Touch me Gently: Recreating the Perception of Touch using a Shape-Memory Alloy Matrix

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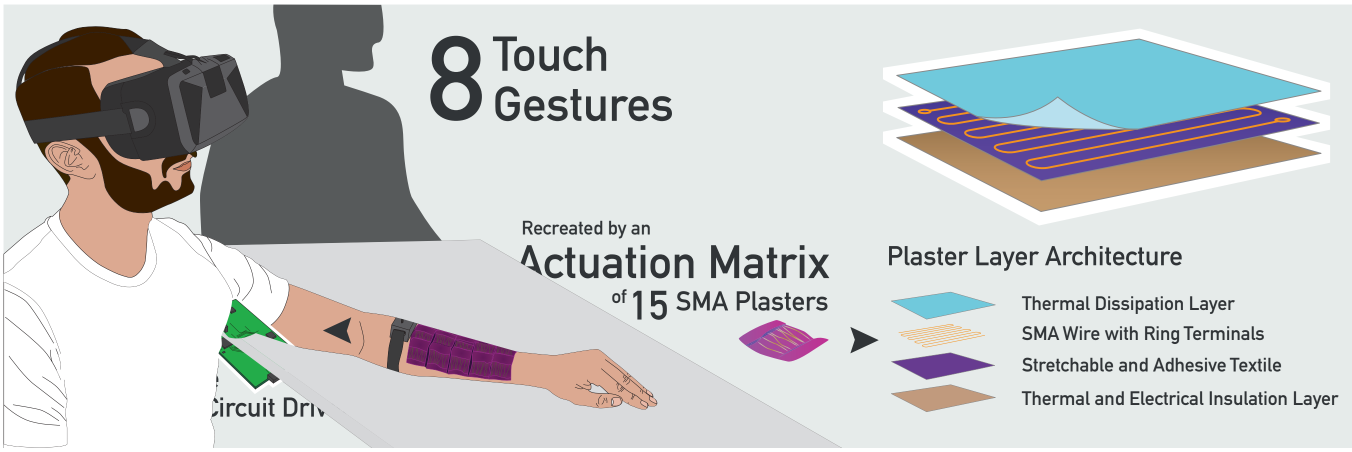

Figure 1. We recreated 8 touch gestures using a matrix built of 15 SMA-based plasters. Our plasters are sticking to the skin and incorporate several layers. Our wearable prototype is driven by a custom made PCB, which is fully mobile and independent from an external power supply.

ABSTRACT
We present a wearable forearm augmentation that enables the recreation of natural touch sensation by applying shear-forces onto the skin. In contrast to previous approaches, we arrange light-weight and stretchable 3×3cm plasters in a matrix onto the skin. Individual plasters were embedded with lines of shape-memory alloy (SMA) wires to generate shear-forces. Our design is informed by a series of studies investigating the perceptibility of different sizes, spacings, and attachments of plasters on the forearm. Our matrix arrangement enables the perception of touches, for instance, feeling ones wrist being grabbed or the arm being stroked. Users rated the recreated touch sensations as being fairly similar to a real touch (4.1/5). Even without a visual representation, users were able to correctly distinguish them with an overall accuracy of 94.75%. Finally, we explored two use cases showing how AR and VR could be empowered with experiencing recreated touch sensations on the forearm.

Author Keywords
Haptics; Pinching; Touch Perception; Recreation of Touch; Wearable; Shape Memory Alloys

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

INTRODUCTION
In HCI, tactile sensation has been extensively explored, such as to provide feedback to compliment auditory and visual channels [57, 64, 59], as well as for sensory substitution [53, 52, 50, 35]. Typical haptic feedback interfaces [16] deploy servomotors, solenoids, and vibration motors. Recently, more silent, light-weight, soft, and flexible haptic actuators entered the research field of wearable computing, particularly the use of shape memory alloys (SMA) [10, 22, 61]. Proposed designs include pressure feedback, such as creating squeezing sensations on the wrist and fingers. Using SMA, researchers investigated the perception and two-point-discrimination threshold for squeezing interfaces [22, 10], as well as user experience evaluation [61].

Building upon previous work like Springlets [23], we developed SMA-based plasters, which are light-weight and stretchable, creating shear forces similar to light pinches on the skin. The advantage of small plasters is that these can be individually distributed among different body parts, potentially covering a large area, such as the forearm. We derived the design of the plasters based on a series of studies. Particularly, we looked into the perception of different sizes, distances, and attachments of plasters on the forearm. We arranged 15 plasters with a size of 3×3cm in the form of a matrix on the forearm. This enables us to recreate the perception of touches, such as feeling the wrist being grabbed or the arm being stroked. These physical experiences are currently lacking in virtual environments. Recreating this experience can increase the feeling of immersion [21]. In summary, our contribution incorporates:

- an artifact creating various touch sensations on the forearm,
- an empirical evaluation informing the design rationale behind our SMA-based plaster matrix, and
- an exploration of two beneficial use cases.

RELATED WORK

Recreation of Touch

Following literature, the perception of touch includes sensing pressure [1, 60], vibration [32, 66], and textures [4, 15]. Four kinds of receptors within the skin allow such perceptions, the Pacinian corpuscles, Meissner's corpuscles, Merkel's disks, and the Ruffini endings [46]. In this work, we focus on recreating touch by exerting pressure. Pressure can be point-based [1, 38], planar-based [67, 68], and compression- / squeezing -based [60], such as around a body part. Independent to the type of touch sensation, commonly used technology includes servos and solenoids [60]. Using compression to create touch sensation primarily relies on pneumatic actuation [56].

Tapping and Stroking (Point- & Planar-based)

Previous work has explored touch actuation, such as tapping by converting servo rotation into linear motion [45]. Using a crank-slider linkage, Stanley et al. [60] implemented a skin dragger to provide touch sensations by applying shear forces utilizing two servo motors. The main drawback is the bulky mechanical design. A few other works recreated touch feedback by deforming the skin's surface through providing tangential shear forces using servos [19]. Using servo motors, shear forces can also be used to create skin stretch sensations [2]. While these approaches can create touch sensations, they are too bulky to use in daily wearables. Skin Drag Display [31] and tactoRing [33] integrated technology into a watch and ring prototype to overcome such issues. Although these designs create a powerful user experience, the mechanical actuators generate noticeable noise, making them rather obtrusive. A possible solution is Tacttoo [65], an electro-tactile feedback layer on the user's skin. Still, a large scale matrix to mimic complex touch gesture has yet to be demonstrated.

Squeezing (Around the Arm & Finger)

Squeezing is typically implemented by using pneumatic actuation, which for instance inflates air into a cuff around the wrist. Previous research has found squeezing feedback as feeling more organic than tapping or dragging [5]. Several works have used blood pressure cuffs to compress hands as a sensory replacement for prosthetics [51, 62]. Researchers also investigated the psycho-physical properties of pressure feedback using pneumatic air compressionand derived general findings on the user's perception threshold [47, 56]. Several other studies explored squeezing actuation using servo motors that loosen and tighten bands [5, 11, 9, 14]. These arm augmentations usually do not aim to recreate touch, but to convey alternative ways for tactile speech communication [14, 58].

In summary, it is apparent that the majority of interfaces aiming to recreate touch feedback rely on mechanical actuators, such as servo motors or solenoids. Integrating these into wearables result in an increased and obtrusive form factor, as noticeable noises from gear friction and vibrations occur. Moreover, a smooth transition between tapping, stroking, and squeezing has not been demonstrated yet. However, very recently, Matthies et al. [45] demonstrated scaling the current of EMS feedback and thus created a smooth transition between tickling to tingling and squeezing sensations. However, driving a current through the body may raise ethical and safety concerns. There have been few attempts to circumvent and overcome such limitations by using soft haptic actuators, which utilize soft robotic materials, such as SMA.

Shape-Memory Alloys (SMA)

Shape-Memory Alloys, Soft Elastomers, Morphing Polymers etc. belong to the state-of-the-art [8] in the rising field of soft robotics [41]. SMA demonstrate a high efficiency in terms of large-amplitude (non-linear) actuation, as they are usually produced in the form of a wire [30]. SMA are extremely reduced in size and weight. The Power-to-Weight ratio makes SMA highly useful in small-scale soft robotics [37]. For instance, milli-size walking robots [28], miniature artificial fingers [27], models of musculoskeletal systems of humans, are some popular examples of SMA-based soft robotics [37].

