Squeezeback: Pneumatic Compression for Notifications

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ABSTRACT
Current mobile devices commonly use vibration feedback to signal incoming notifications. However, vibration feedback exhibits strong attention capture, limiting its use to short periods and prominent notifications. Instead, we investigate the use of *compression feedback* for notifications, which scales from subtle stimuli to strong ones and can provide sustained stimuli over longer periods. Compression feedback utilizes inflatable straps around a user's limbs, a form factor allowing for easy integration into many common wearables. We explore technical aspects of compression feedback and investigate its psychophysical properties with several lab and in situ studies. Furthermore, we show how compression feedback enables *reactive* feedback. Here, deflation patterns are used to reveal further information on a user's query. We also compare compression and vibrotactile feedback and find that they have similar performance.

Author Keywords
Pressure feedback; wearable; compression feedback; mobile haptics; notifications; blood pressure; pneumatics

ACM Classification Keywords
H.5.2 Information Interfaces and Presentation: User Interfaces—*Haptic I/O*

INTRODUCTION
Most haptic feedback today uses vibration. However, vibration feedback captures much of a user's attention and can be disruptive [15]. It is also rather limited in the acceptable stimulus strength. Pressure feedback, on the other hand, can support less attention-demanding [45] or intimate [40] feedback.

In this paper, we investigate *compression feedback* [29] as a form of pressure feedback for notifications. We use inflatable straps to generate uniform pressure around the wrist—a design that translates to other body parts as well. We believe this kind of feedback would integrate well with workout armbands (used, e.g., when running, cycling, or in gyms), smart clothing, or smartwatches/jewelry.

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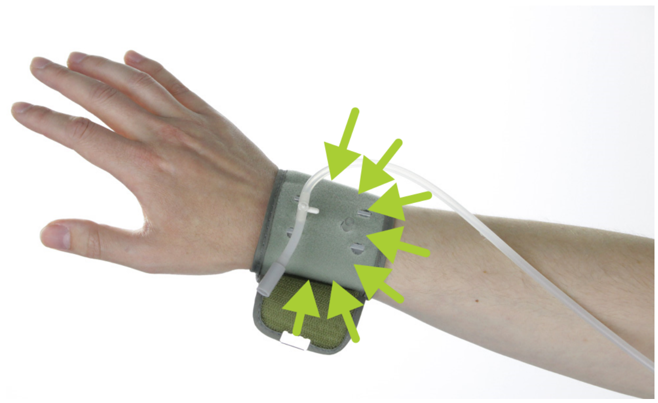


Figure 1. Compression feedback ranges from very subtle to very intense and is well suited for intimate communication and background feedback. We use pneumatic actuation and inflatable straps to create stimuli.

We see a number of advantages of compression feedback:

- It works over a wide range of attention capture—from subtle to inhibiting and forceful. Strong constriction demands instant attention. This range of attention capture also makes it a good feedback channel for *casual interaction* [30].
- It can provide constant background feedback (prolonged vibration would be too disturbing) which can ramp up to slowly bring something to the user's attention (e.g., an approaching appointment). This is similar to wake-up lights—a stimulus level slowly increases and is noticed at some point after the detection threshold is crossed.
- It can feel similar to human attention grabbing behavior—making it potentially useful for intimate communication scenarios. A slight compression on the wrist, e.g., can feel similar to the wrist being grabbed by another person.
- Feedback can be reactive and convey status information in response to users' querying actions. This is done by releasing air in specific deflation patterns, such as in several bursts.
- It allows for distinct inflation and deflation patterns that, e.g., can create calming or hectic sensations. Overall, compression feedback is rated as pleasant.
- Possible attachment positions (arms, legs, waist, fingers, hands) align well with good locations for wearables (i.e., many people already wear items of clothing there). The strap-like nature of the actuators also lends well to direct integration into clothing.

In this paper, we explore compression feedback and investigate how well it works for notifications. We find that at 2.3 kPa (Figure 12 puts this into perspective) users can detect a pressure stimulus (0.7 kPa under lab conditions). Given two stimuli of different pressure levels, users are able to differentiate them with 95% probability when the ratio of the pressure delta over the base pressure is about 2.7. Some reactive feedback patterns can be distinguished with 95 % accuracy and compared to vibrotactile feedback, compression feedback is no more annoying or uncomfortable.

RELATED WORK

Compression feedback systems build upon existing work in pneumatic actuation. There has also been previous work in using pressure as a feedback modality.

Pneumatic Actuation

Pumping air into devices has been used to create dynamic buttons [16], implement virtual buttons [19], create shape changing controllers [18], actuate tangibles [11, 22, 43], provide haptics for increased alertness [9], or give pressure feedback at surgeons' fingertips [6]. We use a similar principle, but inflate straps around user's bodies.

Pressure Feedback

Point pressure actuators (pactors) [2, 44, 45] are a common means for pressure feedback and, compared to vibration feedback, have less attention capture and are less agitating. Instead of point pressure, *ServoSqueeze* tightens a band around the wrist [2]. In contrast to our system, *ServoSqueeze* is rigid and cuts into the arm instead of applying uniform constriction. *HapBand* [4], *HaptiHug* [37], and devices in [32, 33] work similarly. Suhonen et al. used shape memory alloys for the same effect [34]. Balloon actuators around the leg were used for feedback by Fan et al. [10]. This provided discrete point feedback instead of overall compression. He et al. constructed a bracelet with balloon actuators to provide pressure feedback [17]. As their device has discrete chambers, connected by valves, it can also do moving and tapping sensations.

Both Patterson and Katz [27] and Tejeiro et al. [36] use blood pressure cuffs to apply pressure feedback. In both their works, the pressure is used to replace missing tactile feedback when using prosthetics. The focus in their work is on the control aspect and sensory replacement, not on the perception or properties of pressure feedback. Also, only strap placement on the arm is explored, while we look at a larger set of locations.

Pressure via a blood pressure cuff on the forearm was also investigated by Mitsuda [23]. In his work, he investigates how well pressure feedback can be used to communicate forces to the wearer. He finds that putting 6 kPa pressure on the forearm results in a feeling equivalent to a force of ~10 N (as during holding a weight). We study similar aspects of psychophysics, but also explore several other use cases of pressure feedback apart of force displays.

Vaucelle et al. use inflatable straps with embedded *plastic teeth* in *Hurt Me*, to provide sensations *"akin to being bitten"* [38]. In this kind of system, the compression feedback is only used as a means to transport a different, second feedback: the sensation of the teeth pressing down on the skin.

