HapticClench: Investigating Squeeze Sensations using Memory Alloys

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ABSTRACT
Squeezing sensations are one of the most common and intimate forms of human contact. In this paper, we investigate HapticClench, a device that generates squeezing sensations using shape memory alloys. We define squeezing feedback in terms of it perceptual properties and conduct a psychophysical evaluation of HapticClench. HapticClench is capable of generating up to four levels of distinguishable load and works well in distracted scenarios. HapticClench has a high spatial acuity and can generate spatial patterns on the wrist that the user can accurately recognize. We also demonstrate the use of HapticClench for communicating gradual progress of an activity, and for generating squeezing sensations using rings and loose bracelets.

Author Keywords
Haptics; Squeezing; Wrist; Wearable; Compression;

ACM Classification Keywords
H.5.2. Haptic I/O

INTRODUCTION
Our cutaneous senses comprise the submodalities of stimuli that can be perceived by our skin – light touch, vibration, pressure, temperature, pain, and itch [14]. While vibrations have been researched extensively, the pressure modality remains underexplored. Pressure communicates a more intimate [24] and pleasant feedback [22]. For instance, a simple holding of a hand or a finger relies on the pressure conveyed by the clench. This clenching around a body part is termed squeezing feedback. A miniature and portable squeezing feedback mechanism that can fit within today's smartrings and smartwatches would be very useful.

In this paper, we investigate the use of shape memory alloys (SMAs) for squeezing pressure feedback on the wrist and the finger. Most work in wrist pressure feedback uses pneumatic actuation, similar to blood pressure devices,

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Figure 1: HapticClench's squeezing tangential & shear forces

which involves pumps and valves that are relatively bulky for a wearable device. Secondly, the size of the inflated cuffs precludes generation of highly localized compression sensations. Thirdly, pneumatic feedback cannot provide ins-ant compression sequences owing to the inflation and deflation time. Finally, pneumatic actuation provides compression feedback whose perceptual properties are different from squeezing. We investigate squeezing feedback using SMA springs that are lightweight, thin, have high localization acuity, and can quickly generate strong squeezing feedback.

In the following sections, we formalize the definition of squeezing feedback and describe HapticClench – an SMA squeezing actuator, detail its design process and its electro-mechanical properties. We report on the psychophysical analysis of HapticClench including absolute detection and JND thresholds. We then investigate how HapticClench's low bulk and spatial acuity lead to capabilities that are not present or investigated in earlier work in this domain. We end with design guidelines and a discussion.

RELATED WORK
Vibrotactile actuation on the wrist has been extensively explored [8,10,13,17]. Pressure actuation on the body can be point-based [1,11], planar [26,27], or around a body part which can be compression or squeezing-based. Research on compression predominantly uses pneumatic actuation [19]. Although squeezing is not explored much, motor-based approaches have been used for the wrist.

Pneumatic actuation inflates air into a cuff around the wrist. Multiple works use blood pressure cuffs for compression to provide sensory replacement when using prosthetics [18,23]. Mitsuda et al. [15] and Pohl et al. [19] study the psychophysics of pneumatic compression, with both establishing a connection between air pressure and users' detection thresholds. Pohl et al. further found that users took more time to react to compression over vibrations, which is attributed to the inflation time of the straps.

Motor-based actuation tightens a band around the wrist by pulling it towards the top using a motor [2,3,9,21]. Song et al [20] show that temporal squeezing pulses are recognized as well as vibration cues. Baumann et al. [2] show that participants described different squeezing pulses with a larger range of adjectives than tapping and considered it more organic. Chinello et al. [3] show that squeeze actuation using three motor-driven moving plates resembled the squeezing action of the hand. However, no existing work investigates the squeezing load limits and interaction capabilities that a miniature motor-based device can provide. While some of the proposed devices could be small enough for wrist wearables, their strength is limited and the presence of a small mechanical motor still adds considerable thickness, which makes it impractical for flatter wearables, fitness bands, and rings. Further, motors produce noticeable gear noises and vibrations relative to speed and load.

Suhonen et al's [22] work is the only instance of using SMA wires for squeezing feedback. The users found the squeezes as "surprisingly weak", which they would not be able to feel in distracted situations. However, they found the sensations to be "very pleasant" and "massage-like".

