Inhibiting Freedom of Movement with Compression Feedback

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CHI'17 Extended Abstracts, May 06–11, 2017, Denver, CO, USA
ACM 978-1-4503-4656-6/17/05.
http://dx.doi.org/10.1145/3027063.3053081

Abstract
Compression feedback uses inflatable straps to create uniform pressure sensations around limbs. Lower-pressure stimuli are well suited as a feedback channel for, e.g., notifications. However, operating compression feedback systems at higher pressure levels allows to physically inhibit movement. Here, we describe this modality and present a pervasive jogging game that employs physical inhibition to push runners to reach checkpoints in time.

Author Keywords
Compression feedback; pneumatic; jamming; inhibition; exertion games

ACM Classification Keywords
H.5.2 [Information Interfaces and Presentation]: Haptic I/O

Introduction
Current mobile devices primarily rely upon vibrotactile feedback for their haptic output channel. Yet, this is but one of many possible modalities, where other feedback types offer different sensations and possibilities. For example, indirect light feeback [17] can create more subtle visual feedback, or thermal feedback can create a sensation of warmth [18]. Compression feedback is an addition to this modality repertoire, allowing for pressure stimuli around limbs by way of pneumatic inflation of straps worn around them.

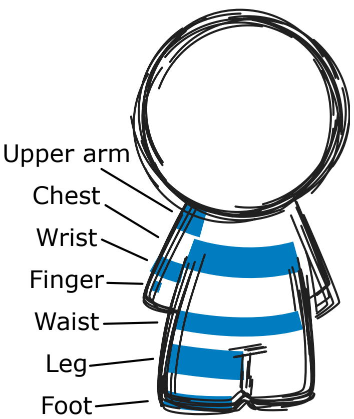

Figure 1: Compression feedback straps can be worn around different attachment points on the body. Where previous work has primarily investigated the wirst, in this work, we focus on feedback on the leg.

Figure 2: We use blood pressure cuffs for our compression stimuli.

Compression feedback for notifications has just recently been investigated [15, 16]. While that work showed how well users can perceive and distinguish pressure stimuli, it only showed so for comfortable lower levels of pressure—as is appropriate for a system designed for general notification usage. Yet, as we will show here, compression feedback can also be used at higher intensities to provide a completely different set of stimuli. Instead of creating light pressure (or squeezing) sensations, we focus on compression feedback stimuli that *inhibit* the user because they reduce the available freedom of movement. Apart from presenting the general concept of compression feedback for inhibiting users, we show how this can be applied to a concrete scenario with a pervasive jogging game.

Related Work

We use pneumatic actuation to inflate straps around a user's limbs. A similar squeezing effect can also be created without inflation. For example, *ServoSqueeze* [2], *HapBand* [3], and *HaptiHug* [20] work by tightening a band or clamps around the wrist or body. This is used to recreate hugging sensations or a sense of being touched remotely.

Where we inflate full straps, other work has used the same kind of actuation to inflate balloon actuators. Fan et al., e.g., had participants wear a set of four such actuators on the leg [5]. Similarly, He et al. constructed a bracelet with balloon actuators to provide pressure feedback on the arm [7]. Having discrete chambers allows for more localized sensations. Instead, we aim for an inhibiting overall effect.

We use blood pressure cuffs for the inflation. Such repurposing was previously done by Patterson and Katz [13], Tejeiro et al. [19], as well as by Mitsuda [10] They all use this setup to explore some form of sensory substitution (e.g., for use with prosthetics).

Compression Feedback Systems

For compression feedback, four components are required: (1) a strap to fit around the area where compression stimuli should be applied, (2) an inflation mechanism, (3) a way to release air again from the system, and (4) a controller to monitor and adjust the system accordingly. As we mentioned above, we use blood pressure cuffs for our straps (also see Figure 2). They are a good fit, as they come in many different sizes (from cuffs for babies to cuffs for the obese), and are designed for comparably high inflation levels (blood pressure normally is in the range of 10.7 kPa to 16.0 kPa). Blood pressure cuffs also already come with suitable connectors, while integrating sufficiently sturdy ones into self-made air bladders can be tricky.