Pneumatic Input

While we use air pressure sensors only to monitor the feedback, such sensors can also be used to detect input. Sudden pressure changes can, e.g., be interpreted as the user touching the wrist strap (or, e.g., resting the arm on a table or armrest). This is used by Vázquez et al. as one possible input channel for their controls with pneumatically actuated resistance to change [39]. By embedding air bubbles in puppets, Slyper and Hodgins could detect presses and bends [31].

COMPRESSION FEEDBACK

In the following, we describe the general characteristics of compression feedback. Compression feedback uses inflatable straps to tighten around body parts (this is illustrated in Figure 2). At low pressure levels the sensation is subtle and only a slight contraction can be felt. With increasing pressure, this grip tightens and users become easily aware of the feedback. At this level, the compression is comfortable and feels neither painful nor does it restrict normal body movement. Pressure can be further increased to levels at which movement is impaired (e.g., because a joint is locked) and discomfort sets in. At such extreme levels, users are effectively forced to react to the feedback.

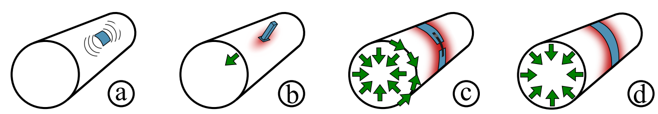


Figure 2. (a) Vibration does not exert a sustained inward force, while (b) pactors [44] provide pressure at a specific location. (c) Tightening bands [2] provide a more uniform squeezing sensation, but also exert shear forces due to the band movement. (d) Inflating straps provide uniform pressure but can do so without the amount of shear force created by tightening bands.

Compression feedback tightens around the body—a sensation comparable to human interactions such as hugging. Hugging interfaces naturally facilitate intimate communication [7, 35, 37]. We believe that this also translates to compression feedback. In fact, previous investigations in using inflatable vests for remote hugging were promising [24].

The difference between pressure and vibration feedback is primarily one of actuation frequency. However, this difference is so strong that they are regarded as distinct modalities [5]. Vibration feedback captures attention more effectively than pressure, but is also seen as less affective [44]. Vibration and compression feedback, however, are highly complementary—compression results in an inward force, while vibration provides tangential forces on the surface.

Traditional high-frequency vibration feedback is mainly detected by Pacinian corpuscles which have highest sensitivity at 250 Hz. This receptor, however, is only one of four types of mechanoreceptors (responding to pressure and vibration) in the human skin [3, 20]. Meissner corpuscles (sensitive to pressure change at 10–50 Hz), or Merkel and Ruffini cells (responding to sustained pressure and stretching) are not stimulated strongly through vibration. Pneumatic compressive feedback is able to stimulate these slow-adapting receptors.

Compared to individual pactors [10, 44], force in compression feedback is less localized and distributed over a wider area. However, with an increasing pactor density, or with larger pactor designs, both methods somewhat converge as the pressure is distributed over a larger area and not as localized. For example, *HapBand* [4] uses three plates to simulate the arm being grabbed by a hand. Similar to our approach, *ServoSqueeze* [2] and *HaptiHug* [37] constrict around an arm/ body, exerting an inward force.

COMPRESSION FEEDBACK SYSTEMS

To evaluate properties of compression feedback, we built several prototypes. At the very least, such a device needs a way to push air into the system, a strap to inflate and a valve to release air from the system.

The first required component are inflatable straps. For the uniform sensation of compression feedback, strap need to wrap around the attachment position and fit comfortably. Such inflatable straps could be manufactured from silicone composites [22, 43] or by heat bonding plastic sheets [25]. We found that the critical part in custom made straps is embedding a connector. As compression feedback can reach higher pressure levels than, e.g., those necessary for actuating origami [25], a sturdier connection is required. We thus chose to repurpose already available straps that come with suitable connectors: blood pressure cuffs.

Blood pressure cuffs commonly consist of an inflatable air bladder enclosed in a band adjustable to different sizes using velcro. Such cuffs have been used before to provide pressure feedback on the arm [23, 27, 36, 38]. However, we experimented with a wider selection of cuffs (see Figure 3) ranging from ones designed for circumferences as short as 3 cm to ones as long as 48 cm. Cuffs are manufactured for patients ranging from newborns to the heavily obese—necessitating such a wide range of sizes.

Figure 3. We used a wide range of blood pressure cuff sizes to test our system on several body locations. The smaller cuffs can be wrapped around single or multiple fingers, the 14-19.5 cm cuff fits around a wrist, while the larger cuffs fit around upper arms and legs.

While blood pressure straps are readily available for use in compression feedback, a complete compression feedback system also needs a controller. It is responsible for inflation and deflation of the strap, as well as monitoring in-strap pressure levels, and thus the force exerted on a user. We have built several different controllers for this purpose (see also Figure 4). They all repurpose miniature pumps and solenoid valves designed for blood pressure monitors, such as the *AEG BMG 5610*. This exemplary wrist-worn medical device is designed for belt pressures of up to 300 mmHg[1] (~40 kPa). At 3 V the pumps (at full power) draws 135 mA, while the valve draws 80 mA while closed. We designed custom PCBs to attach to *Arduino Nano* and *Adafruit Feather* microcontrollers in order to connect them to those pumps and valves. The overall weight of these devices varies, depending, e.g., on the enclosure, but can be as low as 60 g for our smallest board, attached to a pump, valve, and battery.

To measure internal strap pressure, we use *Freescale MPXV5010 series* sensors, which are designed for the 0–10 kPa range. While this is far from the belt's maximum pressure, this lower pressure range is more appropriate for the notification studies we intended to run. Pressure sensors are connected to the attached microcontrollers' ADCs. While we designed the prototype for wireless streaming of sensor data via Bluetooth, we used a USB connection during the lab studies.

We used a PID controller algorithm to adjust pump power for the setups requiring specific pressure levels. Generating a stimulus requires carefully approaching the desired pressure, leveling, and then maintaining pressure over the stimulus' duration. This is challenging due to loss of pressure in the system (e.g., in tubing), and back pressure influencing how the system reacts. For example, loss requires the pump to keep running at a low level to maintain pressure. We also found changes in atmospheric pressure having a noticeable impact on system behavior. Atmospheric pressure varies over the course of a day and can change in the order of several kPa with the weather. We tuned the PID parameters of our system for 13 target pressures and use cubic Hermite interpolation for in-between pressures.

