared to the Synchronized pattern and said it was easy to recognize (21%). The most commonly stated reason for selecting the Synchronized pattern

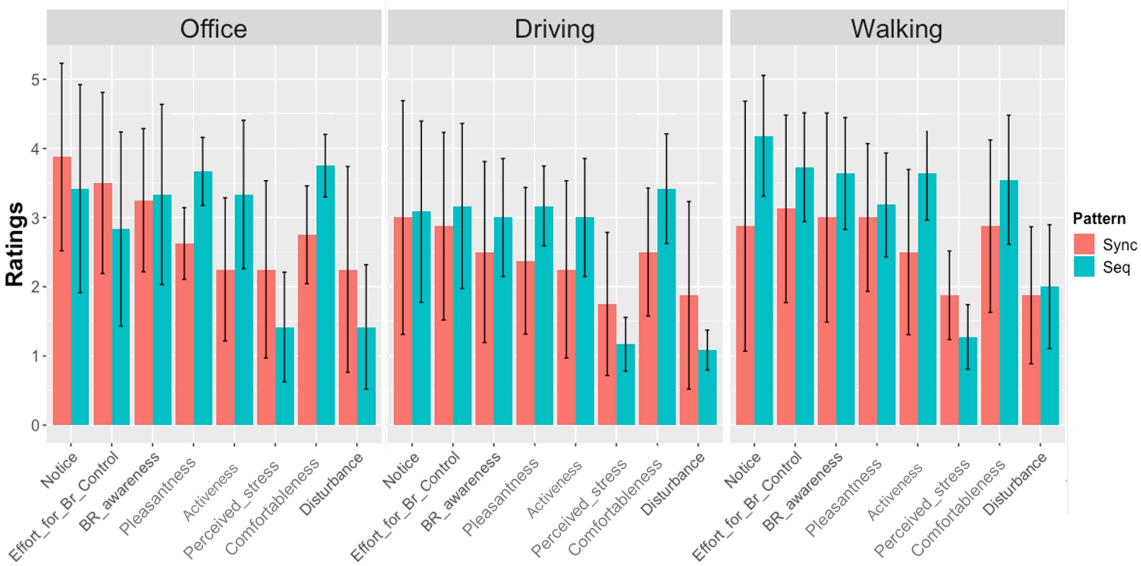


Fig. 16. Average and standard deviation of the self-reports (Survey-b) provided by the participants after each task.

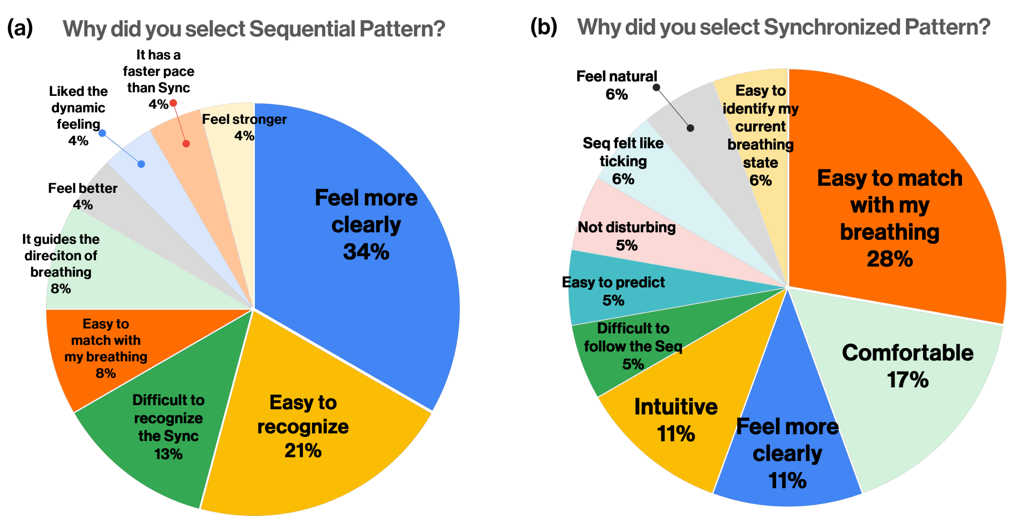


Fig. 17. Result of the open question asking the participants' reason for choosing their preferred pattern. (a) Sequential Pattern (N=24), (b) Synchronized Pattern (N=16).

was because it felt easier to match with their breathing pattern (28%) and comfortable (17%). One participant gave a comment on the sequential pattern and recommended to enlarge the contact area of the individual actuator to resolve this feeling.