For the inflation itself, we use miniature pumps. These are commonly used in blood pressure monitors and provide sufficient power to inflate cuffs of that size, yet are still small and power efficient enough to be integrated into wearables. Similarly, we also repurpose the solenoid and safety valves also originally designed for such devices.

For the controller, we use an *Arduino Nano*. On top of a custom PCB, it controls the pump and the valve, while monitoring internal strap pressure via a *Freescale MPXV5010 series* pressure sensor. This setup allows controlled inflation to specific pressure levels, but can also be used to just switch the pump on or off. To allow for untethered operation, the system can be powered from a battery pack and controlled via a Bluetooth interface. As shown in Figure 3, these two just plug into the main controller. While the Arduino directly controls the pump and valve, the wireless interface is more high level. Here, the system can just be instructed to inflate to a certain level, while constantly reporting back the inflation state of the system.

Figure 4: Different strap positions enable different sensations on strong inflation. While lower and upper leg placement give a feeling of *weighing one down*, placement on the knee can *lock* the leg. Thus one just *feels* restricting while the other one *is* inhibiting movement.

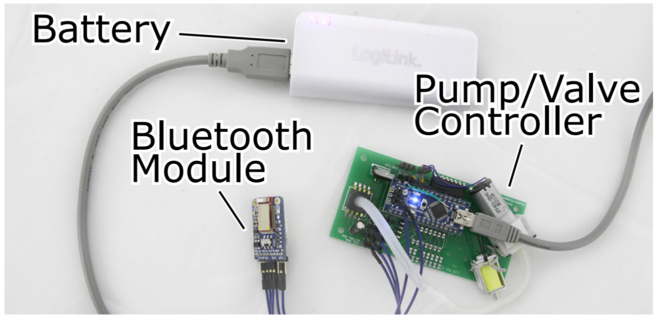

Figure 3: We built a Bluetooth-enabled pump/valve controller to control inflation and deflation of a compression strap in mobile scenarios, such as in our pervasive jogging game.

Compression Feedback for Inhibiting Users

Previous work has used compression feedback to provide notification stimuli [16] or hugging sensations [12]. Yet, compression feedback can also be used to restrict the body's freedom of movement. By placing a strap over joints and inflating it, the range of joint rotation can be limited. For example, placing a strap over the knee allows control over how much the lower leg can be raised. This effect is due to two factors: (1) the inflated strap at the back of the knee restricts the free space available for bending, and (2) the pressure in the strap increases its rigidity and makes it harder to introduce a fold (as required by bending).

As shown in Figure 5, full inflation (to $\approx$11.5 kPa) over the knee strongly decreases the range of motion. While just wearing the strap restricts movement a bit, the remaining range of movement is sufficient for normal walking. Larger inflatable tubes, *air splints*, are already used in medicine to immobilize extremities and for physiotherapy. *Jamming User Interfaces* [6] explored similar changes between rigid and deformable states which occur when placing granular material inside the air bubble and vacuuming it.

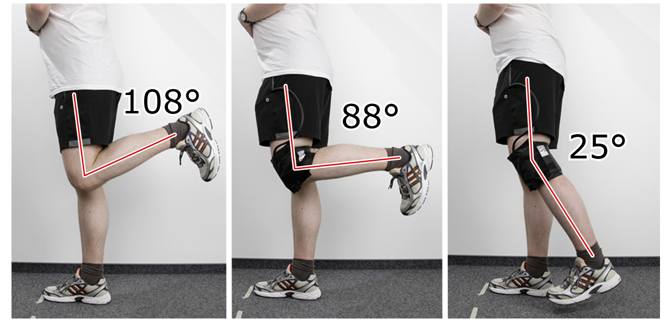

Figure 5: Freedom of leg movement changes with (left to right) no strap, a deflated strap over the knee, and an inflated strap over the knee. While having a strap over the knee limits movement slightly, the effect is much stronger with an inflated strap.

Placement of a strap directly over a joint is needed for direct locking of an extremity. However, other placements can also have an inhibiting effect on the user (as illustrated in Figure 4). For example, placing a strap around the lower leg and inflating it strongly provides a sensation as if the leg is *weighed down* (as described to us by a test user), while not restricting freedom of movement. An inflated strap puts pressure on the underlying muscles, increasing the force needed for tensing. Hence, walking, e.g., does become harder even though the knee bending is not inhibited.