How Air-Pressure Relates to On-Arm Force

While our prototypes measure strap pressure, we are actually interested in the force exerted on a user's arm. Adding a force sensor between the strap and the arm would change the feel of the feedback, though. Hence we confirmed dependency of the two measures in an experiment. For this, we put an *FX1901* compression load cell (50 lbf range) between the strap and a dummy arm and amplified the signal using a *INA125P* instrumentation amplifier. Air pressure is measured with a *Freescale MPXV5050 series* sensor (0–50 kPa range). We then recorded raw force sensor and air pressure values while inflating the strap. As shown in Figure 5, air pressure is indeed a very good predictor of force on the arm. For the remaining studies we hence only recorded air pressure.

[1] Normal blood pressure is in the range of 90–119 mmHg with pressures larger than 180 mmHg being a hypertensive emergency.

Figure 4. We built several compression feedback controller prototypes. They all reuses parts from off-the-shelf blood pressure monitors (shown in leftmost image). We only keep the sensor and valves at the wrist for our first prototype (second image), but move the pump to reduce its influence on the sensation. The second prototype (third image) is designed for mobile evaluation, fits into a pouch, and is controlled from a phone via a Bluetooth module. The third prototype (last image) miniaturizes this setup for even better mobility.

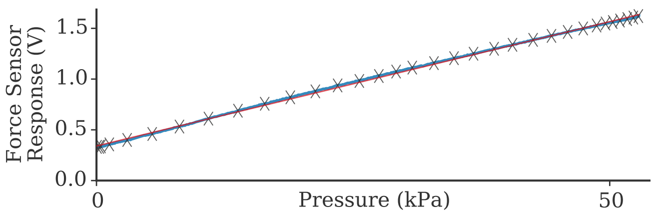


Figure 5. We measured on-arm force (raw sensor response in V) for increasing in-strap pressures (crosses mark every 20th sample). A strong linear relationship ($R^2 > 0.99$) shows that pressure predicts arm force.

PROPERTIES OF COMPRESSION FEEDBACK

So far, we have provided an overview on technical aspects of compression feedback. However, a crucial question for compression feedback is how well it actually works as a feedback mechanism. In this paper we, in particular, focus on the use of compression feedback for notifications. We thus ran a series of studies to determine psychophysical properties of this feedback in the lab and evaluate how it fares in the wild.

Like other kinds of haptic feedback, compression feedback could be used for a wide range of scenarios. For example, virtual reality or pervasive games could also benefit from this kind of haptic feedback. However, here we focus on notifications as a common use case for feedback in mobile computing. Hence, we also designed our prototype around a wrist strap, as the wrist is a common location for wearable devices, such as smartwatches or bracelets. Another relevant location would be the upper arm, which is already a common location for straps worn during workouts which could readily include compression feedback.

Instead of using straps, inflatable pockets can be directly integrated into clothing. Gloves, shirts, pants, shoes, belts, sweatbands, or socks already cover the relevant locations and could incorporate such sewn in pockets. Inflatable vests, e.g., are already available commercially[2] and are used to provide a hug-like sensation. Such vests are, e.g., used to help reduce anxiety in autistic children [8]. Perovich et al. put pneumatic channels in a skirt to enable changing its form interactively [28]. Inflatable garments are also used in physical therapy, however, such garments do not resembles regular clothes.

[2] e.g., from *Squease* (http://www.squeasewear.com/)

Background Feedback

Compression feedback can be applied continuously, making it well-suited for feedback in the background. Instead of springing to the user's attention, the feedback persists and thus moves to the front- or background depending on how much the user concentrates on it. In this characteristic, compression feedback is similar to thermal feedback [42]. This is useful for communicating information not sufficiently urgent to warrant an interruption. For example, compression feedback could be used to represent weather when hiking. As long as the weather only changes slightly, the feedback stays in the background. It becomes noticeable only when payed attention to and does not inhibit the user. When a storm front nears, pressure increases, bringing this to the immediate attention of the user.

We tested the appropriateness of continuous feedback in a small study with 9 participants (all male, age 23–41, $\bar{x} = 30.0$, $\sigma = 6.3$). Participants wore a blood pressure meter around their upper arm, inflated to 10 mmHg (1.3 kPa). This is only a slight inflation which is far from levels where the cuff cuts off blood flow (typical values are 120 mmHg and 80 mmHg for systolic and diastolic pressures, respectively). Participants wore the strap for 1 hour while continuing their daily routine. Afterwards, none of the participants reported feeling inhibited or annoyed by the device. This shows that compression feedback is indeed suitable for prolonged display of state information (in contrast to vibration feedback). However, as participants spend most of the time at their desks, it remains to be investigated whether this holds for more diverse contexts.

Absolute Detection Threshold: In the Lab

When using feedback for notifications, an important question is how strong the feedback needs to be. We hence set out to investigate the pressure threshold where users can first perceive a compression stimulus. By conducting this study in the lab, we can determine the lower range of pressure usable for compression feedback notifications. We used a standard two-down/one-up staircase design [21]. At the start of each trial the pump increased pressure till the stimulus level was reached, which was then held for 5 seconds, after which the outlet valve opened and the strap fully deflated. Starting at a stimulus level of 0.6 kPa (determined as a first estimate for the threshold during pilot studies), we increased pressure by 25% after a stimulus was not felt and decreased by 25% if a stimulus level was perceived twice in a row. The experiment ended after 7 reversals.

In this study we use the stationary prototype. As noise and vibrations from the pump would provide additional cues to participants, we moved the pump away from the strap and connected it via a ~1 m long silicone tube. This makes the device non-mobile, but allows more accurate measurements of in-cuff pressure (the mobile prototypes have the sensor close to the pump, which can affect readings). Participants also wore noise canceling headphones, playing brownian noise. During the study, participants were seated and wore the device on their left wrist (the right hand controlled a mouse), rested their hand on a table and kept that arm stable. With their other hand they controlled a mouse and provided responses via a study interface on a screen in front of them (see Figure 6).

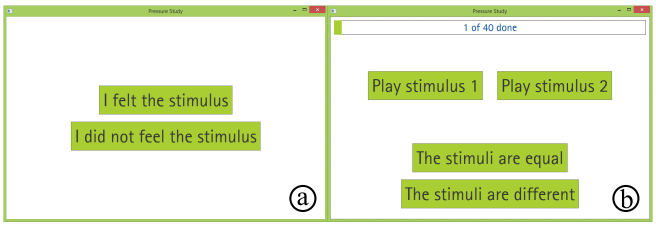


Figure 6. Interfaces used by participants during the (a) absolute detection threshold and (b) just-noticeable differences studies in the lab. During stimulus playback input was blocked.