SQUEEZING FEEDBACK

Prior literature uses the terms squeezing and compression interchangeably to describe pressure that encompasses the wrist. Pohl et al. [19] describe compression feedback as tangential-only compression of the skin all around the body part like an inflatable strap around the wrist pushes into the skin and compresses it tangentially. We delineate the term *squeezing* to refer to pressure sensations around a body part that consist of tangential *and* shear forces on it (Figure 1). When a band tightens around the wrist, instead of directly pushing against it, it results in both shear and compression forces. This is different from perceptual phenomenon since shear forces result in skin stretch that acts upon the Ruffini endings [12] in the cutaneous tissue, while compression acts upon the Pacinian and Merkel endings in the cutaneous and subcutaneous skin tissue [12,19]. When the stimulus solely relies on compression, it can lead to constriction similar to blood pressure monitors, affecting comfort [19]. However, while squeezing & compression are biologically different [9], their perception might not be exclusive from each other [16]. An exploration into this requires designing a pneumatic device with same width and load properties as HapticClench and is a subject for future work.

Squeezing happens when a wire or a band tightens around the wrist. We define three properties of a squeezing feedback device that inform us of its squeezing type and competence: *span*, *load capacity*, and *load throughput.* 1) *Span* is the width of the actuating wire or band on the skin. 2) *Load Capacity* is the maximum load a squeezing device generates. 3) *Load Throughput* is the maximum load a squeezing device can provide in a second. Higher the span of a device, higher the load required to generate the same pressure on the user's skin. The load capacity and load throughput inform us about the limits of strength and speed of a device. However, these properties can only give us a sense of a device's squeezing prowess. Squeezing load can vary differently based on power supplied and time increment. We investigate these issues for HapticClench after discussing its design process.

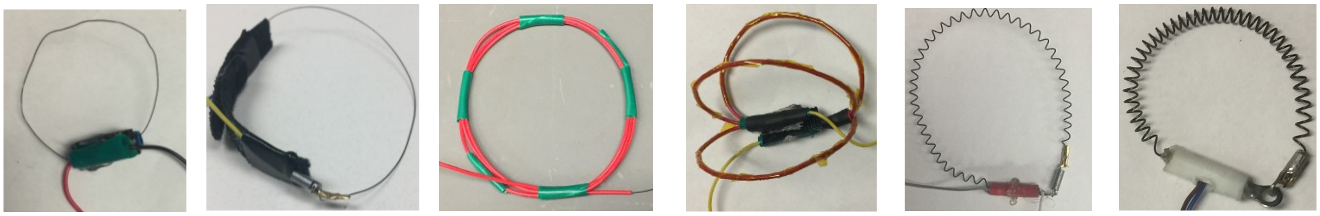
We desire three properties in HapticClench: a small span that enables higher spatial acuity thus allowing for multiple squeezing actuations, a high load capacity to offer a wide range of stimulus strength, and high load throughput to minimize latency upon actuation.

DESIGN PROCESS: MAKING OF A STRONG SMA SQUEEZING ACTUATOR

Shape-Memory Alloys have the ability to deform to a preset shape when heated. HapticClench uses Flexinol®, a commercially available Nickel-Titanium SMA with a low span that contracts like muscles when electrically driven. However, as mentioned, SMA wires were perceived as surprisingly weak. The challenge was to increase the load capacity of the wires while keeping the span smaller and achieving a high load throughput. The basic prototype has a Flexinol® wire tied around the wrist whose contraction modulates based on the power supply. The strength of an SMA wire depends on two factors: (1) the absolute contraction limit of the wire from its original length, (2) the restoration of the contracted wire to its exact original length so that subsequent contractions are consistently strong.

Figure 2 catalogues the HapticClench wire design iterations. The initial prototype (Fig 2a) consisted of a 0.5mm diameter wire attached to the wrist with Velcro straps. However, while the sensation was easily discernable initially, it did not consistently produce the same load capacity. This was because the wires need an external pull force while cooling to restore to their exact original length. While we assumed that the force exerted by the squeezed skin on the contracted wire would restore the wire, it was not enough. To exert the required pull force, we added a 4x12mm extension spring (Figure 2b), to the ends of the wire which was enough for restoration. However, the wire now had to overcome the restorative spring force during its contraction, which weakened the squeezing sensation.