Haptic Feedback

Suhonen et al [61] conducted one of the earliest explorations using SMA to provide haptic feedback. They implemented a wrist-worn squeeze feedback system for interpersonal communication, in particular, to share emotional feelings with one another. Their findings indicate that, in comparison to vibrotactile and thermal feedback, squeezing feedback may be more pleasant for communicating feelings. In another research called HapticClench [22], a wrist-worn squeeze feedback system was developed using SMA springs. The authors report psycho-physical characteristics of the system including absolute detection and JND thresholds. Other work, such as Tickler [40] provides natural stroking sensations by actuating an array of parallel bars using SMA. Similarly, Cherynshov et al. [10] implemented several other SMA wearable prototypes, which also provide squeezing sensation. They present insights focusing on the use of the material. Literature already demonstrated relatively straightforward implementations of SMA into a ring and wristband. Methods to scale squeezing or shear forces using SMA onto various body parts remained unclear, until recently. A recently published solution, Springlets [23], proposes the use of a flexible SMA spring-wire sticker, where the authors extensively explored 6 sensations by actuating a single plaster at different body positions. A challenge we faced was to recreate the perception of human touch on the skin by an arrangement of multiple plasters, with each plaster having limited force and deformation generated by SMA wire integration. Also, we introduced a custom-made PCB to manage power and drive multiple SMA wires.

Haptics in Virtual Reality (VR)

Mimicking realistic haptic user feedback is a significant trend and challenge in VR [44]. Several research prototypes [12], as well as commercially available wearables [6, 24], aim to provide haptic experiences in a virtual environment. Haptic gloves have remained popular in research for decades [17, 12, 7, 26]. Meanwhile, commercial products, such as Haptx [24] and Plexus [55], demonstrate rich haptic feedback sensations

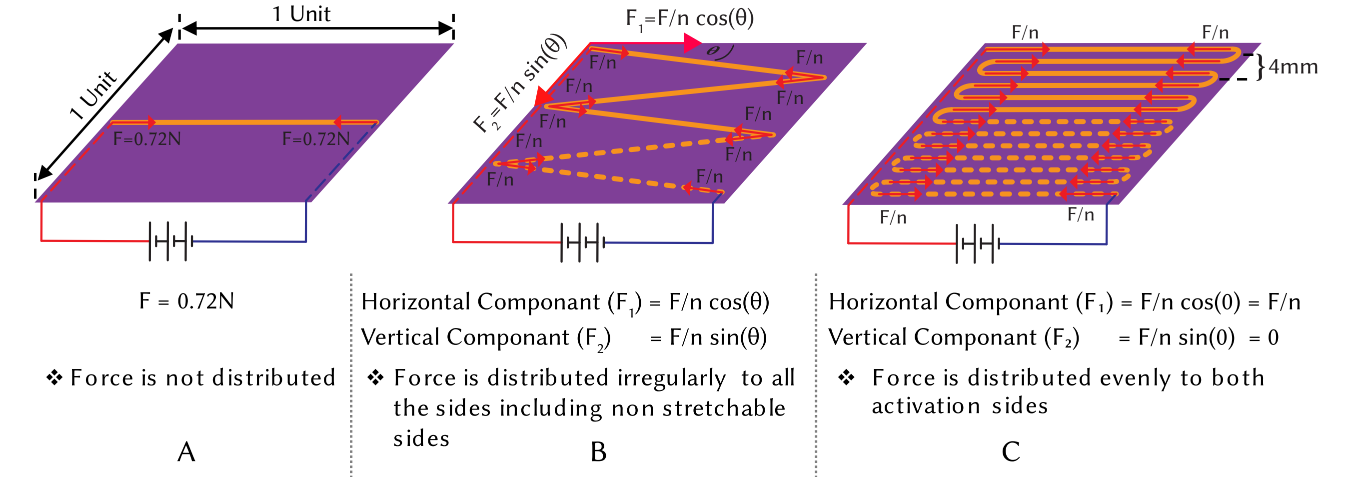


Figure 2. A) Simplest wire layout where force is not distributed evenly and acts at two opposing points. B) To distribute force evenly on a larger area, SMA wires should attach in a zig-zag manner. However, the angle of SMA wires will distribute some force in a perpendicular non-stretchable direction, which results in an irregular contraction C) To distribute force in a single direction, the gap between sewing pattern should be as close as possible, and parallel to the stretching direction of the textile.

to our fingers and hands. Although they created a sensation of perceiving textures, shapes, and motions of virtual objects, the bulky mechanical designs is obtrusive and inapplicable for a mobile interaction context. Recently, Pittera et al. [54] investigated ways to improve VR experiences by creating tactile sensations at the hand using mid-air tactile stimulation with a stationary device. In another recent work, Lee et al. [43] attached vibrotactile motors to a VR controller to recreate haptic perceptions, specifically the sensation of squeezing and shearing an object. Beyond feedback at the hand, a full-body haptic suit deploying electrical muscle stimulation (EMS) is already commercially available [63]. However, driving an external current through our body may not be preferable for many users.

TOUCH ME GENTLY

The motivation of this paper is to explore the capabilities of SMA technology in recreating the perception of a touch sensation on the forearm (e.g., gentle touch, caressing, clenching, or tapping). As elaborated in previous sections, research has already demonstrated the ability of using SMA to create a pinching sensation [23] or the perception of an arm and finger being squeezed [22, 10]. Yet, it remains unclear how SMA can be utilized to create more complex touch sensations. In

Figure 3. We recreate the perception of a human touch using plasters that stimulate the skin with shear forces. Here, the user is experiencing the touch of another's hand on his arm.

our work, we aim to recreate natural touches that appear to be initiated by another person, with the goal to enrich VR and AR experiences. To possibly create these touches, we determined SMA as the technology of choice, given its many advantages. SMA offer large-amplitude actuation, are flexible/bendable, can be integrated with fabrics, and is demonstrably lighter in weight. The greatest limitations of SMA is the actuation delay. Still, SMA are predestined to be used in wearable computing. Therefore, we aimed to explore an SMA wire-based actuation as opposed to conducting a psychophysical study of comparing with different methods, such as voice coils or pneumatic actuators. Regarding the actuation principle, SMA has two distinct crystal structures: martensite in lower temperatures and austenite in higher temperatures. When heating the SMA from martensite to austenite, such as by applying an electrical current, it reverts to its original form, such as from a long to a short wire, like in our case.

Based on the two-point-discrimination of haptic perception on the epidermis, we decided to design small plasters. The single plaster can apply a shear force on the skin, which creates a subtle pressure. Small plasters have the advantage of being individually distributed among different body parts, potentially covering a large area, such as the forearm. Informed by a series of studies, we arranged 15 plasters with a size of 3×3cm in form of a matrix on the forearm *(see Figure 3)*, which enabled us to create the perception of different types of touches. However, fine-grained touches, such as pinching and twisting is limited with our design. Based on technical constraints and previous works related to forearm augmentation for social interactions [13, 25, 29], we decided to recreate 8 types of touch patterns (*see Figure 13*):

1. Grabbing the arm (GA),
2. Grabbing the wrist (GW),
3. Three taps down the arm (TTD),
4. Three taps up the arm (TTU),
5. Stroking down the arm (SD),
6. Stroking up the arm (SU),
7. Encircling / rolling on the arm (RA),
8. Encircling / rolling on the wrist (RW).

IMPLEMENTATION

SMA Wire

For our prototype, we selected the SMA wire: BMF150 SMA. According to the datasheet, this wire contracts to a predefined length when heated up to 70°C. This contraction is 4% of the total length of the wire and can be used to apply a force equivalent to 1.44N, when the recommended current of 340mA is applied. Increasing the voltage from 20.7 V/m on-wards heats up the wire thus changing the wire length.

Plaster Design

The ability of SMA wires to contract enables a variety of actuation possibilities. We stitched the wire into a sticky cloth patch (Kinesiology Muscle Tape), which generates shear forces along the skin, as shown in *Figure 7*. The shear forces subtly deform the skin and hence is interpreted as a touch sensation.