We recruited 14 participants (2 female, age 23–47, $\bar{x} = 28.6$, $SD = 6.6$) from around our institution. None of the participants had their blood pressure measured recently (one participant had so in the last month), so there was no recent familiarity with the provided sensations. Participants completed the study in ~5 minutes and were compensated with a small non-monetary gratuity.

Results

We computed the absolute detection threshold for each participant from the mean pressure between reversals (i.e., between points where pressure was felt and where it was not). As shown in Figure 7, partipants' thresholds varied between ~0.22 kPa and ~1.59 kPa. The distribution of thresholds (also shown in the Figure) is skewed and has the mean at 0.72 kPa and the median at 0.66 kPa. The bootstrapped 95 % confidence interval for the absolute detection threshold ranges from 0.55 kPa to 0.94 kPa. We noticed that those participants with larger absolute detection threshold in general had larger-diameter arms, which might influence inflation characteristics or how well pressure can be perceived. Further studies are thus needed to investigate the relationship between body type and sensitivity to pressure stimuli. However, pressures above 1 kPa are very likely to be detectable for most.

Absolute Detection Threshold: In the Wild

The previous study provided data on lab performance of compression feedback. However, the ideal conditions encountered here would not be found when using compression feedback in actual wearables. We thus ran a second absolute detection study to determine absolute detection thresholds for in the wild situations. While there is less control over the study conditions in this kind of setup, it allows for more ecologically valid data on compression feedback perception.

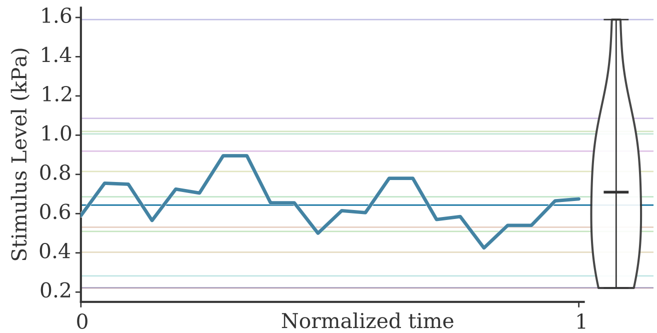


Figure 7. Each horizontal line shows the absolute detection threshold for one participant. The progression of stimuli for one example participant is shown with the threshold highlighted. Absolute detection threshold distribution is shown in the violin plot at the right. The average detection threshold, shown in the violin plot, is 0.7 kPa.

In this study, participants wore a mobile prototype in a pouch (see Figure 8) and used the same pressure cuffs on their wrist as in the lab study. Instead of presenting specific stimuli and recording participants' responses, here we chose a study design more closely aligned with real use. We hence had participants walk around and take public transport, simulating actual use. Participants listened to music on headphones for the entire study and played a mobile game while on public transport. We instructed participants to take note of their environment during the walking portions in order to prepare for subsequent questions. During the study, stimuli were then presented randomly every 1.5–3 minutes. For each stimulus, we programmed our system to slowly increase pressure in the cuff. We instructed participants to press down on the cuff to signal they noticed a stimulus. An experimenter followed participants during the study to record their current state (i.e., walking or on public transport) and their reactions.

Figure 8. During the in the wild study on absolute detection thresholds of compression feedback, participants wore the prototype controller in a pouch around their waist.

The absolute detection threshold is then given by the cuff pressure just before the participant pressed down on the cuff. Pressing on the cuff can be detected as a spike in the pressure readings, as external compression also increases internal pressure. This yields a conservative (slightly higher) estimate for the threshold, as it does not account for participants' reaction time.

For this study, we recruited 12 participants (2 female, age 18–30, $\bar{x} = 24.7$, $SD = 3.0$). None of the participants were familiar with the feedback and none had their blood pressure taken recently. This study took about 40 minutes and was also rewarded with a non-monetary gratuity.

Results

As shown in Figure 9, there was no large difference in the absolute detection threshold for the different settings. A paired samples t-test, comparing transit and walking pressure thresholds, showed no significant difference between the two; $t(11) = -1.62, p > 0.05$. Participants were able to detect stimuli at about 2.3 kPa. It only took participants 7.9 s on average to react to a stimulus. However, one participant was able to react in as fast as 2 s. In this situation the cuff was already constrained a bit, resulting in an increased pressure at the start of the trial. The participant was thus able to notice the feedback much earlier than usual (only a slight inflation was needed to increase the pressure from the initial to a noticeable level). The longest it took a participant to react was 32 s.

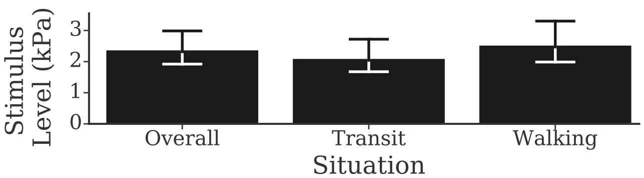


Figure 9. Absolute detection threshold as determined in an in the wild study. Participants were able to detect stimuli at about 2.3 kPa. There was no difference in performance between walking and being on public transport. Error bars show 95 % confidence intervals.

The results thus show that in the wild performance, while slightly below lab performance, is still quite good. Participants are already able to perceive pressures of 2.3 kPa. There is some variability around this threshold, as in the lab study, hinting at participant specific thresholds. Taking into account that the final threshold is influenced by participants' reaction times, we can assume that slightly lower pressures might work as well, though.

Just-Noticeable-Differences

Our first two psychophysical studies have given us good data on the minimum pressure level needed for effective compression feedback notifications. However, we were also interested in how many different levels of notifications users could distinguish. We thus ran an additional just-noticeable-difference (JND) experiment. Note that while we are the first to investigate absolute detection thresholds for compression feedback, the JND has been studied before by Mitsuda [23]. However, our setup differs from this previous work in two aspects: (1) we look at feedback given by a wearable prototype, while Mitsuda used a much larger and powerful electropneumatic regulator. We found that inflation behavior does provide subtle cues (e.g., users sensing the change in pressure, not the absolute pressure) and would expect some differences between these pump types. Also (2), in Mitsuda's study playback of stimuli alternates between pressure levels. Thus, user might pick up subtle cues from, e.g., pump activating, informing them a change is taking place. Instead, we fall back to zero pressure between stimuli. This makes the task much harder, but also covers a different use case. For notifications, it is less relevant to detect the change from one notification to another and more important to identify one notification that is played back. Stimuli have to be detected standing on their own.