To solve this, we considered two solutions: (1) (Figure 2c) a longer wire with multiple coils around the wrist that would increase the maximum overall contraction. However, there was no way to incorporate springs in this design. (2) (Figure 2d) Multiple wires placed in parallel on the wrist. While this increased the overall strength, the resultant force spatially distributed on the skin, resulting in a weak sensation.



(a) (b) (c) (d) (e) (f)

Figure 2: HapticClench wire design iterations. (a) SMA wire+Velcro (b) Wire+Velcro+Restorative Spring (c) Coiled wire in series +insulation (d) Wires in Parallel (e) SMA Spring+Restorative Spring+Hook (f) Final: SMA Spring+Hook, No restorative spring

We tried other SMAs such as the generic Nitinol, but the sensations, although strong for the thickest Nitinol, were highly contingent on an initial manual calibration using an open flame, which could not be made consistent. Flexinol, on the other hand, is pre-treated. Finally, we used Flexinol® springs (Figure 2e). The springs had higher contraction force and maximum possible contraction without any spatial distribution and resulted in a much-improved sensation. The springs also required less restorative force, which the squeezed skin itself could successfully provide. The restorative spring was therefore removed in the final prototype (Figure 2f). While the SMA spring's span is slightly higher than the wire, it delivers much higher load capacity and throughput.

THE HAPTICCLENCH SYSTEM

The final HapticClench prototype (Figure 2f) uses 30-coil Flexinol® springs with a 0.5mm wire diameter and a 3.45mm span (outer diameter) that has a load capacity of 1.63kg. The load throughput is same as load capacity i.e. it can reach a load of 1.63kg in 1s. The system (Figure 3) consists of the spring connected via crimps to a hook that ties around the user's wrist. The end of the springs connect to the driving circuit. The circuit consists of an Arduino Pro Mini that supplies PWM pulses to drive a mosfet, which in turn drives the SMA spring. Varying the PWM varies the supplied power resulting in different squeezing loads.

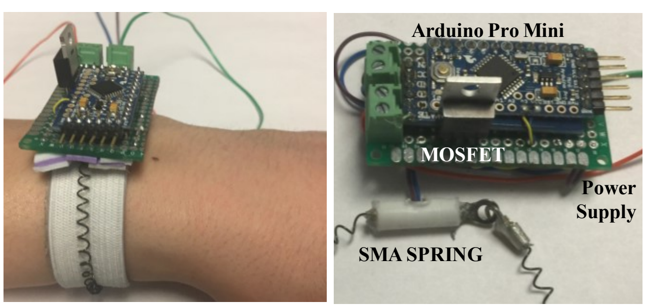


Figure 3: HapticClench circuit+spring assembly

In absolute terms, the strength of the sensation is expressed in terms of the load of the force exerted by the spring. This depends on the power and duration of the supply. We measured the load of the spring using a digital scale horizontally. Figure 4 shows the load strength for different power values supplied for a duration of 2s.

A similar load curve can be obtained within 1s duration by supplying higher power. The load rises slowly, then rises almost linearly until ~1.25kgs and then starts leveling as it reaches its load limit. The spring maintained its consistency over multiple uses and across other similar springs with an error range of +-5%. However, large changes in ambient temperature could have an effect on this consistency. The prototype was always used in an ambient temperature of 21-25°C. We derive a two degree polynomial equation for the curve ($y = -.0015x^2 + .1109x - .3959$, $R^2>0.95$) excluding the first three points and use it for the studies.

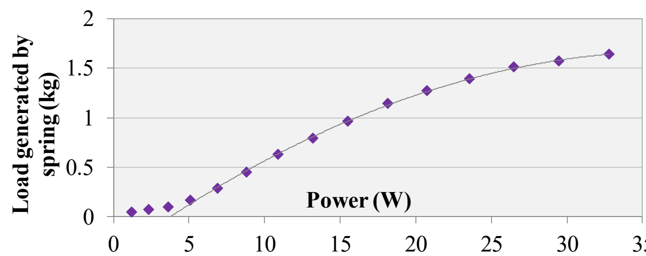


Figure 4: HapticClench Load vs Power supplied

As evident, HapticClench combines a small and lightweight apparatus, with a small span, high load capacity, and high throughput. The system however has its drawbacks. The power required to generate the minimum load at 1.63kg is 33W. This is high and given current battery sizes, it could be a limiting factor in its portability. Multiple SMAs that use lower power with a higher efficiency have been proposed [5,6]. However, other SMAs are not commercially available for non-bulk orders. Another limitation of Flexinol® is that it reaches a temperature of up to 90°C at maximum contraction. This temperature peak stays for only a fraction of a second, rapidly cooling down to the room temperature within 15s. We insulate the user's wrist using two overlaid 33% rubber-67% polyester bands of 0.9 mm thickness each and 19mm width with 2 layers of insulating Kapton tape in between. To encapsulate the spring into a band, heat vents or holes in the band are necessary. Although it should be noted that the temperature remains within comfortable levels for lower loads. As we will see in the next section, users' detection thresholds are much lower than the maximum load.