Wire Layout

The simplest way of attaching a SMA wire to a unit size plaster is attaching a single unit size wire across the bit *(see Figure 2A)*. It will provide 0.72N of shear force if we assume it contracts from both sides. However, this force is distributed unevenly and only acts at two opposing points. To distribute the force more evenly, we can attach a SMA wire in a zig-zag manner, as seen in *Figure 2B*. However, the angle of the SMA wire will also distribute some force in a perpendicular direction. This will cause irregular contractions since the used textile is stretchable in only one direction. Therefore, to distribute force in a single direction, the gap between the sewing pattern should be as close as possible and in parallel to the stretching direction of the textile, such as shown in *Figure 2C*. After conducting a few preliminary experiments, we identified that the gap size should be around 4mm to get wires parallel to the stretching direction. Moreover, attaching wires in a minimum gap size distributes the contracting force, and thus the actuation speed slows down due to an increased SMA wire length.

Layer Architecture

The plasters are designed with a layer architecture as shown in *Figure 1* and *Figure 4*. The carrying layer is a Kinesiology Muscle Tape, on which we stitched the SMA wire (BioMetal Fibre - BMF150). Between the carrying layer and the skin, we use a thin stretchable Polyetheretheketone layer (PEEK film 25 microns) that insulates the skin from any thermal and electrical contact. Given the operating temperature of an SMA wire can reach a maximum of 70°C, this layer is also important for safety reasons. We measured that the thermal and electrical insulation layer is heated only by 1°C - 2°C during activation time, which is typically 1s per one patch. The top facing layer is a stretchable thermal dissipation layer from BERGQUIST, which accommodates a higher thermal conductivity between the SMA wire and the air. Our plaster's surface temperature can raise up to 50°C after actuating the SMA by 3s. The Thermal Dissipation Layer would reduce the surface's temperature to 37°C. We employ a passive cooling by waiting 2s, which provides a sufficient cool-down to restore the wire's shape. The calculated delay is 1.33s assuming passive cooling allows 50% of the maximum elongation rate.

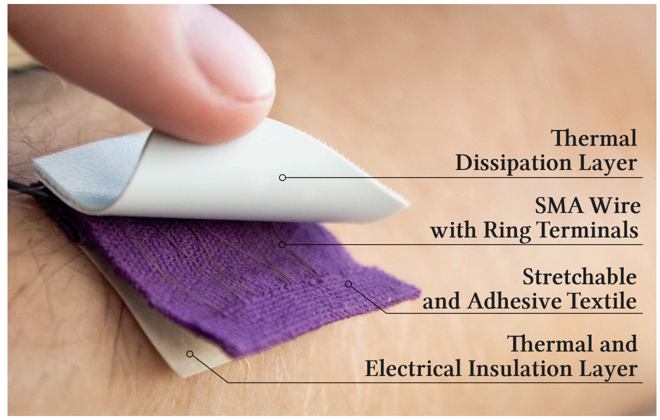


Figure 4. Thermal Dissipation Layer, Kinesio-tape Textile Layer at which we manually stitched SMA wires to, and the Thermal and Electrical Insulation Layer insulating the skin from current and heat. The Textile Layer has two opposing protruding edges that stick to the skin.

Hardware Driver

To drive the SMA matrix, we designed a custom PCB based on a DSPIC33CH64MP202T micro-controller, which can control eight actuator bits independently. To accomplish this, we used two ULN2003F12FN-7 Darlington arrays, which can drive up to four channels each. A single transistor pair can provide up to 500mA at 20V. An individual fully configurable PWM signal generated by the MCU controls each gate. In the circuit, there is also a single channel BTS3080EJXUMA1 power switch that can drive up to 10A. This switch was envisioned to power Nitinol wires capable of sustaining a heavy load, although it was not used in the final version of this research. The SMA driver is powered by a 3.7V Lithium battery, capable of sustaining a continuous discharge current of 7A. A battery protection circuit based on the BQ29700DSER integrated was devised to avoid potential damage to the cell due to over voltage or over current conditions. To drive the SMA, we incorporated voltage regulators and voltage step-ups, one to power the MCU, one for each of the Darlington arrays to alleviate the current load, and one dedicated to driving the high current power switch. Finally, there is an FT230XQ-R FTDI USB interface to easily program the driver through a computer or mobile phone. The PCB dimensions are 55×35mm, with an 18350 Lithium-Ion cell battery used.

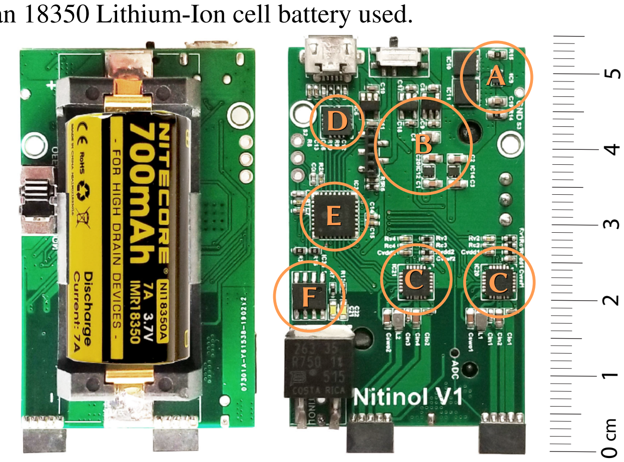


Figure 5. Custom-made driver Circuit which consists of: A) Lithium Battery Controller, B) Voltage Regulators, C) Darlington Arrays, D) USB Interface FT230XQ-R, E) MCU DSPIC33CH64MP202T, F) High Current Power Switch BTS3080EJXUMA1

EVALUATION

Our evaluation comprises of 4 studies. In study 1, we identify the optimum plaster size in a way that it maximizes the perceptual accuracy, given technical and safety constraints. In study 2, we identified the minimum distance we should maintain between two plasters to achieve unambiguous discrimination of touches. Then, we evaluated different types of skin attachments in study 3. In study 4, we evaluated how realistic the participants perceived the recreated touch sensations, as well as how accurately the users can distinguish them. After this evaluation, we implemented two use case scenarios.

Study 1: Plaster Dimension

To find out how users would perceive different plaster sizes, we fabricated five plasters in different dimensions *(Figure 6)*. As we are working with the maximum current recommended, other variables such as force, speed, and acceleration will vary slightly across plaster sizes.

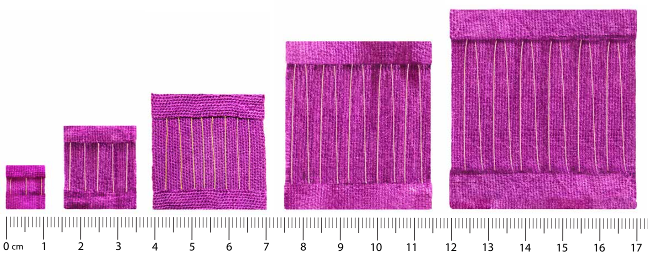


Figure 6. We evaluated the perception of the following plaster sizes: #1: 1×1cm, #2: 2×2cm, #3: 3×3cm, #4: 4×4cm, and #5: 5×5cm.

Study Design

We followed standard procedures including filling a consent form, collecting demographic data, and explaining the study. Then, we applied a plaster to the participant's forearm, one at a time,. We evaluated all five sizes in two different orientations *(see Figure 7)*. We covered the arm with a paper carton to ensure that the participant's visual perception is not cross-talking with their haptic perception.

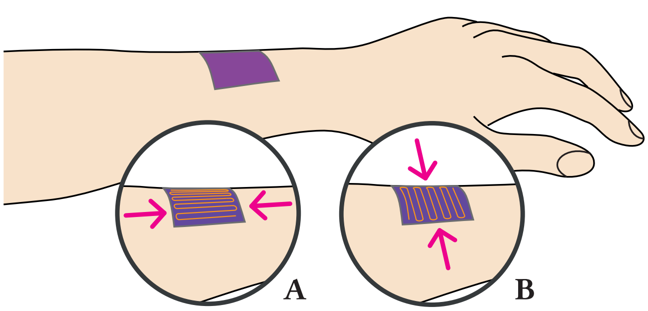


Figure 7. Actuating the SMA wires of the plasters generates shear forces on the skin. We evaluated two orientations in our study.

We developed a Java interface, in which the participant could independently initiate the actuation. The participant had to perform this action in 20 trials × 5 plaster sizes × 2 orientations. However, only in half of the cases, the plaster was actually activated. For each trial, the participants indicated whether they felt the sensation. The sequences, such as the order and orientation of the plasters tested, were fully counterbalanced.