For the JNDs, we gave participants stimuli pairs and asked them to judge whether the two are *equal* or *different*. They could play back each stimulus as often as they wanted (to increase the confidence of their judgments), but had to play each one at least once to proceed (on average, participants played back 3.1 stimuli per trial). During stimulus playback, the pump increased pressure to the target level, which was then held for 5 seconds, then all air is released. During a stimulus, input was disabled and participants had to wait till after deflation to play back another stimulus or vote on stimuli equality. In this experiment we use 4 different base levels (at exponentially increasing levels of 0.5, 1.0, 2.0, and 4.0 kPa) in combination with 5 different offsets (0, 0.2, 0.4, 0.8, and 1.6 kPa) yielding 20 different conditions. Each condition was repeated once for a total of 40 stimuli. Stimulus order was randomized and we also randomly assigned base and offset stimuli to the two playback buttons (see Figure 6).

We recruited 12 participants (1 female, age 22–35, $\bar{x} = 26.8$, $SD = 4.5$), 7 of which had also participated in the first lab study. Participants in this group also did not have their blood pressure taken recently. For repeat participants, the two lab studies were several days apart. In a post-hoc check, we did not find a systematic effect for those repeat participants. We thus only report results for all participants at once and do not further distinguish repeat participants. The study took about 20 minutes and was rewarded with a gratuity.

Results

We define the JND as the pressure difference where 95 % of users were able to tell two stimuli apart. We chose this non-conventional definition as it is a better fit for what we try to find out: how much to space pressure stimuli for different notifications. By picking a 5 % error level, we find that difference where we can assume participants only confuse two different kinds of notifications 5 % of the time. Hence, this is also a conservative estimate and JND for individual users might be lower (as we saw already with the active detection threshold). In a first step, we aggregated a score (% of users who felt that the two stimuli are equal) for each base/offset pair (shown in Figure 10). We can see this was a hard task, especially due to the sequential playback of stimuli (participants played back 3.1 stimuli per trial—1.1 more plays than required).

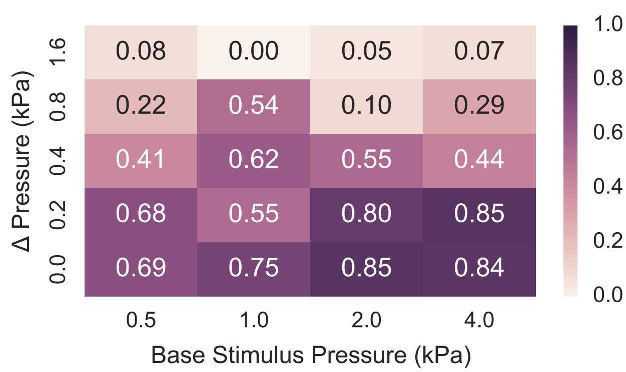


Figure 10. Table showing how often stimulus pairs were judged as being equal (e.g., a 0.8 kPa increase over a 2.0 kPa base pressure was seen as equal only 10 % of the time). This shows that the higher the delta pressure, the more likely a stimulus pair was rated as feeling unequal.

According to *Weber's law*, the JND should be constant proportional to the base level multiplied by the ratio between offset and base level. Hence 5 kPa and 6 kPa stimuli are harder to distinguish than 1 kPa and 2 kPa stimuli. To investigate at what ratio the JND equals our desired 95%, we aggregated our data a second time (per pressure delta to base pressure ratio). We used non-linear least squares to fit a logarithmic function to the data ($R^2 = 0.99$). This allows to predict when 95 % of participants would recognize the difference—at about a 2.77 offset to base pressure ratio. For example, at 0.8 kPa of pressure an increase in pressure of 2.2 kPa is needed to attain 95% chance of users being able to distinguish the two stimuli.

The 95 % level is comparably conservative, and Figure 11 also shows the resulting ratios for other error levels. When we, e.g., want to reduce the error level (make stimuli more distinguishable), we move to the right of the curve. The differences in setup makes our results hard to compare against Mitsuda's. Where he saw a need for an 0.4 kPa offset at a 4 kPa base pressure, our model predicts only 40 % discrimination for this. As he used a descending method of limits [13], he established thresholds after two correct answers, which does not map directly to a discrimination threshold.

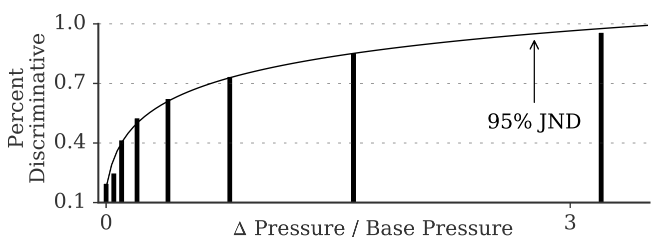


Figure 11. The larger the ratio of offset pressure over base pressure, the better users are able to discriminate the two stimuli. Bars are measured values, while the curve shows a least squares fitted logarithmic function.

Discussion

In the three psychophysical studies we have determined thresholds for compression feedback on the wrist. However, we found that the results can be hard to put into perspective. As can be seen in Figure 12, the found absolute detection thresholds are very low compared to the kind of pressures our straps are designed for. Similarly, the pressure we used when exploring background feedback also is quite low. While compression feedback systems will probably not use the whole pressure range shown (near blood pressure levels the strap would cut off blood supply and could not be used for longer durations), there is still much space to use for stimuli. As shown in the JND study, participants are able to tell stimuli apart once sufficiently spaced. This can be used to communicate different messages (two distinct levels give 1 bit of information).

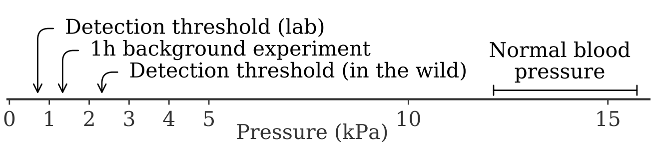


Figure 12. Overview of feedback pressures used in comparison to the normal blood pressure range. The absolute detection threshold and the pressure used in the background feedback experiment are far away from pressures that would restrict blood flow.

