Soft Robotic Compression Garment to Assist Novice Meditators

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Figure 1: Men's haptic/robotic compression garment prototype.

Figure 2: Women's haptic/robotic compression garment prototype.

Author Keywords
Wearable technology; Haptics; Compression feedback; Warm stimuli; Meditation; Attention; Mindfulness; Shape memory alloys; Soft robotics

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Abstract
Long-term mindfulness meditation is known to improve one's health. However, many novice meditators find long-term adoption of the practice challenging due to difficulties in maintaining focused attention (FA). With the positive effects provided by the sense of touch (warmth, compression), this work seeks to investigate if haptic-based wearable technologies can help promote FA in novice meditators and improve the meditation experience. A user study on novice practitioners (n=10, 4M/6F) showed potential in using compression/warmth stimuli to positively augment meditation and we discuss implications for future haptic meditation practices.

CSS Concepts
• **Human-centered computing~ Human computer interaction (HCI)**; *Haptic devices*; User studies

Introduction and Related Work
Meditation and meditation-inspired practices have accumulated considerable evidence linking their practice to physical/mental health benefits, including reduced blood pressure, heart rate, and stress [1][2]. Mindful breathing—slow, mindful breaths while focusing on accompanying sensations—is associated with lower sympathetic nervous system activity [3], improved physiological states, and the treatment of anxiety/pain disorders [3][4]. Many meditation practices, however, involve the training of focused attention (FA)—maintain attention on a single target—which can be a challenge

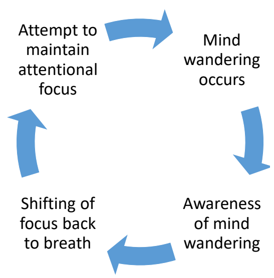

Figure 3: A typical mindful awareness practice session—Mind wandering is a typical occurrence and happens in a cyclical, iterative process.

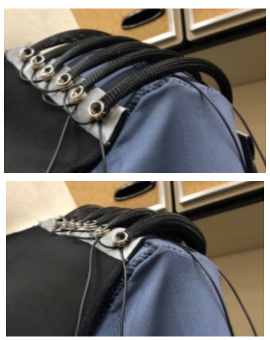
Figure 4: SMA actuators within a braided sheath. Unpowered/ relaxed (top) vs. powered/ compressed (bottom).

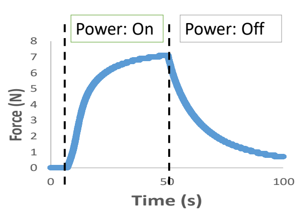

Figure 5: Force output by a single actuator.

for novices or individuals struggling with low-demand activities [6][7]. Mind-wandering in meditation is when attention is drawn away from desired target of focus by unrelated thoughts [6]. A typical mindfulness session entails focusing on an object (e.g., breath) and bringing attention back when the mind wanders Fig. 3) [8]. Mind-wandering is a common human experience, and via its neural correlates in the default mode network (DMN), is associated with a variety of negative mental outcomes, including lower happiness levels [8]. Long-term practice is required to alter DMN connectivity [9]. FA is a known difficulty and may be a barrier to long-term adoption of the practice. Hence, this study aims to investigate if wearables can help promote FA in novice meditators and facilitate better meditation experience.

Given the potential benefits of mindful awareness and the challenges for novices, there are many supportive technologies (e.g., meditation apps with audio output) for guided meditation [10,11]. However, such apps only take advantage of 1 sensory channel and few have tried involving other sensory systems. Here, we take inspiration from Vidyarthi & Riecke's Sonic Cradle to look beyond mobile technologies and consider the role the body plays in meditation [12]. The body is typically the object of attention (e.g., breath related sensations) during meditation, thus is a potentially impactful target for generating positive experiences or addressing attentional challenges. It is known that touch is a very rich communication channel [13], and a natural and common behavior [14]. Various interventions have been designed to improve user wellbeing, e.g., lowering anxiety or modulating affect through haptics. Costa et al.'s EmotionCheck wrist system used vibrations to regulate a user's anxiety by displaying false feedback of slower paced heart rates [15]. Papdopoulou's Affective Sleeve builds upon that, with warmth and pressure on the forearm to better reflect flow-inducing rhythmic sensations closer to human touch [16].