Fig. 18. Participants' activity recommendation for using (a) the Synchronized pattern (Multiple choice), (b) the Sequential pattern (Multiple choice). (c) Their general recommendation for the device usage (Multiple choice). (d) Body location recommendation. (Multiple choice) (e) Activity recommendation for the usage of the device other than driving, office work, and walking (Open question). (f) Device purpose recommendation other than breathing guidance. (Optional question)

We asked the participants to predict which one of the three experienced tasks (driving, walking, office) will be associated with the best efficacy results of the synchronized-based intervention (Fig. 18(a)). Twenty-two participants selected walking, 17 chose the driving task, and 15 selected the office work. For the Sequential pattern (Fig. 18(b)), 27 choose walking, 13 selected driving, and 11 predicted that working in the office is the best setting in terms of the device efficacy. When asked to recommend the best setting or activity in terms of usage and usefulness of the device, independently from the tactile pattern, most participants recommended using it while walking (24). Sixteen recommended the driving task, while 11 suggested the office work. Regarding the preferred potential body location (other than the chest) (Fig. 18(d)), most participants (14) chose that they would put the device around their back. Twelve participants selected the neck (including one who suggested putting it in a pillow). We also asked an open question, "When would you use the device other than driving, walking, office work?" (Fig. 18(e)) shows that eleven participants reported that they would use it for sleep guidance or during sleep. The second most reported activity is meditation (6), followed by both working out or stretching/yoga (5) and relaxing during a break time (5). Four participants suggested using it 'before taking an exam/study/intense interview' in order to reduce the stress and anxiety levels. The other suggestions (4) included: gaming, an immersive experience for listening to music by synchronized with the music's beats, moments in need of parasympathetic nerves such as digestion after eating. Lastly, when asked to provide other purposes for the device usage other than breathing guidance, five participants suggested using it coupled with the light for physical activities such as walking and billiards. Three would recommend using the device for calming purposes. Sleep induction was suggested by three participants. We noticed that most of the participants associated the usage and usefulness of the device with calming and relaxing and with purposes related to stress regulation.

Qualitative Feedback. At the end of the experiment, the participants were asked to report any comments about the study or the device via both the open-ended question of the post-survey and a brief verbal interview. Regarding the short interview, the experimenters asked ‘How was your experience? Which haptic pattern did you choose and why? Do you have any comments to talk about?’ and took a digital note if they provided any specific answers.

Some participants gave feedback about the device design, and others commented about the study protocol. Two participants (P24 and P40) expressed the need for higher intensity, thus a higher pressure, since the experienced tactile feedback was subtle for them. One of the participants (P03) suggested having the technology implemented in the vehicle seat for the driving scenario. Regarding the efficacy of the device, one of the participants (P26) predicted that the tactile feedback would be helpful for the physical activities that need breathing regulation, while two other participants (P12 and P37) thought that the tactile stimulation would be more efficient for the tasks that require stationary position such as driving, working in the office, or even resting after tasks that require high mental workload, compared to the activities that involve physical movements (e.g., walking). One participant (P38) from the control group reported that he was waiting for the tactile feedback during the experiment and doubted the device functioning. While one of the participants (P34) showed his appreciation of the comfortable setup, another (P09) reported that the tactile feedback was slightly uncomfortable to use for the first time.

Regarding the open remarks, one participant (P02) from a pilot study mentioned that "It felt better to have the device on the seat-belt rather than having nothing due to its relaxing feeling, it felt very friendly and I liked the wavy feeling of the sequential pattern. When I drove the car slower, I felt it, while I was not feeling it when I drove faster." Two female participants, P39 and P40, mentioned that when there was a moment where all the actuators were deflated while they exhaled during the operation of the synchronized pattern, it created an empty space between the actuators and their chest area so that they were not able to perceive any tactile feedback from the device. P16 mentioned that he preferred the synchronized pattern because he liked the feeling of his chest’s swelling motion corresponding to when all actuators inflate and deflate. P12 reported that he personally prefers a strong and clear notification which characterized the sequential pattern better than the synchronized pattern. He felt that the synchronized pattern might work better for delivering comfort. He recommended using the device combined with visual guidance for assisting with remote healthcare and stretching. P22 mentioned: "I think the synchronized pattern is more ’predictable’ while the sequential pattern felt like random and unpredictable so that I felt it is difficult to follow breathing with sequential pattern." P20 mentioned that scuba divers often use hand gestures to teach beginners the breathing phases (inhalation and exhalation) underwater. For example, they use the hand gesture going downward to instruct inhalation. This is why he interpreted the sequential pattern’s downward flow as inhalation. P15 mentioned that she felt the sequential pattern was so tickling that it would disturb her task performance. She reported that she got disturbed during the activity due to a family member’s text message, but the tactile intervention made her more aware of her breathing rhythm and therefore she tried to slow it down. P10 said that he felt the most comfortable and relaxed during the driving activity. This state was helpful to make him feel the tactile intervention clearly. P23 reported that when he increased the car speed, the tactile feedback perceived as delivered by the seat belt felt like someone was holding him back.

Users feedback-based findings and recommendations:

- Findings:
  - It feels easy to engage and synchronize the breathing pattern with the device modulation for the synchronized feedback due to its high predictability and comfort feeling.
  - The sequential pattern was more noticeable and felt active.
  - Subjective workload was lower when the participants were having the haptic feedback.
- Recommendations: Synchronized pattern has more potential to help pace the user's breathing, while the sequential one can be helpful as a breathing nudge.