PSYCHOPHYSICS OF HAPTICCLENCH

To establish the fundamental psychophysical properties of squeezing feedback, we study its absolute detection &

discriminatory (JND) thresholds. While earlier work in pneumatic compression has studied these thresholds, this work is the first investigation into squeezing feedback.

Absolute Detection Threshold (ADT)

What is the minimum load of the squeezing feedback that a user can feel? To determine this, we conducted a standard two-down, one-up staircase study. Every squeezing stimulus was applied for a duration of 2s. The experiment started with a high load stimulus that reached 0.6kg at 2s. For every stimulus that was felt consecutively two times, the load was decreased by a factor of 0.6, and increased by the same if the stimulus was not felt once. After three reversals, the factor was changed to 0.75. The load values were administered by supplying the equivalent power based on the curve in Figure 4. The experiment ended after nine total reversals and the average from the last five was taken as the threshold estimate. We hypothesized that ADT would fall in .1 to .3 kg. The 0.6kg initial load ensured an easily detectable start. The 0.6 step factor ensured quick jumps to the .1-.3kg vicinity thus minimizing trials, after which the 0.75 factor ensured convergence to a fine-grained value.

Ten participants (2 female, age 22-27, mean=23.8), all right-handed took part. We recorded wrist circumference (WC) (13.9-17.2, mean=15.9mm) and wrist-top skinfold thickness (SFT) [7] (4.3-8.1, 5.5mm) which is a reliable indicator of body composition [25]. Participants wore the band in their left wrist with the arm rested on a table and hidden from their view during the study. While the squeezing sound was minimal, the participants wore headphones playing Brown noise for complete insulation. They controlled the mouse with the right hand to respond *Felt*/*Not Felt* after every stimulus. A gap of 20s between consecutive stimuli ensured that the spring returned to the ambient temperature.

Results

The mean threshold estimate is 0.16kg (95% CI [0.12, 0.20]). No correlation for SFT or WC was observed. 0.16kg load corresponds to 5W power, which is higher than vibration motors, but manageable in today's wearables.

Distracted Absolute Detection Threshold

In situations where the user is distracted, a stronger stimulus might be needed. We conducted an absolute detection threshold study while the user performed a primary task. The primary task was playing the game CandyCrush [28] on the desktop. The participants first played a practice level to get themselves familizarized with the game. Participants were instructed that their goal was to score as much as possible. At the start of the experiement, the participants began playing the game and the squeezing stimulus was played at a random time between 30s to 75s after the previous pulse. The interface only had one button for *Felt* in a second screen, and participants were instructed to press it whenever they felt something and get back to the game. If there is no response within 8s of the pulse, it is considered as *Not Felt*. The user can pause and resume CandyCrush any time without timing constraints. The 30-75s random gap allowed the particpants to get their focus back into the game and not anticipate the next pulse. The study followed the one-down, one-up, staircase design since the users were not prompted to respond and only responded when they felt the sensation. The other parameters were same as the prior study. Ten participants (3 female, age 22-26, mean=23.34), different from the prior study, all right-handed, took part.

Results

The mean threshold estimate is 0.17kg (95% CI [0.14, 0.20]). This shows that even though the squeezing modality is perceived as less attention demanding, its minimum perception threshold remains similar with or without distraction. However, more cognitively demanding tasks might lead to a different outcome. We also studied response times of the participants to see how quickly they perceive and respond to the squeezing. The mean response time was 1.4s after the pulse stopped playing. Including pulse time of 2s, this shows quick responsiveness to the squeezing sensation.