The results from the absolute detection threshold and JND studies provide a starting point for the exploration of compression feedback. While the results provide design parameters for compression feedback's prime location—the wrist—further work is needed to determine similar parameters for other locations. In the lab setting, we also specifically investigated seated users (a common posture, e.g., for office workers) that were concentrating on the task. The in the wild study also provides data for one common scenario where notifications are used: walking around and taking public transport. Here we have also seen that mobile and distracted users are less perceptive of feedback nuances.

As Figure 12 shows, off-the-shelf wearable electronic blood pressure meters are actually over-dimensioned for typical application scenarios. These devices are able to generate pressure levels high enough to cut off blood flow. For safety reasons, interaction devices based on compression feedback should stay below these levels. We expect pressure levels below 5 kPa to be sufficient for most applications. Creating pressure in this range is possible with thinner inflatable straps and smaller pumps with lower energy requirements.

REACTIVE COMPRESSION FEEDBACK

So far we have looked at *active* feedback—the system plays back a stimulus by inflating the strap to, e.g., signal a new notification. However, compression feedback can also be used *reactively*, i.e., giving feedback in reaction to a user's action. A user could, e.g., press down on an inflated strap to query for state (e.g., whether there is an email waiting to be read). Depending on the state, the strap would either deflate a bit or remain at the same pressure level. This allows for a different kind of notification mechanism: instead of signaling a user when a new notification comes in, users can decide for themselves when to check. The strap would inflate slowly to indicate that there is a message waiting (this is actually a kind of active notification), yet the full content is only revealed as needed.

The resistance of the strap to squeezing it is directly related to the internal pressure level. As illustrated in Figure 13, more complex deflation patterns can be used as well. Furthermore, this user action does not need to be a hand pressing down on the strap, flexing the muscles underneath a strap could also trigger the same procedure (however, the amount of external force on the strap is more limited here). With *Shoogle*, Williamson et al. explored vibrotactile/audio version of feedback mediated through exploration [41].

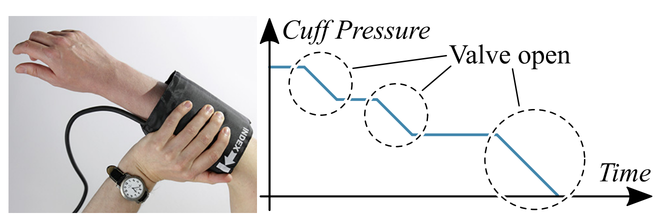


Figure 13. Compression feedback can also be used *reactive* to the user. As the user presses down on an inflated cuff, air is let out of the cuff in two short bursts and another longer burst slightly later. Users sense this deflation pattern by how the cuff *gives in* to the force they apply.

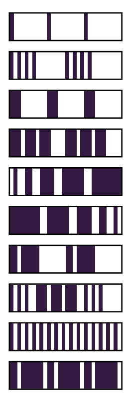
Detecting user's manipulation of a strap can be achieved with the embedded pressure sensor. Outside force on the strap results in an increase of internal air pressure. A quick squeeze thus, e.g., can be detected as a sharp momentary peak in pressure levels. Detecting those pressure changes for use as an input modality has been explored in previous work (e.g., [18, 26, 31]). Internal pressure of controls has also been used to provide different sensations or resistance when those controls are used [14, 39]. However, using deflation patterns to provide additional information during the interaction yet needs to be investigated. As we have shown above, compression feedback is suitable for feedback lasting a longer period of time. Combined with reactive feedback, such systems can be used to communicate a persistent background information and only surface details (e.g., indicating one of three specific cases) when actively queried.

Evaluating Reactive Notifications

Just as we evaluated how well compression feedback can be used for active feedback, we also set out to evaluate how well it is suited to reactive notifications. For this we ran a lab study where participants were presented a range of reactive patterns and were asked to rate and distinguish them. This study makes use of the same prototype as the previous in the wild study. However, instead of wearing the device in a pouch, the system was placed on a table. As in the other lab studies, participants also wore headphones playing white noise.

Reactive feedback makes use of deflation patterns—the way the air moves out of the strap. Hence, such patterns are defined by how the valve opens and allows for release of air. Different patterns can be created by changing how long the valve is opened, e.g., releasing air in small consecutive bursts. Furthermore, pauses of varying length between individual pulses (air releases) can be used to differentiate patterns. For this study, we designed ten different deflation patterns (duration information are for one cycle, e.g., one pulse and break in **P0**):

P0 Short pulses with breaks in between (2.6 s)
P1 Four short pulses followed by a break (4.4 s)
P2 Long pulses with breaks in between (4.8 s)
P3 Three long pulses followed by a break (9.4 s)
P4 Pulses of increasing length (9.8 s)
P5 Pulses of decreasing length (9.8 s)
P6 Heartbeat pattern (3.9 s)
P7 S.O.S. pattern (12.2 s)
P8 Series of very short pulses (0.15 s)
P9 Alternating short and long pulses (3.25 s)



Before a pattern can be played back, the strap is inflated to a pressure level of 8.2 kPa. While this is higher than the detection threshold levels found above, we chose to use a more fully inflated strap in order to test more complex deflation patterns. If lower pressures are desired instead, shorter deflation patterns would need to be used (e.g., omitting **P7**). Yet, while the design space shrinks at lower pressures, note that there can still be large variation. For example, pauses between bursts can be varied irrespective of the initial inflation.

We recruited 13 additional participants for this study (3 female, age 20–53, $\bar{x} = 26.3$, $SD = 8.3$). All participants wore the strap on the wrist where they would wear a watch. Before the actual study, we then gave participants the opportunity to explore the available patterns. Each pattern was represented by an icon representing patterns as a sequence of vertical bars. Participants could click on a pattern to play it back, allowing them to build a connection between the visual representation and the haptic sensation. Once they started the actual study, it was not possible to go back to this exploration mode.

During the study, patterns were presented in randomized order. Each pattern was shown three times for a total of 30 trials. During a trial, participants could play back the pattern as often as they wanted (again, to establish higher confidence in their ratings). Afterwards, they were asked to rate the pattern in four attribute dimensions: calm–hectic, soft–hard, rhythmic–arrhythmic, and pleasant–unpleasant. For each trial and dimension, participants picked a value (0–1000) from a visual analogue scale [12]. Participants also indicated which pattern they felt was played back by picking from the visual representations they trained with before the study. They also rated their confidence in their pattern pick with another scale.