We recruited 10 participants (7 males and 3 females) aged between 21 and 37 years ($M = 26.8$, $SD = 5.55$).

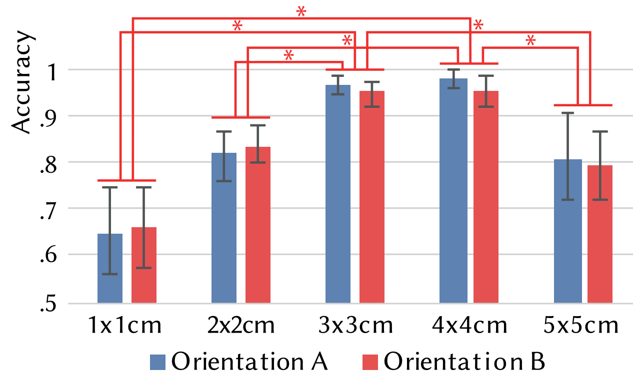


Figure 8. Perception accuracy of 5 sizes in 2 orientations. The size of 3×3cm provides a reasonable accuracy of 96% and 95% for two orientations. (Error bars indicate the 95% confidence interval)

Results

No false-positives were reported for any of the conditions. A two-way ANOVA showed that there was no main effect from orientation for the identification accuracy ($F_{1,90} = 0.064$, $p > .05$) – *see Figure 8*. However, there was a main effect for identification accuracy due to sizes ($F_{4,90} = 33.267$, $p < .0001$). A Tukey's HSD revealed the plaster sized 1×1cm had the lowest perceivability among all sizes. Furthermore, the 2×2cm plaster was perceived worse than the 3×3cm and 4×4cm plaster. The plasters 3×3cm and 4×4cm were not significantly different from each other, however, both were significantly different from all other plasters. Both 3×3cm and 4×4cm plasters demonstrated the highest identification accuracy. In addition, we observed that the identification accuracy reached a maximum at 4×4cm and then dropped for the size of 5×5cm. A possible explanation may be the slower actuation speed due to the increased SMA wire length that was required for the largest plaster. We selected the smallest from those two sizes (3×3cm) for further investigation.

Study 2: Plaster Spacing

In this study, we investigated how the users would perceive different distances between plasters. As there were non-significant accuracy differences with orientation in the previous study, we did not anticipate such differences with spacing.

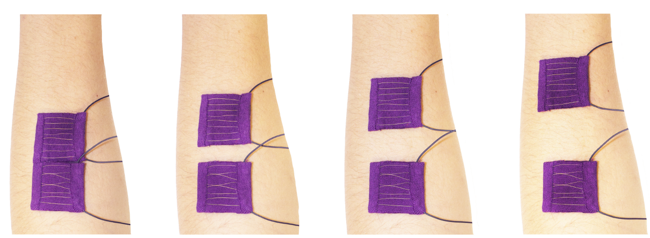


Figure 9. We assessed the perception of 4 distances between two plasters on the arm of the participants: 0cm, 1cm, 2cm, and 3cm respectively.

Study Design

We followed the same standard procedures as per study 1. We then attached two (3×3cm) sized plasters to the left forearm of the participants *(see Figure 9)*. We tested four conditions, in which the distance of the plasters increased by 1cm starting from 0cm up to 3cm. Similar to the previous study, the arm was covered by a paper carton to ensure that the participant's visual perception does not interfere with their haptic perception.

We had 20 trials in total, from which 10 times plaster A and 10 times plaster B was actuated in a mixed, but counterbalanced manner. Immediately after the actuation, participants had to identify the actuated plaster. We provided a Java-interface, in which the participant entered their response independently. In total, each participant generated 20 trials $\times$ 4 distances.

We recruited 10 participants (7 males and 3 females) aged between 21 and 37 years ($M = 28.3$, $SD = 4.42$)

Results

As seen in *Figure 10*, the perception accuracy in distinguishing two patches increases gradually with distance. A statistical main effect was also observed ($F_{3,36} = 15.22$, $p < .0001$) and Tukey's HSD test revealed that the differences between 0cm and 3cm distances, 1cm and 3cm distances, as well as 2cm and 3cm distances, were all statistically significant.

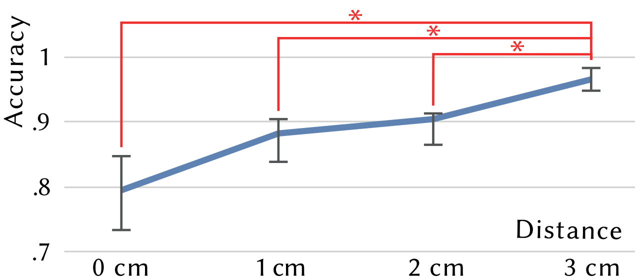


Figure 10. Discrimination accuracy using the 3×3 plaster with respect to four distances: 0cm, 1cm, 2cm, 3cm. Results appear to be in line with the two-point-discrimination of vibro-tactile perception [36, 39] (Error bars indicate the 95% confidence interval)

Study 3: Plaster Attachment

Based on the qualitative feedback throughout our studies, our design appeared to have a practical drawback, as users commented on experiencing discomfort when removing the sticky plasters from the forearm. Therefore, we introduced two non-adhesive solutions, placing a silicone layer (*3M VHB silicone tape*) and a nano-material layer (*NanoGripTech*) to the sticky adhesive layer that used to touch the skin.

Both the silicone layer and the nano material layer fulfil a similar purpose, namely to prevent the plaster from slipping off the skin. However, to prevent the plasters from falling off

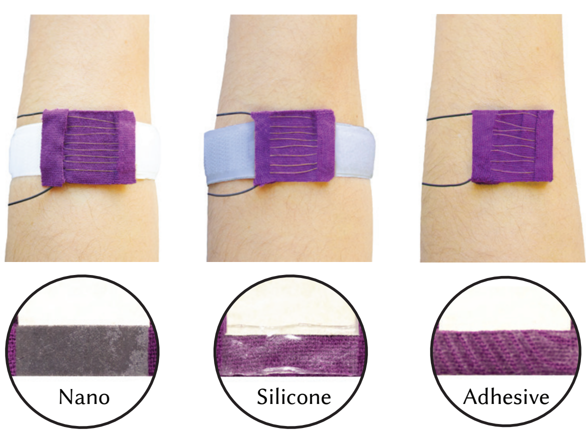


Figure 11. We evaluated three types of skin attachments placed under each plaster: Nano material, Silicone, and the adhesive sticker. To ensure that the plaster remains on the skin, the nano material layer and silicone layer plasters were sewed with velcro tapes surrounding the arm.

during arm movements, we sewed them together with a velcro tape (*see Figure 11*), which also enables quick installation on the user's arm. The purpose of this study was to investigate whether our new designs impacted upon perception accuracy.

Study Design

We applied an armband, incorporating a single 3×3cm plaster on the participant's forearm. Similar to study 1, we covered the participants forearm with a paper carton to eliminate interference with the participant's visual perception. We then randomly activated the plaster (10 of 20 times) and asked the participant to identify whether he or she perceived an actuation. We used the same Java-based interface developed for study 1. We repeated the experiment with both the nanomaterial and silicone pad and compared the results to those the adhesive sticker pad from study 1 gathered (*see Figure 12*).

We recruited 10 participants (8 males and 2 females) aged between 22 and 29 years ($M = 25.4$, $SD = 2.12$).

Results

A one-way ANOVA showed a main effect for the attachment type based on its identification accuracy ($F_{2,29} = 11.76$, $p < .0001$) - *see Figure 12*. A Tukey's HSD revealed the nano pad ($M = 0.78$, $SD = 0.11$) yielded the lowest identification accuracy among all three conditions. The silicone pad ($M = 0.92$, $SD = 0.08$) and the adhesive sticker ($M = 0.95$, $SD = 0.04$) were significantly better than the nano pad. In comparison to the adhesive sticker, the silicone pad's mean accuracy is slightly lower. However, this effect is not statistically significant ($p = 0.386$). Although having a slightly lower accuracy, the silicone pad is a reasonable trade-off, given its increased comfort in terms of wearability.