5.4 Toward a Breathing Pacer

This study zoomed into the raw data from breathing and the tactile pressure rhythm to examine if the two waveforms synchronize, or if there is no synchronizing, then maybe the device is simply nudging a type of haptic breathing awareness. With the ability to personalize the pattern and the rhythm of the haptic intervention of the device, our device might have the potential of a breathing pacer that guides users' breathing rhythm to be in synchrony with the haptic rhythm. We decided to start investigating the settings that would help make the device a pacer. Lehrer et al. [44] reported that respiratory-linked variations in heart rate usually occur in 9 - 24 bpm, and slow breathing within the range of 3 - 9 bpm leads to a high amplitude oscillation of heart rate based on respiratory sinus arrhythmia (RSA). Based on this, we conducted a brief test study with one participant (Female, age = 32 years old) in an office environment to test the efficacy of the device when setting a lower goal breathing rate (7 breaths per minute (bpm)). We asked the participant to wear a cross-body bag clipped with the device, sit in front of a computer in her office and work on daily work tasks (e.g., answer emails, update calendar, write code). Due to COVID-19 regulations, she wore a face mask during the experiment.

The first test consisted of setting up the device modulation frequency to a Goal Breathing Rate GBR=7 bpm while the second was at the participant's GBR determined after 2 minutes of rest period (GBR= 10 bpm) using the same approach detailed in Section 5.2.1. The participant experienced both Sync and Seq patterns for 5 minutes. For the 7 bpm condition, the participant experienced a Sync pattern first followed by a Seq pattern. The order was reversed for the 10 bpm condition. We asked the participant to rest for two minutes between the two conditions. We captured the participant's breathing waveform and breathing rate over time using the same respiration sensor we used for the study described in Section 5.3. The sampling frequency is 18 Hz for the breathing waveform data and 1 Hz for the breathing rate. Fig. 19 and 20 show the captured signals for both conditions: Sync and Seq.

5.4.1 Results. As shown in Fig. 19 (a.1 and 2), the participant's breathing waveform started to be synchronized with the device's Sync haptic pattern and maintained the regular rhythm of 7 bpm for 1 min 24 sec., which also caused to lower the breathing rate close to 7 bpm (Fig. 21 (a.2.)). However, when the device provided the Seq pattern (Fig. 21 (b)), the only synchronization observed between the two waveforms was for a much shorter period of time (24 seconds).

Fig. 20 shows the result when the device was providing 10 bpm-modulated haptic intervention. While it was difficult to find the waveform match during the Sync pattern, there was a short period of time (20 sec) that corresponds to a synchronization between the participant's breathing pattern and the device's haptic feedback pattern when the device was providing Seq pattern intervention (Fig. 20 (b.2) from 50:12 to 50:30). Although 10 bpm is close to the participant's normal breathing rate, interestingly, her breathing waveform made an in-phase pattern with the device's haptic intervention when it was providing the Sync pattern.

Although it is known that breathing at approximately 6 bpm works best for increasing RSA [44], a study by Vaschillo [77] highlights the need for a biofeedback technology to provide an optimal feedback breathing rate "since everyone has different exact cardiac resonant frequency which can change over time within individuals".