Discrimination Thresholds (JND)

To determine the different levels of squeezing load users can feel, we conducted a JND study using the method of constant stimuli. For each trial, participants had to respond if a pair of stimuli felt *same* or *different*. Each pair consisted of a base load and an offset load value. We used four base loads (0.125, 0.25 0.5, 1.0) and four offsets (Δ Load) (0, 0.125, 0.25, 0.5) giving 16 different conditions. In keeping with the JND standard, the base and offsets increased exponentially while keeping within the spring's load limits. Each condition is repeated once. The order of conditions within the stimuli pairs were randomized. Participants could play back a stimuli pair if they wanted to be sure of their response. The same participants as the ADT study took part 4 days later.

Results

Our JND analysis follows from Pohl et al.'s pneumatic JND study [19] which estimates a conservative JND to better fit its use for real world differentiation. JND is defined as the load difference where 95% of the users are able to differential two stimuli. Figure 5 shows the aggregate fraction of responses that found the two stimuli equal for each base-offset condition. For a 0.25 kg base load, 0.25 kg more is required for it to be distinguishable 95% of the time.

	0.125	**0.25**	**0.5**	**1.0**
0	0	0.20	0.20	0.25
0.125	0.90	0.75	0.40	0.25
0.25	1.0	0.95	0.80	0.50
0.5	1.0	1.0	0.95	0.60

Figure 5: Δ Load (kg) (y-axis), Base Load Values (x-axis) Table shows fraction of responses that judged two stimuli as equal. As baseload increases, offset needs to be higher.

We determined the 95% JND for each base value by fitting a logarithmic function to the ΔLoad vs aggregate% data (R^2>0.90 for all) and calculating the ΔLoad at 95%. Figure 6 shows the resultant JND values in Blue. While the 95% JND's general trend adheres loosely to Weber's law (ΔL/L=1.79), the 75% JND follows it more closely.

The 95% JND for Pohl et al's pneumatic actuation [19] was 2.77, which is much higher than 1.79. Further, participants in our study played back an average of 0.15 times per trial, compared to 3.1 times for pneumatic actuation. While part of this difference is attributed to the different nature of compression vs squeezing, and the surface area of actuation, the time pneumatic actuation took to reach the target load was also higher. Our 2s actuation time is much lower and earlier work has shown that feedback around the wrist is better perceived when applied in quick time durations [22].

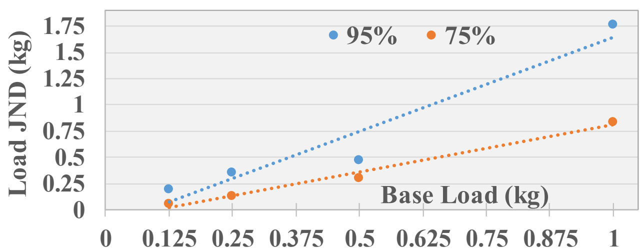


Figure 6: The 75% and 95% JND values for base loads

HAPTICCLENCH: CAPABILITIES AND USE

We have established the psychophysical properties of HapticClench's squeezing feedback and shown that the system can easily generate minimum detection thresholds and has a range of up to four levels of load that the user can differentiate. This can be useful in a variety of scenarios, such as notifications, information communication via patterns, gradual progression of temporal activities, and even emotion communication on the wrist or finger. We investigate three HapticClench capabilities that bolster these user scenarios: MultiClench, SlowClench, and RingClench.

MultiClench: Spatial patterns using multiple springs

HapticClench's small span ensures a narrow surface area of actuation, thus enabling multiple springs to be placed side-by-side (Figure 7) which can generate multiple squeezing patterns that can communicate more details about the standard notifications, or a codified message. For instance, a user wearing a force sensing band could squeeze her own wrist and make a spatial pattern, and then send it to a friend who feels the analogous sensations via the HapticClench band and understands the message. The question is, are the generated squeezing sensations good enough for the user to distinguish spatially? If yes, what are the perceptual constraints, and recognition accuracy for these patterns?

Figure 7 (left) MultiClench, (right) RingClench

We investigated duration patterns lasting 3s for the three springs. Considering triplet patterns of 1s each, 27 such patterns are possible. A pilot with 3 users with 27 patterns indicated that triplets with repeating springs led to huge ambiguity and were therefore removed. For instance, if 1-2-3 was played, it was clear, but with 2-3-1, there three potential answers: 1-2-1, 2-3-2, and 2-3-1. To get rid of the confusion, we removed repeating patterns. Further, we included all single and double stimulus patterns to make a set of 15 patterns, with no repeating sensations: 1, 2, 3, 12, 13, 21, 23, 31, 32, 123, 132, 213, 231, 312, 321. Doubles played for 1.5s, singles for 3s. We conducted a study to see how well can the users disambiguate these patterns.