Building upon past work, we shift the focus away from the wrist/arm, towards other areas better reflecting human behaviors (e.g., hug, shoulder massage). Compression and warmth have been shown to provide calming effects, serving as some emotional 'grounding', reducing the impact of negative thoughts/emotions [17–21]. With that, we designed a haptic garment that applies compression and warmth on the shoulders rhythmically. Supported by the work of Levinson et al. [6] who found that low-demand tasks like meditation may lead to mind-wandering, we also aim to ground attention. We hypothesize that the cyclic haptic stimuli, while increasing bodily sensations, may attract more attentional resources to the target—the body—and leave fewer resources available for mind wandering. With this, we investigated if the use of wearable haptics can aid novices with FA during mindful meditation.

Haptic Garment Design

The prototype compression garments (Fig. 1-2) utilized NiTi shape memory alloys (SMAs) to create dynamic compression [22-23]. The SMAs were coiled into spring like configuration (Ø ~ 1.2 mm), providing large active displacements [24]. The SMAs apply compression through coil contraction when heat (or current) is applied and the forces they provide scale with applied current, affording system controllability [25]. SMAs provide both compression and warmth stimuli, induced by single material actuation. The SMAs were housed within braided sheaths (Techflex ¼") for electrical isolation and to support cyclic resetting of SMAs (Fig. 4). SMAs have a one-way shape memory effect; they

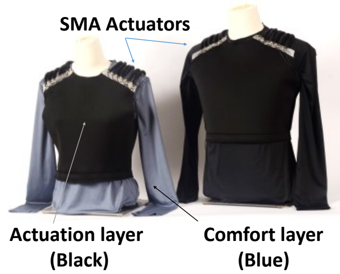

Figure 6: Women's (left) and Men's (right) garments.

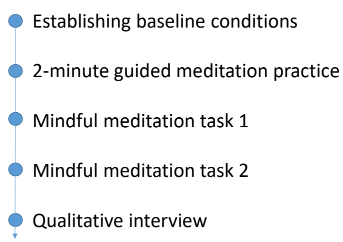

Figure 7: User study procedure.

Figure 8: Positioning of breath rate sensors (on the diaphragm and the abdomen).

can only constrict when powered and must be manually reset prior to subsequent actuation, which does not support our need for rhythmic action. Using braids as a coaxial sheath forms an antagonistic system, allowing SMAs to utilize elastic energy stored in braids as they are compressed during activation to re-expand when unpowered, attaining compression-relaxation behavior. 6 actuators (16.5cm) were attached on each shoulder vertically using snap connectors, ½" apart. Each SMA received ~0.6A of current, each providing a linear force up to 7.1N based on mechanical tests (Fig. 5). The actuators were programmed to actuate for 5 seconds and unpowered to relax for 12 seconds. The garment was remotely controlled (Bluetooth, MOSFET-driven), using Processing UI to control stimuli presentation.

The garments were designed for both male and female, size medium, and consisted of 2 layers (Fig. 6): (1) an outer actuation layer with 2-way stretch Neoprene knit fabric (non-stretch oriented in the lengthwise direction to which the SMAs connect), with Velcro© closure for adjustability and an elasticized silicone-lined hem for garment anchoring. (2) an under comfort layer (athletic crew neck long-sleeved knit shirt 90% polyester, 10% spandex) with an insulating Neoprene shoulder pad for heat generated by SMAs. The SMA-integrated shoulder area surface directly interfaced with the skin was 34^{o}C after 8 mins of actuation. A textile force sensitive resistor [32] was integrated into the top of shoulders to observe force changes with compression, showing users were exposed to pressures around 26-34mmHg. Two breath rate bands (above diaphragm and on waist) were worn in-between comfort and actuation layers.

User Study

The within-subjects study (n=10, 4M/6F, age 19-26, mean=21) included only novices (<3-month experience). The study consisted of 5 phases (Fig. 7). Subjects were first fitted with a biometric-collection wrist device and completed baseline surveys. Then they were guided through a 2-minute practice of Samatha meditation, a cognitively directed method in which the participant's eyes are closed and attention is concentrated on the breath [33], common in Western proliferation of meditation. During practice, subjects were also instructed on the way of tracking attention—pressing a button on the wrist device when the mind wanders. The 2 meditation tasks lasted 8 minutes each; the control (without garment) and intervention (with garment) was randomized; all 10 subjects experienced both with and without garment conditions. This study was designed with guidance from 2 meditation experts with over 10 years of teaching experience. The study was conducted in a 10 by 10 ft. closed room (central ventilation, well-lit, isolated from most external noise) and subjects were seated during the tasks. Subjects completed questionnaire after each meditation task and qualitative interview at the end.