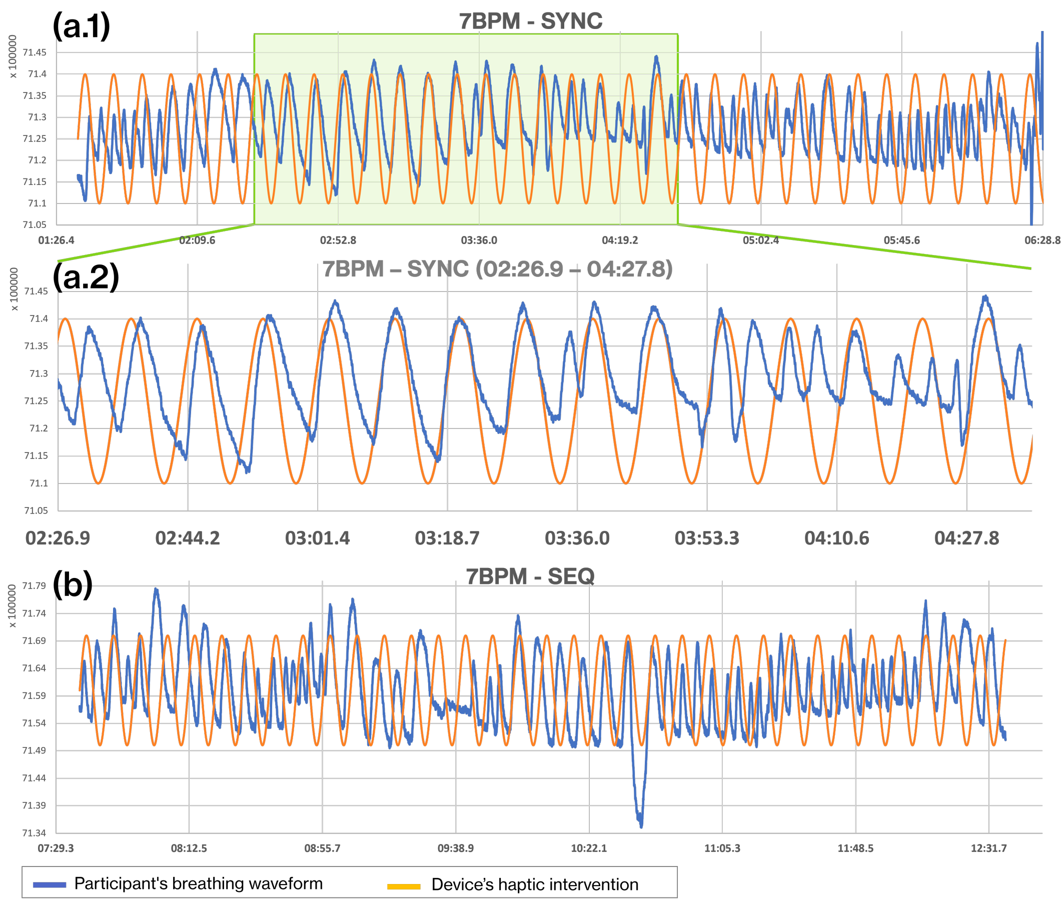


Fig. 19. Example data from one participant with the device running at 7 bpm (a.1) Breathing waveform raw data with device's Sync haptic intervention pattern, (a.2) Zoomed in section of the graph (a.1) in the time period of 02:26.9 - 04.27.8, (b) Breathing waveform raw data with device's Seq haptic intervention pattern

Hence, setting a different **GBR** within the range of 3 - 9 bpm (for high amplitude heart rate oscillations) or 9 - 24 bpm (for high frequency heart rate oscillations) would work and that may differ from person to person. Also, findings from our study underscore that users have different preferences of haptic pattern, and different patterns can have varied efficacy.

Although this test was conducted only with one participant, we think that these data show the potential of the device as a breathing modulator while the user is mainly engaging in a daily cognitive task. Future work, with a different study design with a large sample size while measuring heart rate variability and raw breathing waveform, may help to validate the practical ability of the device to serve as a breathing pacer.

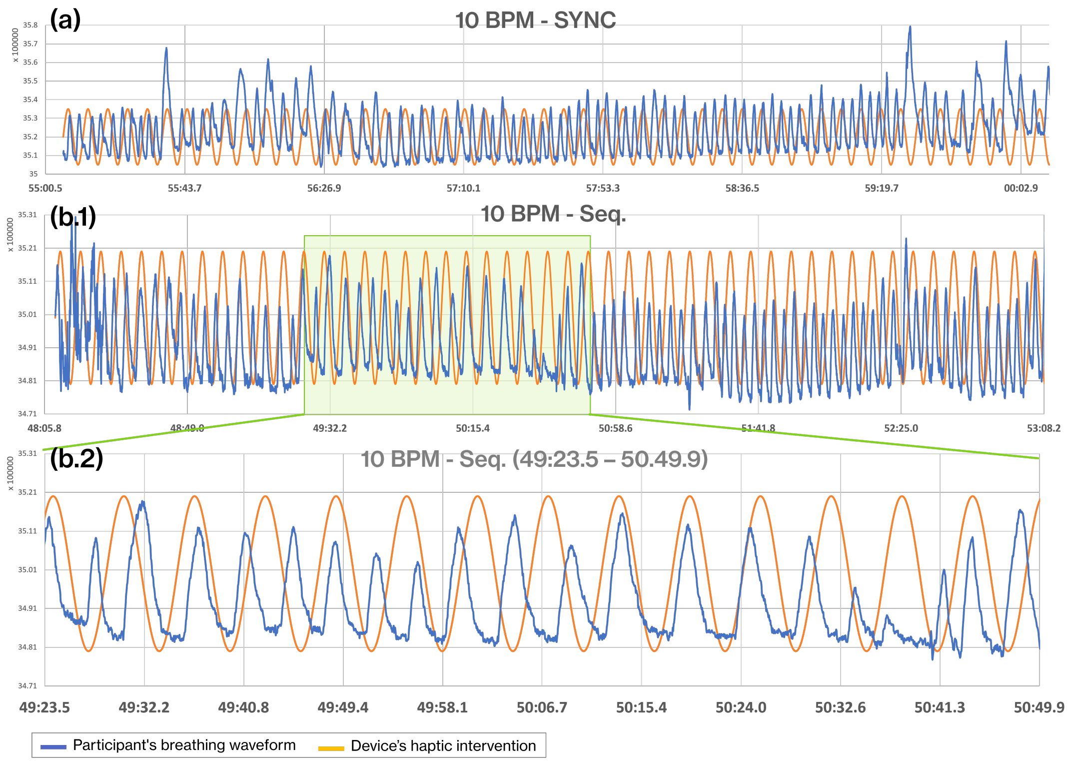


Fig. 20. Example data from one participant with the device running at 10 bpm, (a) Breathing waveform raw data with device's Sync haptic intervention pattern, (b.1) Breathing waveform raw data with device's Seq. haptic intervention pattern, (b.2) Zoomed in section of the graph (b.1) in the time period of 49:23.5 - 50.49.9

6 DISCUSSION AND FUTURE WORK

The study results show that the tactile intervention was subtle enough to not interfere with the participants' ongoing foreground tasks. It helped to significantly increase their breathing awareness without inducing extra perceived stress, anxiety, or arousal.