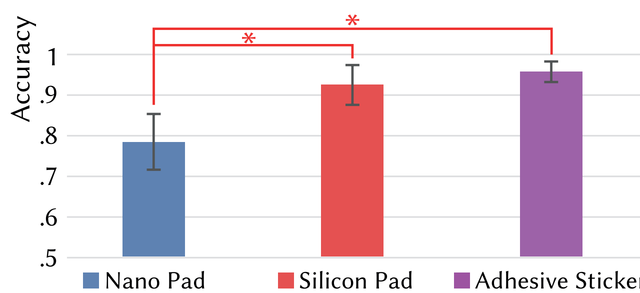
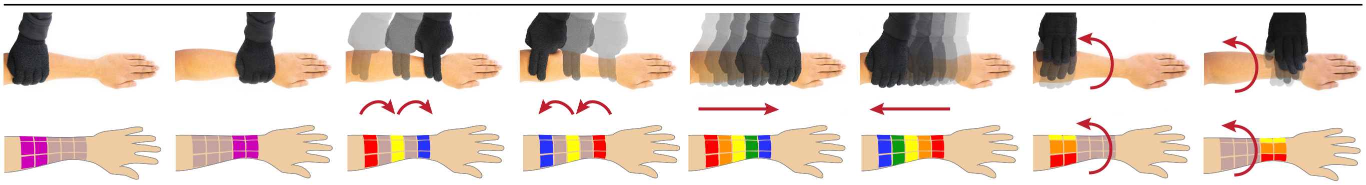


Figure 12. Identification accuracy of skin attachments: The nano pad achieved significantly lower accuracy than the silicone pad, as well as the adhesive layer. (Error bars indicate the 95% confidence interval)

Study 4: Touch Perception

In previous studies, we identified the size of 3×3cm as an optimal plaster size for our particular setup. We learned that to create distinguishable taps, plasters should be placed 3cm away from each other. Moreover, we explored more practical plaster setups that increase comfort in terms of wearability. Silicone pads showed only minimal, but non-significantly different results for the detection of stimuli. The aim of this study was to evaluate if gentle touch sensations can be recreated using a matrix of plasters. We arranged 15 plasters without gaps in a 5 (rows) × 3 (columns) matrix. We tested both designs (A) the adhesive stickers – our performance reference and (B) a silicone pad sleeve with higher wearing comfort *(Figure 14)*.



		GA	GW	TTD	TTU	SD	SU	RA	RW
Design A	*Subjectively rated perceived realism*	**4.1**/5	**3.8**/5	**4**/5	**4.5/5**	**4.3**/5	**3.9**/5	**3.7**/5	**4.3**/5
Design A	*Accuracy of correctly identified touches*	**92%**	**98%**	**88%**	**96%**	**96%**	**98%**	**90%**	**100%**
Design B	*Subjectively rated perceived realism*	**3.9**/5	**3.7**/5	**3.5**/5	**3.6/5**	**4.4**/5	**4.7**/5	**3.7**/5	**3.7**/5
Design B	*Accuracy of correctly identified touches*	**88%**	**86%**	**84%**	**88%**	**84%**	**86%**	**92%**	**90%**

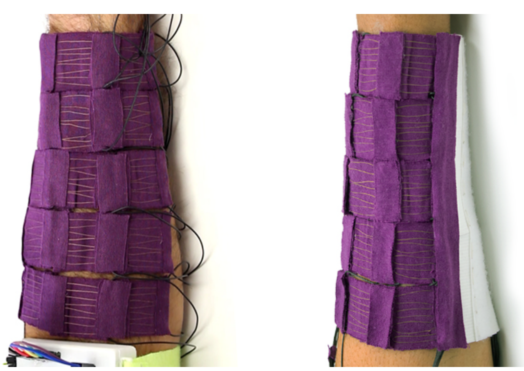
Figure 13. We recreated 8 touches (GA - Grabbing the arm, GW - Grabbing the wrist, TTD - Three taps down the arm, TTU - Three taps up the arm, SD - Stroking down the arm, SU - Stroking up the arm, RA - Encircling / rolling on the arm, RW - Encircling / rolling on the wrist) with Design A (individually attached adhesive plaster matrix) and Design B (sleeve with Silicone pads). To recreate these touch patterns, we actuated the plasters with different timings: 0-1s, 0.6-1.6s, 1.2-2.2s, 1.8-2.8s, 2.4-3.4s, 0-2s. Users had to rate the perceived realism of the recreated touch on a 5-point Likert scale. Also, we measured how well the user could identify the recreated touch sensations without any visual representation.

Study Design

We instrumented the participants' left forearm with the plaster matrix and asked them to lay their arm down on the desk in front. In a between subject study, one group tested Design A, with plasters individually attached to the forearm, while another group tested Design B, which included a prepared plaster sleeve using silicone pads.

Independent from the prototype tested, the study design consisted of two parts. In the first part, the participant learned about 8 touch patterns as listed earlier in section *Touch me Gently*. For each touch gesture, we designed an individual actuation pattern lasting between 1s and 3s. We discovered that such margins closely mimic a real touch sensation. We recorded 8 videos from the same angle showing a left arm being stroked and touched with 8 patterns by a strangers hand wearing a black glove (*see Figure 13*) using an Oculus Rift.

At the same time, we activated a predefined actuation pattern synchronously, simulating a touch sensation on his forearm. In a random order, we presented each touch gesture three times. After each trial, we asked the participant to report on a 5-point Likert scale (1: unreal, 5: very real) how realistic the recreated touches felt. In the second part of the study, we randomly provided one of the 8 touch patterns 5 times without providing any visual stimulus. The participant was asked to identify which touch gesture he perceived. Based on these results, we calculated the accuracy of correctly identified touches.



Design A
(Adhesive Plaster Matrix)

Design B
(Silicone Pad Arm-Sleeve)

Figure 14. We evaluated two designs augmenting the forearm using 15 plasters. Design A: plaster matrix with adhesive attachment. Design B: plaster matrix with Silicone pads attachment.

We recruited 10 participants (6 males and 4 females) aged between 22 and 32 years (M = 26.3, SD = 2.87) testing Design A. Design B was tested by 10 participants (8 males and 2 females) aged between 19 and 27 years (M = 23.7, SD = 2.31).

Results

Subjectively rated perceived realism: All touch gestures were perceived to be fairly real *(see Figure 13)*. On average, the perceived realism of the recreated touches was rated M = 4.07 (SD = .27) using Design A across all users. The perceived realism of Design B was rated as M = 3.9 (SD = .42), which is slightly lower than Design A, although an independent t-Test did not show significant differences (t = .98, p > .05). For Design A, a one-way ANOVA for independent samples ($F_{7,72}$ = 1.24, p > .5) did not indicate a main effect between all 8 touch patterns in terms of realism. Therefore, no particular touch pattern was perceived significantly more realistic or unrealistic. However, in Design B, a one-way ANOVA for independent samples indeed showed a main effect ($F_{7,72}$ = 3.75, p < .01). A post-hoc analysis using Tukey's HSD found the gesture *TTD - three taps down* to be perceived significantly less realistic than other gestures, such as *SU - stroke up*, *SD - stroke down*, and *GA - grab arm*.

Accuracy of correctly identified touches: For Design A, users were able to correctly identify all 8 touch patterns with an overall accuracy of M = 94.75% (SD = 4.27%). The accuracy was significantly lower with Design B (M = 87.25%, SD = 2.82%), which an independent t-Test confirmed (t = 4.15, p < .01). The discrimination accuracy for *TTD - three taps down* yielded the lowest accuracy in each of the designs (A: 88% and B: 84%). We observed that it was confused with the *SD - stroke down* gesture. The confusion could be due to the *"cutaneous rabbit illusion"* [18, 48, 42], where steady hopping taps on the arm is perceived as continuous stroking. One of the participants (P3) during study 4 also mentioned such an effect. The touch patterns *GW - Grab Wrist* (98%), *SU - Stroking up the arm* (98%), and *RW - Encircling / Rolling Wrist* (100%) resulted in the highest identification accuracy in Design A. However, a one-way ANOVA for independent samples ($F_{7,72}$ = 1.79, $p > .05$) and ($F_{7,72}$ = 0.43, $p > .05$) did not show a main effect for the accuracy of perceiving touch gestures for Design A and Design B. More details can be seen in the generated confusion matrix *(see Video Figure)*.