Objective Measures

Biometric data was collected using an Empatica (E4); using only electrodermal activity (EDA) and heart rate (HR). For each participant, HR data was averaged across each meditation period. EDA was normalized (0 to 1; min-max) to eliminate individual differences. Using Ledalabs continuous decomposition analysis, Skin Conductance Responses (SCR) were calculated for each meditation period (threshold= 0.05μS). E4 was also used to track mind wandering; subjects pressed the event button to acknowledge mind wandering before returning to their breath. The button was to replicate common practice in mindfulness practice where

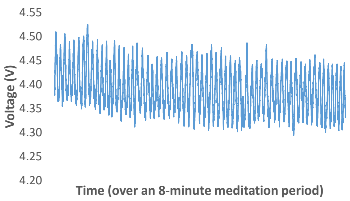

Figure 9: A representative graph (P1) collected from BR sensor.

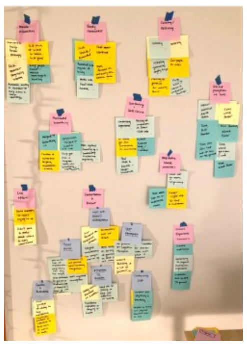

Figure 10: Affinity mapping (only small selection is shown).

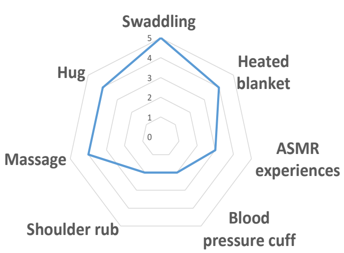

Figure 11: Participant comparing sensations provided by the garment to everyday activities.

practitioners follow a ritual upon loss of attention before returning to their object of focus, e.g., breath, and is also a method used in other research studies as a means of tracking attention [6-7,28]. The number of button presses in each meditation task was calculated. To track breathing rates, a low-profile, soft stretch sensor was used (Fig. 8) [28] to preserve wearer comfort and avoid potential distractions from rigid components. Two sensors at different locations were used (Fig. 8) to capture diverse breathing styles; only data from sensor with larger amplitude changes were used. The sensors were validated against manual thorax rise/fall counts by an observer. There was an average discrepancy of 1.58 ±1.02 breaths over 8-minutes; differences could be from variances in start/stop time between observer and sensor. The peaks recorded were extracted over 8-minutes (Fig. 9) and the number of breaths per minute were computed.

Subjective Measures and Qualitative Interview

The questionnaire consisted of (1) State-Trait Anxiety Inventory (STAI) to measure changes in anxiety [29], (2) Flow State Scale (FSS) [30] measuring enjoyment, concentration, perception of time, and (3) experiences with 9 semantic differential scales (SDS). FSS items are 5-level Likert scale (completely disagree to completely agree) with levels of agreement mapped to 1-5. The 5-level SDS featured differential labels anchored at the extremes. A qualitative interview was also performed and participants were encouraged to share their thoughts. Questions were posed for self-assessment of focused attention, for comparing experiences with and without garment, and for time perceptions. We also probed their insights on the haptics experienced, meditation preference with/without garment, likes/dislikes, and thoughts on the system's purpose/future use. The interview data was sorted using affinity mapping to cluster ideas and extract themes (Fig. 10).

Results and Discussion

Overall Experience

The compression was mostly well-received (n=6); with a perceivable but not overwhelming intensity that was 'almost forgotten when meditating' (n=3). However, many stated that the initial compression was strange/alarming (n=7); they eventually acclimated, after which the comfort was akin to regular clothing (n=3). The rhythmical pulsing was positively received, some comparing the sensation to slow breaths (n=3). While the garment reception was mostly positive, some (n=3) did not care for compressions provided—consistent with past studies where some individuals are averse to on-body haptics [31]. They felt that the haptics were not suited for meditation, for reasons including limited gut expansion for breathing (n=1), unpredictability of the haptics/non-synchrony with their breaths which was agitating (n=2)/claustrophobic (n=1). The garment warmth was very well-liked (n=9). The sensations were compared to actions for physical relaxation (massage, swaddling, weighted/warm blankets) or comfort (hug, being close to a warm fire) (Fig. 11). Many commented that with warmth and compression, their muscles were physically relaxing (n=5) and the garment's pulsing helped them get into a breathing rhythm (n=5).