During the driving task, the mental workload and frustration ratings reported by the intervention group were significantly lower than for the control group. This might be due to multiple factors: The device may have actually reduced workload and frustration; the control group may have felt distracted by expecting to feel the tactile feedback that was never delivered during the experiment (three of the twenty mentioned that they were not feeling it at all and were trying to feel it), or there may be some other explanation outside of our controlled and measured effects.

During the walking task, the perceived energy and disturbance levels reported by the intervention group were higher than in the control group. Finally, in the office environment, the participants who experienced the tactile feedback reported significantly more comfort compared to the control group.

In terms of the comparison of the feedback efficacy between the synchronized and sequential tactile pattern among the intervention group, the sequential pattern was associated with higher perceived pleasantness, comfort, and disturbance than the synchronized pattern during the driving task. For the walking task, the sequential

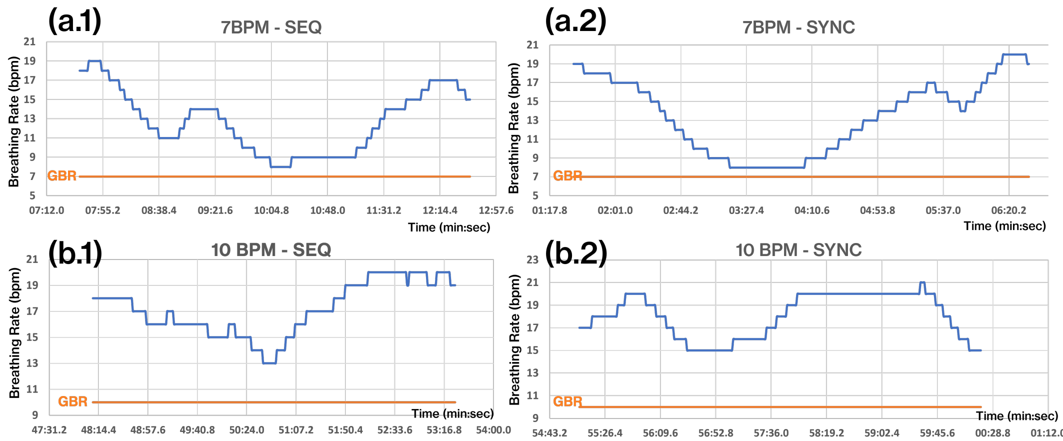


Fig. 21. Breathing rate (BPM) variation of the participant for 5 min at 7 bpm (a.1) with Seq pattern and (a.2) Sync pattern intervention. BPM variation for 5 min at 10 bpm (b.1) with Seq pattern and (b.2) Sync pattern intervention.

pattern was associated with higher perceived energy level and lower stress level compared to the synchronized pattern. In the office environment, the group of the participants who selected the synchronized pattern reported lower required effort than the group who selected to use the sequential pattern during the study. In addition, the sequential pattern was associated with higher perceived pleasantness, energy and comfort, and with lower stress levels than the synchronized pattern. We discuss in the rest of this section these results together with limitations of our work, and we highlight the potential usage of our device.

6.1 The Role of Personalization Ability

Design insights suggested by Balters et al. [3] highlighted the potential of personalizing tactile patterns and their intensity for better user engagement. Also, Miri et al. [50] and Parades et al. [58] showed that allowing the users to choose their preferred feedback method or personalize it had a significant effect on their engagement with the feedback. Following these findings, we implemented the option of tactile feedback personalization by adjusting the intensity, frequency, and activation of the individual actuators. During the try-out session of our user study, despite the same instructions given to the participants to choose their preferred tactile pattern based on the intuitiveness and level of disturbance, we found that each individual preferred a different pattern based on different reasons (Fig. 17). Some participants preferred stronger tactile intensity regardless of predicted disturbance level, while others preferred subtlety. Their standards to define their own clear and obvious feeling were sometimes very different, even when giving the same answer to explain the reason behind selecting their different patterns. Some participants chose their pattern just based on the induced feeling such as tickling or a wavy comfortable feeling for the sequential pattern for example. The individual's standards for defining the 'intuitiveness' of the breathing guide referred mainly to their previous experience with different breathing practices, work-out or sports practice, and their natural way of breathing. Several participants mentioned they liked both tactile patterns but would choose each one for different activities and purposes. Based on these participants' feedback and reasoning behind their choice, we found that providing the ability to easily personalize the tactile patterns would play a significant role, especially when the device is to be used in multiple contexts.