Study Design

In the study, each pattern was played twice for a total of 30 trials, which were randomized. Participants chose one out of the 15 pattern options in the interface. They were not given feedback on the correctness of the response. All sensations were played at the load of 0.9kg. 8 participants (1 female, all right-handed, age 19-25, mean=23.5), all different from prior studies, took part. Before the experiment, participants did a practice run of 8 random patterns.

Results

The mean accuracy is 85% and varied heavily depending on the patterns. Figure 8 shows accuracy by pattern.

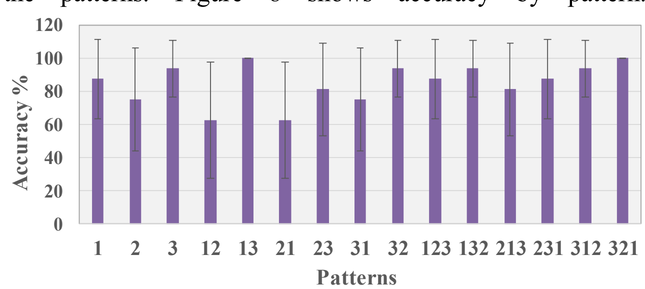


Figure 8: Accuracy of MultiClench patterns (95% CI)

For patterns 1, 3, 13, 32, 123, 132, 231, 312, 321, at least 14 out of 16 total trials (87.5%) are correct. We noticed a trend in patterns with low accuracy:

2	**75%** confusion from pattern	**3**
12	**80%** confusion from pattern	**1 3**
21	**80%** confusion from pattern	**3 1**
31	**100%** confusion from pattern	**3 2**

The high triplet but low doubles accuracy indicates that participants used relative positions of springs. Post-study interviews confirmed that while the users could accurately identify if a sensation was to the left or right of the previous one, they had trouble with its exact location. Absolute positioning might thus depend on separating the springs further. For singles, 1 & 3 have higher accuracy than 2. However, participants erred more on the side of misidentifying middle spring as 3. While we did not record each pattern's perceived difficulty, participants reported judging spring position based on how far the squeeze was from the head of ulna. This might have resulted in a bias for spring 3. Based on the results, we recommend removing the middle spring from single and double patterns, resulting in the final pattern set: 1, 3, 13, 31, 123, 132, 213, 231, 312, 321.

In addition to this, we asked the users to rate the sensations felt in the study. Figure 9 shows the comfort and annoyance. Participants felt that the sensations were fairly comfortable. One participant mentioned that they felt a bit tighter than they liked. Since the perception of the load varies from participant to participant, an initial calibration where participants can set their comfort levels will be useful.

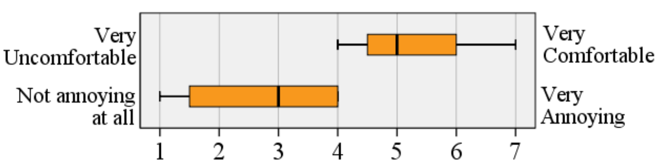


Figure 9: Comfort & annoyance boxplots for MultiClench

SlowClench: A Gradual Progression of Squeezing

Given its intimate nature, the squeezing sensation could be perfect for ambient delivery of a gradual change of state or progress. For instance, while waiting for a friend to arrive, a slowly incremental squeezing sensation could signal the narrowing distance. A user waiting for a download could passively track it via the incremental sensation. While the evaluation of temporal progression is a wide topic, we evaluate the feasibility of HapticClench to deliver moderately slow squeezing sensations of 1min and of 30s durations. For a continuing task, its progress can either be increasing or be paused. Further, as the duration of a tactile sensation increases, its perception by the user decreases [4]. Therefore, the question is, can the user passively differentiate a squeezing sensation that is either increasing or paused? To evaluate this, we propose two different types of squeezing load increments: continuous and staggered. Drawing from visual progress bars that update continuously or update in a staggered way, the continuous squeezing sensation rises uniformly from a low 0.3kg load to 1.1kg in 30s/1min. The staggered pulse rises in four steps of 0.2, 0.4, 0.8 and 1.6 at equal intervals in 30s/1min. The third pulse for denoting a pause is a holding pulse that starts at 0.6kg in 1s and then stays there until 30s/1min end. One problem was that the longer actuation times generated higher heat. To combat this, we added another polyester band with a layer of Kapton tape.