Since we observed differences in preferences, we presented quantitative measures based on intervention preferences: 'liking' (solid, green) and 'dislike' (shaded, red). All bar graphs were presented as differences of control minus intervention (i.e., positive number means intervention had a lower measure than control, vice versa) and the x-axis were rank ordered from highest

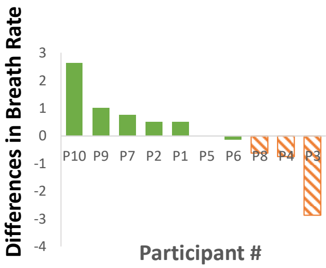

Figure 12: Differences in BR between control and intervention.

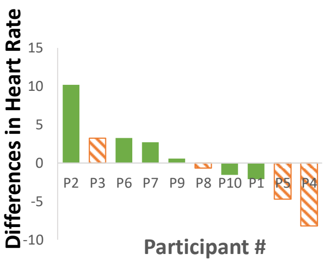

Figure 13: Differences in HR between control and intervention.

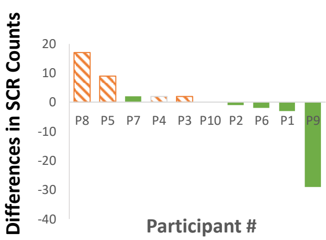

Figure 14: Differences in the number of SCRs between control and intervention.

to lowest score. From Fig. 12, for n=5, the intervention lowered their BR (+ve values), n=4 had an inverse effect, and n=1 had no change. Interestingly, these results aligned well with subjects' preferences; P3, P4, P5 and P8 were in the 'dislike' group and we can see from Fig. 12 that they had equal or higher BR with the garment than without. Fig. 13 presents the differences in HR between control and intervention. Somewhat consistent with preferences, ¾ of those in 'dislike' group (P5, P8, P4) all had higher HR with the garment; with those of the highest HR belonging to P4 and P5 from the 'dislike' group. SCR counts for EDA in Fig. 14, we see a trend where those in the 'dislike' group had lower SCR counts for the intervention than control. This decrease in arousal compared to the control may be a reflection of their subjective reports of annoyance/ distraction towards the stimuli. However, since EDA only detects arousal but not valence, conclusions based on the quantitative measures alone cannot be drawn.

Emotional Effects

From user responses, we found the garment's haptic stimuli led to subjective emotional changes. Many said the garment sensations were calming/relaxing (n=6) or comforting/secure (n=5). From STAI results for 'liking' group, the STAI scores decreased by an average of 4.17 points (pts) for control and 8.83 for intervention compared to baseline. In contrast, for 'dislike' group, STAI scores decreased by 4.50 pts for control and only 2.25 pts for the intervention compared to baseline. The improvement aligns with expectations for meditation; liking the garment enhanced the anxiety-reducing effect, while disliking it partially canceled the effect.

Cognitive Effects

Perhaps more interesting is the garment's cognitive impact. One theme that emerged was concentration and focus. From the attention tracking task (Fig. 16), n=5 had improved attentional focus (+ve values) and n=4 had weaker FA. From interviews, P3, P5, P8 from 'dislike' group felt the garment worsened their attention (stimuli drew attention away from breath, which made the mind wander more (n=3)), consistent with Fig. 16 measures displaying equal/worse performance for intervention compared to control. However, while P4 was from 'disliking' group, when asked about garment distraction, she did not think it was distracting except the first actuation, consistent with her attention results. For the n=7 subjects that thought garment improved their focus, the haptics were said to reduce distractions from external stimuli (n=4), resulting in fewer thoughts (n=3). As reflected in the FSS (Fig. 15), attention was said to improve (Q5, 36) for 'liking' group.

Q. ID	Item	Avg. 'Liking' Group		Avg. 'Disiking' Group	
		Control	Int.	Control	Int.
5	My attention was focused entirely on what I was doing.	**2.8** ± 1.3	**4.0** ± 0.6	**3.8** ± 1.3	**2.3** ± 1.3
8	Time seemed to have sped up.	**2.0** ± 1.1	**2.7** ± 1.4	**2.3** ± 1.3	**3.8** ± 0.5
9	I really enjoyed the experience.	**3.7** ± 0.5	**4.7** ± 0.5	**4.0** ± 0.8	**3.5** ± 1.3
14	It was no effort to keep my mind on task.	**2.0** ± 0.6	**3.2** ± 1.0	**3.0** ± 1.4	**3.0** ± 1.8
27	The experience left me feeling great.	**3.8** ± 0.8	**4.3** ± 0.8	**4.0** ± 0.8	**3.5** ± 1.0
23	I had total concentration.	**2.2** ± 0.8	**3.0** ± 1.1	**3.8** ± 1.3	**2.5** ± 1.7
36	I found the experience extremely rewarding.	**3.3** ± 0.8	**4.0** ± 1.1	**4.0** ± 0.8	**3.3** ± 1.0

Figure 15: Flow State Scale selected items.