The ’subtle’ tactile intervention represents an intervention that does not interrupt an ongoing foreground task [7] and thus is less likely to reduce task performance. Zepf et al. [81] showed that using a conscious auditory-based breathing guide was more effective in lowering the BR compared to using a less-conscious one. However, it was associated with deteriorated driving performance measured by a higher number of crashes and infractions in a simulator. We believe that there may be a trade off between the level of subtlety of the intervention, its effect on BR regulation, and the participants’ task performance. We believe that there may be a trade off between the level of subtlety of the intervention, its effect on BR regulation, and the participants’ task performance. We saw our participants rarely lowered their BR to the GBR; instead, they focused on task performance. Also, individual standards for defining the level of subtlety and perceived intensity are different even when the same objective intensity input is delivered. In addition, when physical and dynamic activities are involved, each individual’s intensity threshold to perceive a certain tactile intervention may also keep varying. In this aspect, we think that personalizing the intervention intensity is important for improving the engagement as well as the safety of its use during tasks.

6.2 Design of the Pneumatic-haptic Feedback Device

Designing a haptic interface that contacts the body requires us to consider a lot of different design parameters. We can think of changing and improving the interaction with the pneumatic-haptic feedback device by varying the design parameters of interaction time, numbers of soft actuator modules, size of the actuator module, and the arrangement of the modules. We discuss how these design parameters affect interaction with the pneumatic-haptic feedback device and suggest future directions for continued investigation.

A few participants of the study mentioned that they would be interested in using the device with more actuator modules to cover a larger body area. For driving, clipping the device with more than three soft actuator modules on the entire seat belt would be visually more natural, and acceptable [80] than having it on a cross-bag or a waist belt, which can be awkward socially, adding "social weight" [74].

Also, having more soft actuator modules will allow users to create a greater variety of haptic feedback patterns. However, we expect there might be a limited number of tactile stimulation patterns that users can distinguish. Users might settle on specific patterns as they interact longer and more frequently with the device and get familiar with it. It might be interesting to investigate when the user starts to select a certain number of patterns as their favorite ones, how many of them, and then try to find a relationship between different patterns and daily occasions/contexts when the user wants to use the patterns.

Some of the study participants also mentioned that they would like to experience the device with a larger soft actuator module size to feel the stimulation from each individual module (in the case of Seq.) through a bigger area of their body. Finding 1) an optimal size with its weight distribution for pneumatic-haptic feedback device’s actuator, 2) targeted for a different body location which has a different tactile sensitivity, 3) while maintaining high social acceptability [80] remains as future work.

The last design parameter we considered is the arrangement of the soft actuator modules. Although we only explored one configuration that arrays the three soft actuator modules in a line, varying the module array arrangement to form various shapes would be worth exploring. Considering the comments from the study participants who mentioned that they would like to use the device when they sleep or guide their baby to sleep, one interesting design to consider is having the modules arranged in a 2D array. This way, the device can cover a bed mattress or be arranged to be like a plush toy, making it huggable for kids. We plan to investigate the efficiency of various tactile patterns and the actuator arrangement on users’ bodies in terms of engagement and acceptance.

6.3 Closed-loop BR Feedback

The current system of our device requires the manual **GBR** input. We are interested in integrating the BR sensor to our device to provide real-time closed-loop biofeedback. It would be beneficial to have a feedback system adaptive to the individual's different breathing patterns. Since the breathing is coupled with the body muscles [68], integrating an ability to detect the muscle motions and guide the corresponding breathing rhythm especially for aiding athletic training, would be worth exploration. People may ask why we need tangible biofeedback [44] if we can simply tell a person to breath 6 times per minute; indeed, for some people they can remember just to breathe at different rates. However, many times people get busy thinking about other things, and a biofeedback system that gently nudges them toward their desired BR may be beneficial. Also, it may assist a person who wishes to develop a new practice or habit, and after the new behavior is established, the system is no longer needed. In such a case, a haptic device that serves only to comfortably nudge as a cue to help users learn to slow down their breathing may support improved breathing awareness and provide benefit.

6.4 Limitations of the User Study Design

6.4.1 Improving the Engagement. Although there was a tendency to lower the BR when the device was in use compared to when it was not operating, there was no statistically significant group-level difference. To improve the engagement with the device for helping to lower BR during different daily life tasks, we discuss the following parameters: (1) Duration of the interaction with the intervention, (2) the goal breathing rate **GBR**, and (3) the device placement.

(1) During the user study, we tested different daily life tasks for 5 minutes. It is possible that the efficacy of the tactile feedback, in terms of regulating the breathing rate, might increase or decrease as the interaction time increases. It might also reach a certain level after a specific time and then plateau as users get more familiar with interacting with the device. These trends could be observed for the perceived experience in terms of disturbance, notice, and comfort of the tactile intervention. Considering the participants' recommended device usage hours (2.14 hours per day on average), we recommend conducting a longitudinal study allowing users to use the device over the whole day or week. This could help determine the optimal device exposure and interaction time in daily life settings.