Study Design

Participants play an obstacle game as their primary task. The 30s/1min pulse plays at a random time 30s-1min after the participant starts playing the game. After the pulse is over, a pop up appears after a random time of 10-20s is elapsed instructing the participant and select if they felt a *Holding* or *Increasing* pulse earlier. The users are not asked to distinguish between Continuous and Staggered increasing pulses. After the response, participants get back to the game. The next pulse then plays at a random time 30s-1min after the participant's previous response. The procedure ensures that the participants respond based on the general feeling and not by tracking the starting and stopping of pulses. In contrast with the distracted detection threshold study where the participant has to pause the game on their own when they feel a sensation, here the user is prompted to respond. Therefore, we selected an addictive obstacle game that requires constant user attention [29]. The participants were introduced to the three pulses before starting the game. Given the nature of the squeezing sensation and the fact that user perception decreases as the stimulus duration increases, we hypothesize that the staggered pulse will perform better.

10 participants (3 female, all right-handed, age 20-27, mean=24.5), different from earlier studies took part. Each participant did 2 trials for every duration and pulse combination. All trials were randomized. In total, we have 10 participants **x** 3 pulses **x** 2 durations **x** 2 trials = 120 trials.

Results

A two-way repeated measures ANOVA shows that the pulse type significantly affected accuracy ($F_{2,18} = 6.00$, $p<0.05$, $\eta_{partial}^2=0.4$) (Figure 10). Pairwise comparisons with Bonferroni correction show significant difference between Continuous and Staggered (mean diff=30%, p=0.039). While no effect of time or time*pulse was observed, higher 1min accuracy could be because participants were distracted and had more time (opportunities) to register what's happening with the ambient squeeze. Whether this effect continues for >1mins needs investigation as increments spread over longer durations might not be as easily perceivable.

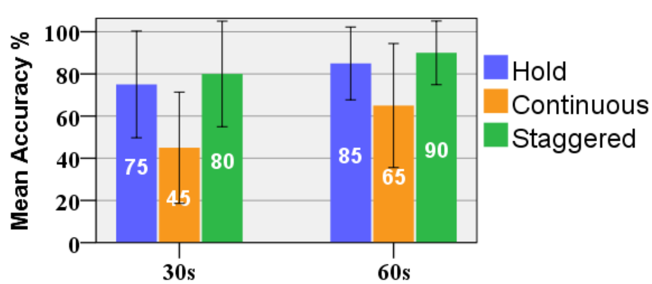


Figure 10: Mean Accuracy % for all three pulses for both durations. Continuous pulse is least accurate. [95% CI]

Participants successfully recognize Holding and Staggered pulses to reasonable accuracy, but expectedly, the Continuous pulse is not recognized well. Consequently, staggered pulses should be preferred for designing gradual progression. Deeper investigations into staggered pulses with different periodic increments will help expand it to larger time durations and optimize accuracy.

RingClench: HapticClench on a Finger

The small spring assembly can also be used on other body parts such as the finger. In addition to the obvious possibilities for squeezing multiple fingers, squeezing a finger is one of the most intimate ways for communicating emotions. No existing work has proposed finger squeezing feedback devices or studied squeezing sensations on the finger. We study the absolute detection threshold of miniature HapticClench prototype at the bottom of the ring finger (Figure 7). The spring is the same with a shorter length. We conducted the same abolute detection threshold study conucted earlier for the wrist with the same parameters and the same participants to draw a direct comparison. They participated 7 days after they completed the JND study. The mean threshold estimate came out to be 0.25kg (95% CI [0.18, 0.32]). This is higher than the wrist threshold.

DISCUSSION

Visual+Haptic Feedback: Squeezing Bracelets

So far we have talked about squeezing sensations in bands that are tight around the skin to begin with. We can also use HaptiClench's system to shrink loose bracelets that hang on the wrist. Figure 11 shows a faux-leather bracelet with the spring and circuit inside which shrinks from a loose grip to a tighter one. The circuit is the same as HapticClench. In this case, the user does not feel the force as much as they simply feel the material sticking to the skin. Since the restorative force of the skin is only enough to restore it to a less tight grip, the user simply pulls the bracelet to stretch it back to its loose form.