The garment was said to act as a focal point (n=4) and require less conscious effort to keep attention on breath (n=3), "like I wasn't trying at all" (n=2). Evidenced by FSS item Q14 (Fig. 15), we see intervention performed better than control in regards to effort required to keep the mind on task for the 'liking' group. One participant (P6), said that he had aborted past meditations because he struggled with negative thought loops. He compared the haptics to sensory grounding techniques used to interrupt panic attacks. Some also commented on enhanced body awareness with the intervention. The haptics were said to draw focus to the body (n=2) and

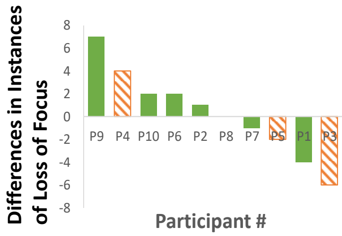

Figure 16: Differences in the number of instances of loss of focus between control and intervention.

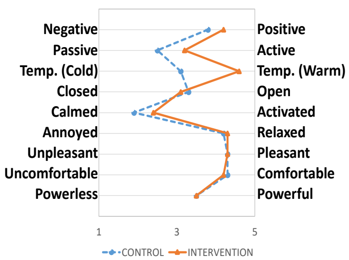

Figure 17: Semantic differential items.

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created more centered/grounded feelings (n=3). P7 commented, "with the garment, it feels like the body is not my enemy and it's actually helping me."

Another theme was the garment's role in altering the perception of time. From FSS (Fig. 15) Q8, time was perceived to pass faster with the garment for both 'liking' and 'dislike' groups. This was also reflected in the interview, where participants commented that with the garment, they weren't worried about time (n=3) and that it passed much faster than without garment (n=4). With fewer thoughts about time, they felt more immersed in a meditative state and could continue longer (n=3). Such reports of more immersive/pleasant experiences may reflect the reduction of DMN activity that is associated with skilled attentional focus [7].

Conclusions and Future Work

The designed haptic garment received generally positive feedback; the warmth and compressions were largely welcomed, though as in previous studies we noted some individual differences in how compression is received. While many report positive opinions of compression as a mode of haptic stimulation, some individuals generally (and fundamentally) dislike the sensation of compression, and generally responded negatively to the study's intervention. Overall, we found evidence that haptic assistance may be worth pursuing for improving the meditation experience and helping individuals with FA, particularly those who report affinity for compression as a form of on-body stimulation. Though the quantitative data was more ambiguous, the majority of participants reported improved sense of focus with the garment. This discrepancy between self-reported perception and captured mind-wandering instances should be examined, but the subjective perception of an improved performance could be sufficient to encourage ongoing meditation practice. Also promising is the fact that feedback on enhanced body awareness/immersiveness appears in line with our initial theory that increasing bodily sensations may draw more attentional resources and reduce mind-wandering. However, the positive effects were only observed for those who liked the haptics. The feedback did not rule out that different haptic stimuli, e.g., different intensities/patterns/ locations, could improve the experience for those users, and should be an emphasis for future studies.

Many also described the haptic garment as a calming/ secure experience, but currently, how that affects mindfulness is unknown. From Fig. 17 SDS, however, we suspect that users are not overly relaxed to dullness since they reported feeling more activated with the garment than control. More work has to be done to understand the garment tradeoffs in allowing users to pursue a balance between the functional (mindfulness) and emotional (relaxation). Further, it would also be important to dissociate how each of the two haptics (compression/warmth) contributed to different aspects of the experience. While some biometrics were shown, it was not intended to drive conclusions in this pilot because physiological benefits can only be seen with long-term practice; longitudinal studies have to be done. Further, this study did not establish a true baseline (baseline was captured during survey completion)—future work aims to remedy that. We believe that there is potential in using haptics to augment mindfulness practices. With further research, we hope that the haptic system will be able to inspire new practitioners through an improved meditation experience and long-term adoption of the practice.

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