Furthermore, participants expressed their amazement as follows: *"Am I imagining this sensation or not?"*, *"Wow, this is like someone touches me"*, *"It feels more real, once it is synchronized with the visual [representation]"*. Another participant said *"I feel this sensation is located somewhere between pinching and stroking"* emphasising on the strong perception. All participants expressed interest towards our project.

USE CASE DEMONSTRATION

To demonstrate the usefulness of a natural touch sensation on the forearm, we developed two use cases: (1) Augmented Reality (AR) application: learning correct Cricket batting, and (2) Virtual Reality (VR) application: immersive surgery training. We selected these use cases at which we can deploy a controlled delay of the visual stimulus to match the actuation.

AR App: Learning Correct Cricket Batting

In our first example, we show how this technique of touch recreation can be employed in a sports context. We selected a cricket training scenario and built an indoor AR stadium. Cricket is considered as a complex sport that requires a significant amount of effort to learn. Particularly when batting, the gripping force and orientation of the cricket bat (*bat-lift-angle*) plays an important role in performance. Prior work, such as CricketCoach [49] has shown that vibrotactile feedback at the wrist visualizing the actual gripping force can be useful to increase the confidence of a beginner cricket batter during training. When learning how angle the bat correctly, the coach would touch the user's forearm tilting the bat into a correct orientation.

Figure 15. A participant receives guiding feedback via an arm-guard, augmented to receive natural touch sensations.

We can recreate these touch sensations on the forearm to provide guiding feedback by seamlessly applying this technique on sports gear, such as cricket arm-guards *(see Figure 15)*. We invited 5 participants (1 female, 4 males) aged between 23 and 29 (M = 26.4, SD = 2.19) to perform a cricket batting stroke session *(see Figure 15)*. The orientation of the bat was sensed using an Inertial Measurement Unit (*MPU 9250*), and depending on the orientation of the bat, we provided feedback to the users through the augmented arm-guard. We employed *SU - stroke up*, *SD - stroke down*, and *RW - rolling wrist* to provide guidance to lift the bat up, lower the bat down, and rotate the bat inward and outward. All participants were beginners and learned using this method to execute the correct batting strokes. The participants indicated that the overall system successfully assisted them without catching much attention to complete the expected task properly.

VR App: Immersive Surgery Training

One of the most common ways of training a medical student is to first observe expert surgeons in practice and then progressively perform the surgical methods under different levels of supervision [3]. With the advancement of technology associated with medical devices, VR-based training simulators, such as virtual surgical operations are becoming increasingly popular due to the high availability and the re-usability [34]. These immersive VR trainings are deemed to prepare the candidate for challenging real cases.

Figure 16. A participant interacts with a medical-surgical training simulation, enhanced with additional feedback provided on the forearm.

To demonstrate the usefulness of our system, we connected the system with a VR medical training application developed using a *Samsung HMD Odyssey mixed reality headset*. The users were asked to control a cutting tool during a surgery *(see Figure 16)*. We conducted a pilot study with 5 participants (2 females, 3 males) aged between 23 and 30 (M = 27.2, SD = 2.68). Initial instructions about the task were given to the participants prior the study. A virtual surgeon provided real-time guidance on handling the cutting tool by touching and guiding the participant's arm. We applied our prototype on the participant's dominant hand (i.e. the hand at which the cutting tool was held). Orientation, position, and speed of the device were assisted using a virtual avatar, and in each touch gesture, we activated the prototype accordingly. To guide the participant's hand, we applied *RA - rolling arm*, *RW - rolling wrist*, *SU - stroke up*, *SD - stroke down* on the participant's forearm. In conclusion, each participant stated the touch sensations as feeling natural, as well as recognisable, enabling them to complete the intended operation successfully. All participants obviously enjoyed the actual feeling of how the touch gestures blended with VR.

DISCUSSION

Summary of Key Insights

Previous work, such as in HapticClench [22], Gupta et al. provided design guidelines for SMA squeezing feedback, particularly at the wrist and finger. Some of those guidelines were also considered in our design. We complemented previous work with the following suggestions, specifically targeting SMA-based actuation feedback.

1. *SMA Wire Selection:* Commercially available thin SMA wires (such as BMF 150) provide high flexibility and are easy to attach to a textile. SMA wires also have a limited actuation load and identifying the correct size and wire arrangement for the desired design is essential.

2. *Type of Textile:* In our pilots, we tested several textiles and finally identified that stretchable adhesive textiles (e.g., kinesiology tape) should preferably be used as a base layer when planning to properly attach SMA wires to the body.

3. *Interfacing with our Skin:* The kinesiology tape has an adhesive sticky layer, which helps to transfer actuation shear forces to the skin. However, removing the plaster from the skin can result in discomfort. An alternative is using a silicon pad, which is non-slippery on our skin. Although the sensation is slightly lower, this could be worth the trade-off depending on the use case.

4. *Shape, Size, Actuation time vs. Perception:* The actuation time is dependent on the SMA wire length if using the recommended current. Therefore, it is important to identify the optimum size of an actuation bit / plaster for a selected shape and SMA wire arrangement. This can be done by a user perception study as presented. In our study, we focused on square shaped plasters and found the optimum size to be 3×3cm on the forearm. This may vary for other body parts.

5. *Cooling and Restoration:* To increase the cooling speed, we propose a heat dissipation layer at the top of the plaster. We used a thermal dissipation layer from BERGQUIS and laser cut patterns into it to make the material stretchable as well. Also, we found that the skin's restoration force was sufficient to restore the SMA wire to its initial shape.

6. *Creating Complex Sensations:* There are different types of sensations we can create with SMA springs, such as pinching, directional stretching, pressing, pulling, dragging, and expanding, as Hamdan et al. [23] pointed out. In contrast, wires are less bulky, more flexible, and thus can be seamlessly integrated into textiles [20] and wearables, as they can also create shear forces that usually propagate unidirectionally. Arranging a matrix of plasters can provide more complex sensations. Furthermore, we could observe that these pixels (plasters) should not connect at the attachment layer to reduce interference.

Limitations and Future Directions

Active Cooling and Heating

Currently, the design dissipates heat via air cooling plus a heat dissipation layer, which is also necessary to avoid burning the user. The heat dissipation layer can reduce the surface temperature from around 70°C to 40°C, which does not create any danger for users. Currently, the system is not actively monitoring the temperature level. We envision an integrated thermal sensor for monitoring and tiny peltier elements for active cooling. This enables a close-loop system with a temperature feedback controlling the wire's current.

Perceivable Warmth

Depending on the thermal protection, the user may perceive an increased warmth on their skin. Our thermal protection layer was heated up by 1°C - 2°C during actuation. Although improved insulation can overcome this limitation, our thermal protection layer also has positives. In fact, a touch by hands is usually perceived as a warm and pleasant feeling. A long-lasting gesture, such as *encircling / rolling at one's wrist* also creates the perception of slight warmth. We speculate that this may also have contributed to a higher rated perceived realism.

Silicone-based Stretchable Base Layer

We used Kinesio stretchable textile as the base layer to attach SMA wire. As this layer is only stretchable in one direction, the application of shear forces is, therefore, only possible in one direction. To provide shear forces in multiple directions, we envision a silicone-based adhesive stretchable base layer.

Touch Perception Levels

Technical limitations of the BMF150 SMA wire govern the current actuation force. According to the datasheet, it can provide a maximum load of 1.44N by using an actuation current of 340mA. To increase the load, the wire could also be driven by a higher current. However, this is not recommended, since it will reduce the life-span and increase heat. A possible solution includes the training of a generic nitinol SMA wire.

Synchronisation Discrepancy due to Actuation Delay

The passive cooling limits us to a cooldown delay of up to 2s. Also, the activation shows a latency of up to 1s. Therefore, some use cases are also compromised when ad-hoc interactions (e.g., VR chat room) are required, which may create a mismatch between the visual stimulus and delayed actuation.

Generalizability of Findings

The presented findings are connected to our current hardware setup. Another type of SMA demonstrating different properties might result in a slightly deviating perception. However, we consider our results as providing reference points, given we presented a viable procedure on methods to evaluate future setups. Moreover, in study 4, individual differences would have confounded the independent variable since we evaluated the system between subjects with separate groups of participants.