Figure 11: A loose bracelet squeezing into the skin

Such bracelets provide a visual+haptic stimulus which could be used for priority notifications that grab the user's attention. The visual component could be useful for providing socially meaningful notifications.

Design Guidelines for SMA Squeezing

Based on our design process, we suggest guidelines for designing squeezing sensations using SMAs – 1) Commercially available SMA wires do not provide enough load for satisfactory squeezing sensations and require a spring for restoration. SMA springs provide higher loads and do not require external restoration. 2) The actuation span, load capacity, and load throughput all have an effect on perception and must be fixed before designing the sensations. 3) SMA springs do not conform to a linear power vs load curve. The power-load curve should be derived for a particular spring type to make the design process simpler. The curve might be subject to fluctuations based on ambient temperature, overheating or physically extending the spring beyond its limits. 4) Thicker springs provide a very high load, but also consume and dissipate more energy and have higher cool down times. Thinner springs can provide loads that are comfortably detectable, consume & dissipate lower energy, and cool down quickly.

Design Guidelines for Squeezing Perception

Based on our studies, we suggest guidelines for the perceptual properties of squeezing hardware – 1) The detection (wrist: .16kg, ring: .25kg) and JND thresholds (95% JND: 1.79) from our study should hold for squeezing sensations with similar spans even if they are generated using other wires or motor-based mechanisms. These can be directly used to get a sense of a wrist squeezing device's perceptual capabilities. 5) Rings require a higher load than wristbands, implying a higher minimum power. 3) For application requiring multiple patterns, spatial patterns with three springs that remove the ambiguities of the middle sensation work well. Given reasonable JNDs, spatio-temporal patterns can also yield promising results. 4) For gradually increasing pulses, a staggered increase in load is more effective than a continuous increase. The step increases should be exponential in accordance with Weber's law. 5) However, spring temperature rises with time and needs to be guarded against, when designing longer duration pulses.

Limitations

As mentioned, SMA springs have increasing power and temperature constraints as the load requirement increases. The problem for continuous longer-duration actuations isn't the heated spring, but heat accumulation over time. For this, 1) a mechanism for gradual release needs to be devised. A holed insulation with a micro-fan can speed up this process. 2) Doing the actuation in smaller bursts rather than continued actuation will also accumulate less heat. Second, while the spring relaxes to its original length instantly, quick temporal pulses of a very high load are not possible because of higher cooling times. An easy workaround is to use multiple springs alternately to mirror repetitive actuation. Third, while the springs perform consistently in a controlled environment, we need more investigations to ensure they maintain their loads in the wild. Since Flexinol's contraction has a direct relationship with its temperature, a closed feedback loop with constant accurate temperature measurements would be most useful. This won't be trivial.

Future Work

We have touched upon some of the applications of squeezing sensations. However, in-depth investigations need to be carried out to see how squeezing sensation with or without using SMA fare for different use-cases. There are three specific areas where we intend to continue our work: 1) *Replicating human squeezing attributes*: One of the most intriguing applications is communication of human- generated squeezing sensations reliably. If a user uses their own hand to send a squeeze of a particular duration and intensity variation to a friend, can that be exactly replicated for the friend? This requires gathering accurate data from the first user and converting it into a stimulus from the device that takes into account the perception of the receiving user. 2) *Affective communication*: Squeezing sensations could be perfect for communicating different emotions, probably more so than vibrations. A reliable mapping of squeezing sensations to emotions could be very useful. 3) *Ambient awareness*: The SlowClench investigation suggests that squeezing could be useful for ambient temporal awareness. Deeper investigations into different contexts, tasks, and longer durations could shed more light on the capabilities of squeezing sensations for ambient use.

CONCLUSION

We investigated squeezing sensations using HapticClench, a system for generating squeezing SMA springs. To this end, we formalized squeezing feedback and its attributes. We described the design process of HapticClench and its load properties. We conducted psychophysical evaluations of squeezing using HapticClench that gave us the baseline detection thresholds for active and passive use, as well as the JND values. We further investigate different capabilities of HapticClench for gradual progression, spatial patterns, actuation on the finger, and squeezing loose bracelets to tighten onto the skin. We summarize by suggesting design guidelines for future squeezing investigations with and without SMA springs. Squeezing is one of the most intimate forms of human contact, but it has not seen much investigation in HCI. Our work intends to address that gap.

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