Results

Participants played back 1.3 patterns per trial. Their confidence ratings go down as they replayed patterns more (linear regression: adjusted $R^2 = 0.2, p < 0.001$). This shows some patterns are inherently hard to distinguish and multiple playback does not help a lot. But overall, participants correctly identified the pattern in 82 % of trials (see Figure 14). A subset of patterns were generally identified correctly. For example, patterns **P1**, **P2**, and **P7** all have recognition rates of 95 %. One pattern with slightly lower performance was **P3**, which was only identified correctly in 54 % of trials. Participants sometimes confused it with the steady series of pulses, indicating that the break between longer pulses was hard to detect.

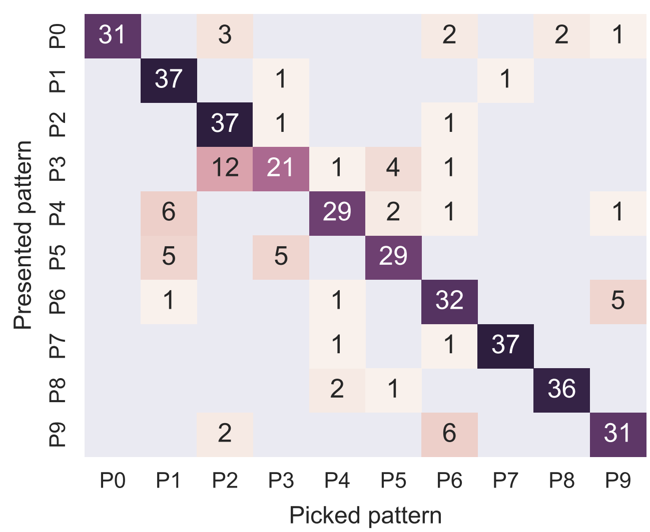


Figure 14. Presented with ten different reactive feedback patterns, participants correctly identified the pattern in 82 % of trials. The confusion matrix shows that while the results are overall good, patterns P3 was slightly harder to identify than the other ones.

So far we have only looked at quantitative measures of compression feedback. However, we can also analyze the attribute ratings to see whether participants tended towards either end of the scale. As shown in Figure 15, participants rated compression feedback as slightly more soft, pleasant, and rhythmic. A paired samples t-test showed no significant difference for the calmness attribute; $t(120) = 0.24, p > 0.05$. However, paired samples t-tests showed that for the *soft*, *pleasant*, and *rhythmic* dimensions, participants rated the patterns significantly higher than the average rating of 500; $t(120) = [-3.90, -8.21, -5.92], p < 0.001$. This indicates they perceived compression feedback positively in these attributes, e.g., leaning to rating it as pleasant.

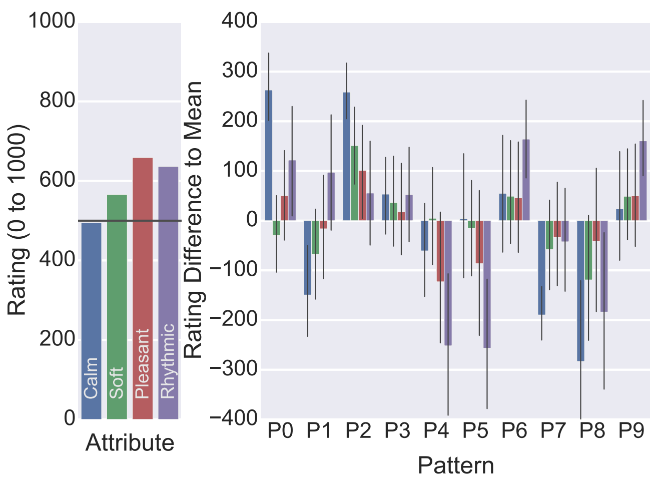


Figure 15. Asked to rate the patterns in four dimensions, participants found the patterns rather calm, pleasant, and rhythmic. This varies strongly by pattern though. Pattern P8, e.g., is particularly less calm than the others. Error bars show 95 % confidence intervals.

We also took a look at how ratings vary for different patterns. With a repeated-measures two-way ANOVA, we found significant main effects of pattern ($F(9,108) = 9.47, p < 0.001$) and attribute ($F(3,36) = 8.94, p < 0.001$). We also found a significant interaction of pattern and attribute ($F(27,324) = 6.47, p < 0.001$). To investigate this, we ran pairwise permutational two-tailed t-tests with 1000 permutations for pattern combinations within an attribute (p-values adjusted for multiple comparisons with the Holm-Bonferroni method). These post-hoc tests showed that there were no significant differences between patterns for the *pleasant* and *soft*. However, the *calm* and *rhythmic* attributes both saw a large number of significant differences between patterns.

Discussion

The results show that reactive feedback is a viable format for notifications. Limiting a system to a smaller number of patterns (e.g., only for three app categories) would further boost the recognition rate. Participants also tended to rate the patterns favorably, particularly with respect to how pleasant they felt. We believe this kind of notifications could fill a gap in current systems. Not all notifications require immediate reaction, but can instead *pile up* over time and only reveal more details after the user queries them.

VIBRATION VS. COMPRESSION FEEDBACK

So far, we have investigated compression feedback on its own. However, we were also wondering how it compares with vibration feedback. As the two are complementary, we were primarily interested in whether one would fare or be perceived significantly worse than the other. We thus ran a study to look at the differences between those two feedback methods.

We recruited 12 more participants (3 female, age 17–50, $\bar{x} = 25.0$, $SD = 8.3$). The study was a within-subjects design with feedback modality as only factor. Participants sat at a PC and wore headphones playing white noise. On their wrist, they wore our miniaturized device in a bracelet-like enclosure. We attached both, compression and vibration feedback actuators, to the controller. They kept a phone in their pocket, which also provided vibration feedback. Participants could set the compression feedback strength (they did so from 4.5–8.2 kPa), in order to balance intensity with the vibration stimuli.

We designed four distinct feedback patterns for each, compression and vibrotactile feedback. This was intended to create some variability of feedback. For compression and vibrotactile feedback, respectively, those patterns were:

- Inflate then deflate
- Inflate, hold pressure briefly, deflate
- Inflate, let out some air, inflate again, deflate
- Inflate in four equal-sized steps with brief plateaus in between then deflate

- vibrate once for 1 s
- vibrate twice for 0.5 s with a 0.2 s pause in between
- three short 0.2 s vibrations with 0.2 s breaks in between
- two longer (1.5 and 2 s) vibrations with a 0.2 s pause in between

The three feedback conditions were counterbalanced and patterns were randomized. As a primary task, participants repeatedly played a memory game on the computer (ten minutes per condition). While playing the game, a notification triggered every 40–60 s. If participants noticed this, they took out the phone and acknowledged the stimulus. Before the study, participants were given 10–15 minutes to familiarize themselves with the devices. Afterwards, they filled out a questionnaire, rating the different feedback types on 5-point Likert scales.