We see a number of uses for such inhibiting compression feedback. While it would likely not be appropriate to restrict a user's freedom of movement for an incoming email, there is promise for this kind of feedback in the area of pervasive games (such as [1]) and exertion games. For example, pressure could be directly related to player actions: The weight of a picked-up virtual object could be represented by compression feedback around the lower leg. A virtual path with rising and falling slope could be represented as increasing and decreasing pressure around the thighs.

Figure 6: We created a jogging game where runners are pushed to reach checkpoints in a given time via compression feedback. Runners wear a compression feedback strap around one knee. The strap is controlled from a controller board in a waist bag.

More interestingly though, compression feedback could be used to physically inhibit some players or whole teams, with a direct impact on game-playing difficulty. This can be as simple as tightening a strap around a player's arm holding the egg in an egg-and-spoon race. High pressure on the arm reduces dexterity and agility, thus increasing the challenge in getting the egg safely to the finish line. Similarly, other limbs can be inhibited to, e.g., reduce throwing abilities or influence a runner—a scenario we will further explore below. This could also be used to achieve real encumbrance when carrying virtual items. In fact, Mitsuda investigated a similar effect, by controlling pressure in a cuff to simulate the weight of holding an object [10]. For every additional 1.41 kPa in pressure, his participants felt as if they were holding an object exerting an additional 1 N force. In general, the ability to temporarily inhibit players is useful for skill balancing and giving virtual objects and events a physical effect.

Using Inhibiting Feedback in a Jogging Game

While we have looked at inhibiting feedback in the lab and how it could be used for pervasive games, we have yet to see how this works in actual use. We thus decided to implement a case study for a pervasive game—centered around jogging—that uses compression feedback. By using slow changing feedback we could keep the small pump and pack everything into a mobile system. To further keep things simple, we only created a single player experience.

Our game concept is based on a classic arcade game design pattern, *checkpoints*, introduced in *Namco's Pole Position*[1] in 1982. Here, players need to reach a checkpoint in a given amount of time. Should the timer run out before such a checkpoint is reached, the game ends. This added challenge can increase excitement [4]. The app *Zombies, Run!* [21] tries to create a similar situation by using audio feedback, to give players the impression that zombies are chasing them. Instead of having a virtual source of stress, we set out to create a physical stress force.

In our game, runners put a compression feedback strap around their knee (see Figure 6). It is connected to our previously described compression feedback controller that is placed in a waist bag (see Figure 7). This system is controlled by a phone app that connects to the controller via Bluetooth and tracks the jogger via GPS. During jogging, the strap around the runner's knee slowly inflates. The system is designed in a way that freedom of movement is not noticeably restricted in the initial state. As the strap inflates, joggers feel their corresponding leg being more and more inhibited. They need to reach virtual checkpoints to trigger the system to stop inflating and let out the air. This cycle of slowly increasing inhibition and release once a checkpoint is reached then repeats.

[1] See, e.g., https://www.youtube.com/watch?v=FFs1Xc82Q0U

Figure 8: In the game *Pole Position* players have to reach checkpoints in a given amount of time. As shown in the above screenshot, the player has 60 s remaining. After crossing the line, additional time is added, as also indicated by the text “EXTENDED PLAY.” © 1982, Namco Ltd.

Figure 7: While running, participants carried the compression feedback device and a battery pack around in a pouch. It connects to a strap worn on the leg.

Checkpoints are spaced at 200 m intervals. Runners are free to take any path they want, as the system only tracks overall distance. Due to the constriction, there is an added dimension of urgency added to their run. Some parts of the route (those closer to checkpoints) are more intense than others (just after release). By adjusting how much urgency is induced, the system acts as a kind of pace maker for the runner (like the quadcopters in [11]). As the pressure increases, users’ desire to achieve relief increases as well. Hence the system is designed in a way to push users towards *preemptively* changing their pacing, as they feel the onset of the feedback.

We tested our system in a park with 7 participants (1 female, age 19–26, M=23.4, SD=2.3), three of whom were regular joggers. Participants ran for 6–10 minutes on a self-chosen course (i.e., we did not instruct them to run any specific route). We interviewed participants after they returned from their run and asked them to fill out a questionnaire.