CONCLUSIONS

In this paper, we presented a matrix of shape memory alloy (SMA) - based plasters, which are silent, unobtrusive, lightweight, and stretchable. This forearm augmentation is attached to the skin and recreates touch sensations by applying subtle shear forces. A set of studies investigating the perceptibility of different sizes, distances, and types of attachments of plasters on the forearm informed our design. Overall, our results showed that the recreated touch patterns are perceived reasonably close to real touch, as users provided positive feedback. Finally, we explored two scenarios in which our system could provide added value in AR and VR. We concluded this research with several insights for future designs relying on SMA-based haptic feedback.

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REFERENCES

[1] Christian Antfolk, Christian Balkenius, Göran Lundborg, Birgitta Rosén, and Fredrik Sebelius. 2010. Design and technical construction of a tactile display for sensory feedback in a hand prosthesis system. *Biomedical engineering online* 9, 1 (2010), 50.

[2] Karlin Bark, Jason Wheeler, Pete Shull, Joan Savall, and Mark Cutkosky. 2010. Rotational skin stretch feedback: A wearable haptic display for motion. *IEEE Transactions on Haptics* 3, 3 (2010), 166–176.

[3] Cagatay Basdogan, Mert Sedef, Matthias Harders, and Stefan Wesarg. 2007. VR-based simulators for training in minimally invasive surgery. *IEEE Computer Graphics and Applications* 27, 2 (2007), 54–66.

[4] Olivier Bau, Ivan Poupyrev, Ali Israr, and Chris Harrison. 2010. TeslaTouch: electrovibration for touch surfaces. In *Proceedings of the 23nd annual ACM symposium on User interface software and technology*. ACM, 283–292.

[5] Matthew A Baumann, Karon E MacLean, Thomas W Hazelton, and Ashley McKay. 2010. Emulating human attention-getting practices with wearable haptics. In *2010 IEEE Haptics Symposium*. IEEE, 149–156.

[6] bhaptics. 2019. Ready to feel the future. (2019). Retrieved April 2, 2019 from `https://teslasuit.io/`.

[7] Jonathan Blake and Hakan B Gurocak. 2009. Haptic glove with MR brakes for virtual reality. *IEEE/ASME Transactions On Mechatronics* 14, 5 (2009), 606–615.

[8] Pinar Boyraz, Gundula Runge, and Annika Raatz. 2018. An Overview of Novel Actuators for Soft Robotics. In *Actuators*, Vol. 7. Multidisciplinary Digital Publishing Institute, 48.

[9] Chia-Yu Chen, Yen-Yu Chen, Yi-Ju Chung, and Neng-Hao Yu. 2016. Motion guidance sleeve: Guiding the forearm rotation through external artificial muscles. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 3272–3276.

[10] George Chernyshov, Benjamin Tag, Cedric Caremel, Feier Cao, Gemma Liu, and Kai Kunze. 2018. Shape Memory Alloy Wire Actuators for Soft, Wearable Haptic Devices. In *Proceedings of the 2018 ACM International Symposium on Wearable Computers (ISWC '18)*. ACM, New York, NY, USA, 112–119. DOI: `http://dx.doi.org/10.1145/3267242.3267257`

[11] Francesco Chinello, Mirko Aurilio, Claudio Pacchierotti, and Domenico Prattichizzo. 2014. The HapBand: A cutaneous device for remote tactile interaction. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 284–291.

[12] Inrak Choi and Sean Follmer. 2016. Wolverine: A Wearable Haptic Interface for Grasping in VR. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16 Adjunct)*. ACM, New York, NY, USA, 117–119. DOI: `http://dx.doi.org/10.1145/2984751.2985725`

[13] Heather Culbertson, Cara M Nunez, Ali Israr, Frances Lau, Freddy Abnousi, and Allison M Okamura. 2018. A social haptic device to create continuous lateral motion using sequential normal indentation. In *2018 IEEE Haptics Symposium (HAPTICS)*. IEEE, 32–39.

[14] Nathan Dunkelberger, Jenny Sullivan, Joshua Bradley, Nickolas P Walling, Indu Manickam, Gautam Dasarathy, Ali Israr, Frances WY Lau, Keith Klumb, Brian Knott, and others. 2018. Conveying language through haptics: a multi-sensory approach. In *Proceedings of the 2018 ACM International Symposium on Wearable Computers*. ACM, 25–32.

[15] Yurika Ebe and Hiroyuki Umemuro. 2015. Emotion Evoked by Texture and Application to Emotional Communication. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*. ACM, 1995–2000.

[16] Abdulmotaleb El Saddik, Mauricio Orozco, Mohamad Eid, and Jongeun Cha. 2011. *Haptics technologies: Bringing touch to multimedia*. Springer Science & Business Media.

[17] Don Samitha Elvitigala, Denys JC Matthies, Vipula Dissanayaka, Chamod Weerasinghe, and Suranga Nanayakkara. 2019. 2bit-TactileHand: Evaluating Tactons for On-Body Vibrotactile Displays on the Hand and Wrist. In *Proceedings of the 10th Augmented Human International Conference 2019*. ACM, 3.

[18] Frank A Geldard and Carl E Sherrick. 1972. The cutaneous" rabbit": A perceptual illusion. *Science* 178, 4057 (1972), 178–179.

[19] Brian T Gleeson, Scott K Horschel, and William R Provancher. 2010. Design of a fingertip-mounted tactile display with tangential skin displacement feedback. *IEEE Transactions on Haptics* 3, 4 (2010), 297–301.

[20] Rachael Granberry, Kevin Eschen, Brad Holschuh, and Julianna Abel. 2019. Functionally Graded Knitted Actuators with NiTi-Based Shape Memory Alloys for Topographically Self-Fitting Wearables. *Advanced Materials Technologies* (2019).

[21] Oliver Grau. 2003. *Virtual Art: from illusion to immersion*. MIT press.

[22] Aakar Gupta, Antony Albert Raj Irudayaraj, and Ravin Balakrishnan. 2017. HapticClench: Investigating Squeeze Sensations Using Memory Alloys. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17)*. ACM, New York, NY, USA, 109–117. DOI: `http://dx.doi.org/10.1145/3126594.3126598`

[23] Nur Al-huda Hamdan, Adrian Wagner, Simon Voelker, Jürgen Steimle, and Jan Borchers. 2019. Springlets: Expressive, Flexible and Silent On-Skin Tactile Interfaces. *In proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (2019), 488. DOI:http://dx.doi.org/10.1145/3290605.3300718

[24] HaptX. 2018. HaptX Gloves Development kit. (2018). Retrieved April 2, 2019 from https://haptx.com/.

[25] Matthew J Hertenstein, Dacher Keltner, Betsy App, Brittany A Bulleit, and Ariane R Jaskolka. 2006. Touch communicates distinct emotions. *Emotion* 6, 3 (2006), 528.

[26] Ronan Hinchet, Velko Vechev, Herbert Shea, and Otmar Hilliges. 2018. DextrES: Wearable Haptic Feedback for Grasping in VR via a Thin Form-Factor Electrostatic Brake. In *The 31st Annual ACM Symposium on User Interface Software and Technology*. ACM, 901–912.

[27] Toshiyuki Hino and Takashi Maeno. 2004. Development of a miniature robot finger with a variable stiffness mechanism using shape memory alloy. In *International Symposium on Robotics and Automation, Querétaro, México, Aug*. 25–27.

[28] Aaron M Hoover, Erik Steltz, and Ronald S Fearing. 2008. RoACH: An autonomous 2.4 g crawling hexapod robot. In *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 26–33.

[29] Gijs Huisman, Aduen Darriba Frederiks, Betsy Van Dijk, Dirk Hevlen, and Ben Kröse. 2013. The TaSST: Tactile sleeve for social touch. In *2013 World Haptics Conference (WHC)*. IEEE, 211–216.

[30] Filip Ilievski, Aaron D Mazzeo, Robert F Shepherd, Xin Chen, and George M Whitesides. 2011. Soft robotics for chemists. *Angewandte Chemie* 123, 8 (2011), 1930–1935.

[31] Alexandra Ion, Edward Jay Wang, and Patrick Baudisch. 2015. Skin Drag Displays: Dragging a Physical Tactor Across the User's Skin Produces a Stronger Tactile Stimulus Than Vibrotactile. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 2501–2504. DOI: http://dx.doi.org/10.1145/2702123.2702459

[32] Ali Israr and Ivan Poupyrev. 2011. Tactile brush: drawing on skin with a tactile grid display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 2019–2028.