Results

We first checked whether performance in the primary task was impacted differently by the three feedback types with a repeated-measure one-way ANOVA. The used feedback method had no significant effect on how fast participants completed individual memory games ($F(2,22) = 0.97, p > 0.05$), how many mistakes they made in the game ($F(2,22) = 0.87, p > 0.05$), or how many notifications were missed ($F(2,22) = 0.58, p > 0.05$). However, the time it took participants to react to a notification was significantly different between the feedback types ($F(2,22) = 22.96, p < 0.001$). To investigate, we ran a pairwise permutational two-tailed t-test with 1000 permutations with p-values adjusted for multiple comparisons with the Holm-Bonferroni method. While there was no significant difference between the two vibrotactile conditions, compression feedback resulted in significantly ($p < 0.05$) slower reactions to the notifications. Participants in both vibration feedback conditions reacted in 9.1 s while it took them 12.0 s to react to pressure feedback stimuli.

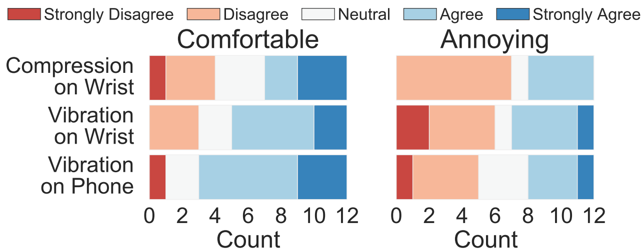


Figure 16. Comparing vibration and compression feedback, both elicited similar responses from participants asked to rate how comfortable and annoying they found them.

If we compare how participants rated vibration and compression feedback after the study (see Figure 16), we see that there are no strong differences in how they were perceived. We checked for differences between the ratings with Friedman tests. For comfort ($\chi^2(2) = 0.84, p = 0.66$) and annoyance ($\chi^2(2) = 0.55, p = 0.76$) ratings we found no significant differences between the feedback modalities. Both modalities polarized users with respect to how annoying they found them. Asked whether they found the feedback comfortable, the vibration phone received slightly higher scores than the two wrist-mounted methods. This might be due to the unfamiliar prototype or the additional weight of it. We also checked whether participants' compression intensity choices had on influence on their ratings with linear regression. While there was no influence on annoyance ratings ($p = 0.16$), choosing higher intensity feedback lead to lower comfort ratings ($p < 0.01$).

Discussion

Overall, this study shows that compression and vibrotactile feedback have similar impact on primary task performance. The only difference was that it took participants slightly longer to react to compression feedback stimuli. This is most likely the case because it takes a short moment for compression feedback to become noticeable. While vibrotactile feedback is instantaneous, compression feedback straps need to inflate beyond a certain level to become noticeable at all. Qualitative responses by participants also showed that this kind of feedback is not more annoying than vibration feedback. Comfort levels could be further improved by future prototypes that conform better to the wearer's wrist.

CONCLUSIONS AND FUTURE WORK

We have investigated *compression feedback*, which differs from other forms of pressure feedback or vibration feedback. It can be rather subtle but can scale to strong sensations as well. We have concentrated on the performance of compression feedback as a notification mechanism. In three psychophysical studies, we quantified minimal pressure levels at which a stimulus is felt (in the wild and in the lab) and how well two stimuli can be distinguished. We find that, on average, users can feel compression stimuli above 0.7 kPa (1.2 kPa when out in the wild). However, for some users this threshold can be as low as 0.22 kPa. Hence tuning feedback parameters to individual users would be worthwhile and can open up more of the pressure range. Moreover, users are able to distinguish two stimuli with 95% probability when the ratio between test level and base level is 2.7. We verified suitability for longer use with a 1 h long acceptability experiment.

In two additional studies we explored the properties of reactive compression feedback and compared compression feedback to vibration feedback. In both cases, different patterns are explored—an important feedback aspect to differentiate different types of notifications. We find that with a subset of three different patterns, participants were able to identify them in 95 % of cases—sufficient for real-world use. Results from those two studies thus further underline the general suitability of compression feedback for notifications.

While compression feedback can already be mobile, the needed components are still relatively large. We expect to see further miniaturization enabling even better integration into wearables and other devices. Our smallest prototype only weights 60 g, including the battery, pump, and valve. However, the housing adds additional weight and the low integration of the components means the overall design is comparably bulky. Where we had to resort to parts from blood pressure monitors, these are designed for higher pressure ranges than required for compression feedback. Pumps and valves specifically designed for our purpose could help with further miniaturization. In this challenge, integrating the inflatable air bladders themselves is comparably straightforward. For decades there have, e.g., been shoes on the market that have an inflatable interior.

Many more design properties remain to be explored, though. For example, acceptability of sustained pressure feedback in everyday scenarios, different inflation mechanisms, or differences of strap placement all require further investigation. With internal valves between adjacent chambers, a sensation of spreading pressure in a wave pattern could be achieved. Composite layers with cut patterns [43], could be used to further distinguish different pressure levels. Straps could stay rigid in some places, adding a displacement force to the feedback. We also found that strong inflation in straps around joints can be used to jam those joints, creating a strong physical inhibition. While this might not be a suitable kind of sensation for notifications, this kind of effect might be worthwhile to explore for scenarios such as pervasive games (e.g., [1]).

There are also a large number of additional application areas beyond notifications to be explored, such as compression feedback when watching movies. Passengers waiting at an airport could be notified with increasing urgency of gate times or train passengers of approaching stops. Students could literally put pressure on professors giving a lecture when they struggle. Straps over elbows integrated in shirts could inflate when unhealthy food is detected. This would provide a noticeable resistance to eating said food which is not easily perceivable to bystanders. Straps could provide subtle information about what a user's pet is doing: if her cat is hunting the feedback is different than when it is napping. Similarly, sentiment of larger groups such as sports fans or celebrity followers could be communicated or a more personal grasp on your arm could be sent from distant friends and family. Instead of showing outside state, compression feedback can also be used to increase self-awareness. For example, mirroring a user's heartbeat in a strap could help users focus on and better understand their body's reactions. In general, compression feedback is an interesting addition to the haptic feedback repertoire of interactive systems, providing an additional design space to explore.

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