Results

Three participants rated the system as neither particularly comfortable nor uncomfortable, while two each rated comfort as a bit lower/higher than neutral. As this is a system that actively adds discomfort at regular intervals, this shows us we did not make the feedback too intense. All but one participant thought such a system could be an interesting companion for joggers, and three participants noted they themselves were open to using something like it. Participants gave varying reports on the effectiveness of the system: two reported not having been inhibited during their run, while two others thought the feedback was quite strong (one more participant noted too much pressure on the knee). This variance could be due to differences in individuals’ perception or to physiological differences, where the strap is more effective on some legs than others (e.g., due to placement on, or anatomy of the leg).

Discussion

A limitation of our prototype was that only one leg was inhibited—a limitation due to our available hardware. While we only had one complete system, replicating the device would enable inhibiting both legs. This would create a more even effect (yet, only one participant remarked on a perceived disparity between the legs). However, the basic concept of pushing runners would remain the same.

Because we used an off-the-shelf arm strap, the fit at the leg was not perfect. We noticed that differences in placement could influence the strength of the effect. As noted earlier, the inflation in the back of the knee in particular has a strong influence on the level of inhibition. If the air bladder does not align well with this location, the effect hence weakens. Thus, a future prototype where inflation is integrate into textiles (as in [14]) could help better control the feedback by better aligning the inflatable parts with the body.

Conclusion and Future Work

We have investigated using compression feedback for stimuli that physically inhibit users. Compared to previous work on pressure feedback systems, inhibiting feedback goes a step further and actually restricts a user's freedom of movement. In the lab, we saw how this can, e.g., be used to restrict how much a leg can be bend at the knee. We have also found that the sensation depends on the kind of inhibition. Both, joint locking and muscle blocking, offer distinct possibilities, where the former reduces the freedom of movement while the latter just makes movements require more effort from the user.

Inhibiting the user by strongly inflating straps around extremities might seem risky. However, note that we only applied the feedback for brief stretches of time and also did not apply pressures that cut off the blood supply. Furthermore, a safety valve in the system ensured no overly strong pressure could build up. By using miniature pumps, instead of large compressors or pressurized air, we also limit the risk of too strong inflation. With pressurized air, inflation can actually be dangerous and the sudden sensation of strong inflation could also startle users and thus make them more prone to having an accident.

We see particular promise for this kind of feedback in the area of pervasive and exertion games. A common goal here is to blend the virtual game world and the real world, e.g., by having players run in real-life to move in the game. Yet, reflecting changes in virtual game state in the real world is not straightforward, particularly in mobile settings. Inhibiting compression feedback is one way to make such changes physical and exert actual force on the user. Yet, the effect of muscle blocking can be comparably subtle (i.e., compared to locking), and thus might not immediately alert users of the external influence on their body.

Another way such physical constraints are created is via electrical muscle stimulation. For example, with *Impacto*, Lopes et al. attempted to create the sensation of being hit on the arm [9]. In addition to a tapping sensation by a solenoid, they use electrical muscle stimulation to move the arm, as if it was affected by the force of such a hit. A similar approach was also used in an earlier project by Lopes et al., where a mobile devices was outfitted with a muscle stimulator and electrodes to provide force feedback to the player holding it [8]. One exemplary game here is a flight simulator where virtual wind is translated to a force on the user's arms, in order to make it harder to steer in a given direction.

In general, electrical muscle stimulation makes use of the player's own body to create the feedback. Instead of *actuating* the body, compression feedback *constrains* it. The two approaches thus tackle the problem from opposite directions. An advantage of electrical muscle stimulation is that the hardware required is light—the bulk of the work is performed by the user's muscles themselves. Compression feedback, on the other hand, needs to build up sufficient power to restrict the user's muscles, thus requiring a similar amount of counter-force. On the other hand, where electrical muscle stimulation *overrides* the user's control over her own body, there is no such loss of agency with compression feedback.

We believe both methods bring their own unique aspects to the table and could also be used complimentary. Where we have mostly looked at jogging games and leg inhibiting in general, there also might be interesting aspects to explore with other placements. Earlier, we already mentioned that restricting the arm could be equally fruitful. This and other configurations open up an interesting space for further exploration of compression feedback for inhibiting users.

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