(2) Prior studies personalized the **GBR** to be in the range between 70% and 80% of the users' mean breathing rate (MBR) for lowering the breathing rate [3, 13, 30, 45, 58]. Leslie et al. [45] showed that the personalized intervention rate fixed at 75% of the individual's baseline BR showed a significant efficiency when compared to the non-personalized intervention that considered the individual's real-time BR variance. Based on findings from prior work, we personalized the **GBR** as 70% of the participants' **MBR** acquired from the calibration session. However, we noticed that the 70% of the participants' **MBR** collected at a resting-state might be already too low to be considered as a targeted breathing rate during the performance of physical activity like walking and a cognitive task such as working at the office. Because the outdoor walking task was performed in a cold weather with an average temperature of 1.7°C and all the participants were wearing a mask (due to the COVID-19 mask mandate), providing a tactile intervention with a **GBR** set to 70% of **MBR** might not be able to make a significant impact to the participants on the move. Also, our study required participants to walk between the parking lot, office, and park to perform different activities and to answer the surveys between those tasks so that their BR tended to be higher than the resting state during all activities. We expect that measuring the baseline before each task in the same environment of the performed task (e.g. measuring the resting breathing rate while in the driver's seat or outdoors while standing) and personalizing the intervention frequency for each task would improve the participant's engagement with the device. *BrightBeat* [30] took into account that the BR tends to be faster during a cognitive task so that they set **GBR** as 120 - 140 % of **MBR** measured from the participants' resting state. Also, *Affective Sleeve* provided its stimulation rate as 100 - 125 % of the participants' baseline. However,

PIV [50] personalized the intervention frequency to be lower than the baseline to fall within the range of 5 to 9 breaths per minute (BPM), although they required the participants to solve compound remote associate questions. Hence, it might still be ongoing work to find out which **GBR** would work best for which circumstance. Future work would be investigating the most effective **GBR** in a different situation. Also based on our study result, instead of providing the pre-personalized **GBR**, letting the study participants choose their own preferred frequency would increase their engagement with the device in terms of maintaining the lower breathing rate. Lastly, finding out which **GBR** setup with which tactile pattern would work best for which activity remains as future work.
(3) The results showed that the participants engaged most with the tactile intervention in terms of lowering the perceived mental demand and frustration during the driving task while maintaining high breathing awareness. We assume that the way of wearing the device might contribute to this result. The idea of integrating the feedback into the seatbelt is what led to our decision to use the same form factor with the chest strap and fanny-pack during the walking and office activities, to keep the feedback relatively comparable across the three tasks. At the same time, we recognize that while this is very natural when driving, it is unusual to wear a bag and belt like this during an office hour or an outdoor walk. This aspect of the study could be improved by designing a user study allowing the participants to wear a waist-belt clipped with the device as demonstrated in the Fig. 22 and by clipping the device on the lap part of the seat-belt, or by relaxing the requirement that it be the same form across tasks, and allowing the form factor that is most comfortable to each task to be chosen by the users (e.g., chest strap, vs. backpack strap, vs. desk-chair-back-pad, vs waist-belt, etc.)

Also, the post-survey result regarding the question about the preferred potential body location of the device showed varied options (Fig. 9 (d)). We assume that the interactions with the device might vary depending on the applied location. Since there are various breathing techniques using different part of body muscles; clavicular, thoracic, and diaphragmatic breath [6, 21], getting tactile feedback via chest versus abdominal areas might cause different effects due to different tactile sensitivity of different parts of the body [29, 80], and the users' different innate breathing techniques. Also, applied pressure may feel more or less acceptable applied against firm, fit muscles than against an area where a person has excess fat and might feel self-conscious when pressure is applied. Investigating the relationship between the device location on the body and user's perceptions and differential effects on regulating the BR, remain as future work.

6.4.2 Control and Intervention Group Assignment. Although we explained that the device would/would not provide the tactile intervention during the study, and it is subtle, so that it is totally normal even if the participant feels nothing, three participants from the control group (N = 20) verbally reported that they were confused because they never felt the tactile intervention throughout the all activities. However, other three participants of the control group even reported that they noticed the tactile intervention during office task, and one participant did during walking. This confusion might affect their mental demand level perceived toward each activity. Making the post-survey include a extra question asking whether the participants of the control group felt confusion due to they were not able to feel any tactile intervention during the whole study, and taking account of the number of them and their confusion level for data analysis might improve the study design and the analysis result.

6.5 Potential Applications

6.5.1 Breathing Guidance during Athletic Activities and Meditation. During weightlifting, coordinating limb motions with the proper breathing phase helps trainees to engage their core muscles [68], reduces risk of injury [54], and improves performance [6, 8, 69]. However, respiratory adjustments require considerable attention from training coaches [6], and can be confusing for beginners to follow correctly while coordinating their body motions. As depicted in Fig. 22(a), we think that our device could potentially assist weightlifters with tactile breath guidance.