[33] Seungwoo Je, Brendan Rooney, Liwei Chan, and Andrea Bianchi. 2017. tactoRing: A Skin-Drag Discrete Display. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 3106–3114. DOI: http://dx.doi.org/10.1145/3025453.3025703

[34] Yvonne Jung, Ruth Recker, Manuel Olbrich, and Ulrich Bockholt. 2008. Using X3D for medical training simulations. In *Proceedings of the 13th international symposium on 3D web technology*. ACM, 43–51.

[35] Maria Karam, Carmen Branje, Gabe Nespoli, Norma Thompson, Frank A. Russo, and Deborah I. Fels. 2010. The Emoti-chair: An Interactive Tactile Music Exhibit. In *CHI '10 Extended Abstracts on Human Factors in Computing Systems (CHI EA '10)*. ACM, New York, NY, USA, 3069–3074. DOI: http://dx.doi.org/10.1145/1753846.1753919

[36] Thorsten A Kern. 2009. *Engineering haptic devices: a beginner's guide for engineers*. Springer Publishing Company, Incorporated.

[37] Mohammad Mahdi Kheirikhah, Samaneh Rabiee, and Mohammad Ehsan Edalat. 2010. A review of shape memory alloy actuators in robotics. In *Robot Soccer World Cup*. Springer, 206–217.

[38] Ryo Kikuuwe and Tsuneo Yoshikawa. 2001. Haptic display device with fingertip presser for motion/force teaching to human. In *Proceedings 2001 ICRA. IEEE International Conference on Robotics and Automation (Cat. No. 01CH37164)*, Vol. 1. IEEE, 868–873.

[39] Jacob H Kirman. 1974. Tactile perception of computer-derived formant patterns from voiced speech. *The Journal of the Acoustical Society of America* 55, 1 (1974), 163–169.

[40] Espen Knoop and Jonathan Rossiter. 2015. The tickler: a compliant wearable tactile display for stroking and tickling. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*. ACM, 1133–1138.

[41] Cecilia Laschi and Matteo Cianchetti. 2014. Soft robotics: new perspectives for robot bodyware and control. *Frontiers in bioengineering and biotechnology* 2 (2014), 3.

[42] Susan J Lederman and Lynette A Jones. 2011. Tactile and haptic illusions. *IEEE Transactions on Haptics* 4, 4 (2011), 273–294.

[43] Jaeyeon Lee, Mike Sinclair, Mar Gonzalez-Franco, Eyal Ofek, and Christian Holz. 2019. TORC: A Virtual Reality Controller for In-Hand High-Dexterity Finger Interaction. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, 71.

[44] Nadia Magnenat-Thalmann and Ugo Bonanni. 2006. Haptics in virtual reality and multimedia. *IEEE MultiMedia* 13, 3 (2006), 6–11.

[45] Denys JC Matthies, Laura Milena Daza Parra, and Bodo Urban. 2018. Scaling notifications beyond alerts: from subtly drawing attention up to forcing the user to take action. In *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings (UIST '18 Adjunct)*. ACM, 45–47.

[46] Francis McGlone and David Reilly. 2010. The cutaneous sensory system. *Neuroscience & Biobehavioral Reviews* 34, 2 (2010), 148–159.

[47] Takashi Mitsuda. 2013. Pseudo force display that applies pressure to the forearms. *Presence* 22, 3 (2013), 191–201.

[48] Makoto Miyazaki, Masaya Hirashima, and Daichi Nozaki. 2010. The "cutaneous rabbit" hopping out of the body. *Journal of Neuroscience* 30, 5 (2010), 1856–1860.

[49] Sachith Muthukumarana, Denys JC Matthies, Chamod Weerasinghe, Don Samitha Elvitigala, and Suranga Nanayakkara. 2019. CricketCoach: Towards Creating a Better Awareness of Gripping Forces for Cricketers. In *Proceedings of the 10th Augmented Human International Conference 2019*. ACM, 43.

[50] Suranga Nanayakkara, Elizabeth Taylor, Lonce Wyse, and S H Ong. 2009. An enhanced musical experience for the deaf: design and evaluation of a music display and a haptic chair. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 337–346.

[51] Patrick E Patterson and Judd A Katz. 1992. Design and evaluation of a sensory feedback system that provides grasping pressure in a myoelectric hand. *J Rehabil Res Dev* 29, 1 (1992), 1–8.

[52] Benjamin Petry, Thavishi Illandara, Don Samitha Elvitigala, and Suranga Nanayakkara. 2018. Supporting Rhythm Activities of Deaf Children using Music-Sensory-Substitution Systems. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 486.

[53] Benjamin Petry, Thavishi Illandara, and Suranga Nanayakkara. 2016. MuSS-bits: sensor-display blocks for deaf people to explore musical sounds. In *Proceedings of the 28th Australian Conference on Computer-Human Interaction*. ACM, 72–80.

[54] Dario Pittera, Elia Gatti, and Marianna Obrist. 2019. I'm Sensing in the Rain: Spatial Incongruity in Visual-Tactile Mid-Air Stimulation Can Elicit Ownership in VR Users. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, 132.

[55] plexus imersive corp. 2018. We make high performance VR/AR gloves to feel the digital reality. (2018). Retrieved April 2, 2019 from `http://plexus.im/`.

[56] Henning Pohl, Peter Brandes, Hung Ngo Quang, and Michael Rohs. 2017. Squeezeback: pneumatic compression for notifications. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 5318–5330.

[57] Anil K Raj, Steven J Kass, and James F Perry. 2000. Vibrotactile displays for improving spatial awareness. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Vol. 44. SAGE Publications Sage CA: Los Angeles, CA, 181–184.

[58] Charlotte M Reed, Hong Z Tan, Zachary D Perez, E Courtenay Wilson, Frederico M Severgnini, Jaehong Jung, Juan S Martinez, Yang Jiao, Ali Israr, Frances Lau, and others. 2018. A Phonemic-Based Tactile Display for Speech Communication. *IEEE Transactions on Haptics* 12, 1 (2018), 2–17.

[59] Mark Schrope. 2001. Simply sensational. *New Scientist* (2001).

[60] Andrew A Stanley and Katherine J Kuchenbecker. 2012. Evaluation of tactile feedback methods for wrist rotation guidance. *IEEE Transactions on Haptics* 5, 3 (2012), 240–251.

[61] Katja Suhonen, Kaisa Väänänen-Vainio-Mattila, and Kalle Mäkelä. 2012. User experiences and expectations of vibrotactile, thermal and squeeze feedback in interpersonal communication. In *Proceedings of the 26th Annual BCS Interaction Specialist Group Conference on People and Computers*. British Computer Society, 205–214.

[62] Camilo Tejeiro, Cara E Stepp, Mark Malhotra, Eric Rombokas, and Yoky Matsuoka. 2012. Comparison of remote pressure and vibrotactile feedback for prosthetic hand control. In *2012 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*. IEEE, 521–525.

[63] TESLASUIT. 2019. Ultimate tech in Smart Clothing. (2019). Retrieved April 2, 2019 from `https://teslasuit.io/`.

[64] Jan BF Van Erp, Ian Saturday, and Chris Jansen. 2006. Application of tactile displays in sports: where to, how and when to move. In *Proc. Eurohaptics*. Citeseer, 105–109.

[65] Anusha Withana, Daniel Groeger, and Jürgen Steimle. 2018. Tacttoo: A thin and feel-through tattoo for on-skin tactile output. In *The 31st Annual ACM Symposium on User Interface Software and Technology*. ACM, 365–378.

[66] Zhuoming Zhang, Robin Héron, Eric Lecolinet, Françoise Détienne, and Stéphane Safin. 2019. VisualTouch: Enhancing Affective Touch Communication with Multi-modality Stimulation. In *2019 International Conference on Multimodal Interaction*. ACM, 114–123.

[67] Ying Zheng and John B Morrell. 2012. Haptic actuator design parameters that influence affect and attention. In *2012 IEEE Haptics Symposium (HAPTICS)*. IEEE, 463–470.

[68] Ying Zheng, Ellen Su, and John B Morrell. 2013. Design and evaluation of pactors for managing attention capture. In *2013 World Haptics Conference (WHC)*. IEEE, 497–502.