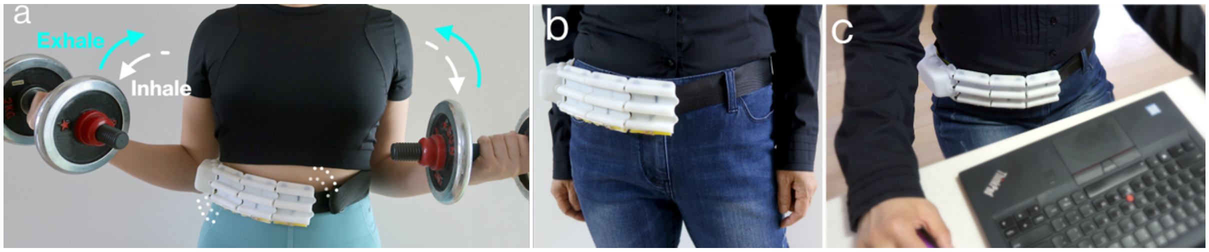


Fig. 22. Application scenarios when the pneumatic-haptic device around waist area (a) for breathing rate and phasing (when to exhale/inhale for how long) guidance during weightlifting, in this case, bicep curl. (b) the device on a waist-belt (c) for stress relief during a office work.

In Yoga, it is a key practice to coordinate the breathing phase with a posture transition [10, 72]. Getting tactile feedback from the device may be helpful for yoga beginners who are struggling to multitask: observing how the instructor poses, moving their limbs accordingly, and listening to the instructors' voice guidance of breathing and posing. Augmenting this auditory channel with tactile feedback, guiding only the breathing phase and rate, may reduce information overload.

In walking practices, studies have shown that short walks (even for 15 min) can be therapeutic for mitigating excessive stress and stress-related diseases [18, 22, 26]. Also, as previous works [12, 14, 46, 73] showed beneficial effects of different methods of breathing guidance during walking meditation sessions, we think that our device might achieve a similar effect if we suggest users to use it during a walking meditation and pay full attention to follow the guidance unlike what we did for this study (where we gave freedom to ignore the tactile intervention and asked them to prioritize the main task which was walking). As demonstrated in Fig. 22.(d),(e), the clippability of our device allows users to turn their accessories like a backpack and cross-bag into a tactile feedback interface. Future tests may explore how effectively the introduced device supports a walking meditation practice by engaging in breathing exercises whenever users are walking on the street or commuting, and observe the users' behavior on clipping or placing the device on different bags, clothes and locations of their body.

6.6 Awakening

Given a pneumatic-haptic device's demonstrated potential to support reaching a lower **GBR** in a focused-on-breathing study [13], we think that setting a higher **GBR** might also be effective. A few participants reported that the sequential pattern felt somewhat alarming or like giving a ambient notification, and others recommended the device's usage in increasing focus or treating people who have a lack of concentration. The work by Russo et al. [66] presented benefits of increasing the BR as alerting and increasing focus. Thus, future work should evaluate the potential of device's programmability, using different settings, to help users achieve different types of desired benefits.

6.7 Ambient Haptic Stimulation for Relaxing and Increasing Productivity

The important role of social touch in relieving anxiety, pain, stress, and improving mood is well-known [23, 27, 31]. The health benefit of hugging also comes from this power of touch [15]. A study [13] showed that their pneumatic-haptic device deployed in a seat-belt provided passengers with a sensation like hugging someone. Nakanishi et al. showed the effectiveness of the mediated hugging by a human-like cushion device in reducing negative thoughts and stress. We think that our device could provide a similar effect to users not only by increasing breathing awareness but also by providing a calming and relaxing tactile feeling. Also the post-survey result asking about other activities and purposes (Fig. 18 (e, f)), showed that many participants recommended the device usage for guiding/inducing sleep and calming. Related work has used the sound of modulated ocean waves [14, 30] for regulating breathing or guiding meditation. Also, when people want to focus on their primary tasks, often they tend to play an ambient sound as background music to increase their focus and productivity [67] while maintaining calmness. Especially when the task requires monotonous work, adding a variety of stimuli to the brain may improve productivity [41]. In a similar manner, we think that repetitive-periodic and subtle modulations of tactile stimulation might induce the tactile equivalent of the well-known auditory benefits. With our device's novel programmable tactile patterns, it is now possible to investigate these and many other opportunities for reducing monotonous work and increasing focus, productivity and human wellbeing.

7 CONCLUSION

We presented (1) a mobile device that delivers a personalizable pneumatic-haptic feedback designed to guide slow and mindful breathing via different tactile patterns and (2) its hardware implementation process with a novel, cost-effective stretchable sensor fabrication method. We conducted a technical evaluation to validate the hardware system. Then, a user-based evaluation was conducted to collect feedback to help make the device an efficient breathing guide. The user-based evaluation focused on four aspects; (1) Selection of the most promising sequential feedback pattern (Seq.). (2) Recommendations for the haptic feedback intensity and frequency. (3) Comparison of two distinct tactile patterns (Sync. vs. Seq) in daily activities. and (4) A preliminary examination of the device's ability to potentially serve as a breathing pacer. All of these evaluations included self-reports and objective physiological data. The recommendations suggested based on the users' feedback concern the tactile feedback intensity, pattern, and the frequency of the feedback modulation.

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A APPENDIX

User Study Survey Forms: https://github.com/mallcong/IMWUT21. These also can be found from the supplemental material in ACM digital library.