Skin Drag Displays: Dragging a Physical Tactor across the User's Skin Produces a Stronger Tactile Stimulus than Vibrotactile

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ABSTRACT

We propose a new type of tactile displays that drag a physical tactor across the skin in 2D. We call this *skin drag.* We demonstrate how this allows us to communicate geometric shapes or characters to users. The main benefit of our approach is that it simultaneously produces two types of stimuli, i.e., (1) it moves a tactile stimulus across skin locations and (2) it stretches the user's skin. Skin drag thereby combines the essential stimuli produced by vibrotactile *and* skin stretch. In our study, skin drag allowed participants to recognize tactile shapes significantly better than a vibrotactile array of comparable size. We present two arm-worn prototype devices that implement our concept.

Author Keywords

Haptics; wearable; hands-free; eyes-free.

ACM Classification Keywords

H.5.2. [Information interfaces and presentation]: User Interfaces - Haptic I/O

INTRODUCTION

Tactile devices that are in continuous physical contact with the wearer's skin allow sending simple messages to the user. Devices based on a single vibrotactile actuator [2,7,10], for example, allow pulsing "Morse-like" messages [11].

In order to allow sending more expressive and memorable messages, such as characters or simple icons, researchers extended the concept of vibrotactile actuators to two-dimensional arrays [7,13]. Fading from one vibration motor to the next, these devices produce the illusion of a dot moving across the skin, which allows drawing simple shapes [5]. This approach is popular because it is easy to implement and miniaturizes well to mobile and even wearable size.

Provancher et al. [e.g. 4], in contrast, have explored a different type of tactile display. They push and stretch the user's skin with a physical contactor to communicate directional cues, i.e., north, south, east, west. The resulting skin stretch triggers the skin's directional sensitivity [9].

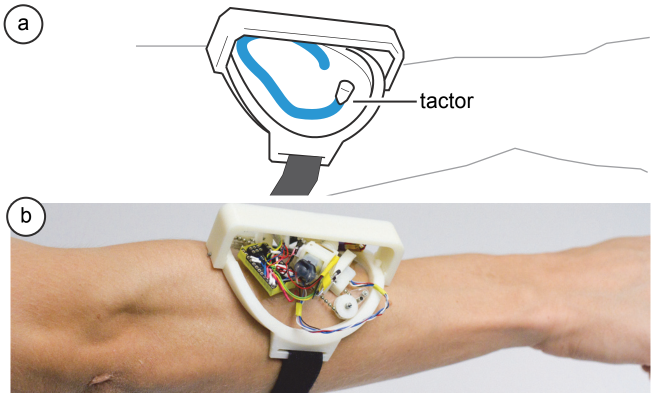

Figure 1: Skin drag displays drag a tactor over the wearer's skin in order to communicate a spatial message, (a) e.g. write a 'C' on the user's arm. (b) Our self-contained prototype.

Unfortunately, both approaches are limited since they excite only a subset of tactile receptors. Vibrotactile reaches only fast adapting receptors (Pacinian corpuscles, PC) on a usually larger area, while skin stretch reaches slowly adapting receptors (SA1 and SA2 afferents), however on a small area.

In this paper, we propose combining the benefits of both approaches so as to achieve a stronger, combined stimulus in two dimensions.

SKIN DRAG DISPLAYS

We propose *skin drag displays*, i.e., tactile displays that drag a physical tactor along a 2D path across the user' skin. As illustrated in Figure 2, the main benefit is that they combine the benefits of vibrotactile arrays and skin stretch, i.e. (1) skin drag reaches a large area and thus crosses a higher number of receptive fields like vibrotactile arrays and (2) stimulates the slowly adapting skin stretch receptors in the skin.

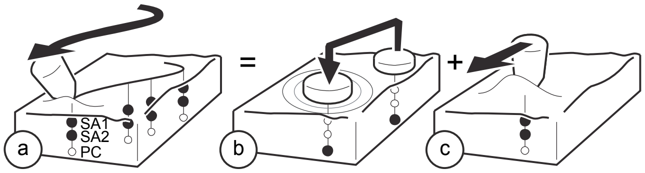

Figure 2: (a) Skin drag combines the benefit of both, (b) vibrotactile arrays which excite a large number of receptors, and (c) skin stretch, which reaches two types of receptors.

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We have created two prototypes. Our main prototype is worn on the forearm and its mechanisms are designed to respect the arm's curvature to keep constant contact between the tactor and the skin. We also present a smaller, watch-sized prototype at the end of this paper demonstrating the potential for miniaturization of our mechanical design.

RELATED WORK

Our work builds on research in tactile displays and in particular is inspired by Li et al.'s concept [8] of back-and-forth "rubbing" simulating human-to-human touch interaction.

Vibrotactile feedback

Due to their compact size, vibrotactile actuators have not only been integrated in large objects like chairs [5,15], but also in mobile devices [3,16] and wearable devices [6,14].

Vibrotactile devices allow sending non-visual messages to the user using patterns of varying amplitude. *Tactons* [2] are a general concept of tactile icons, which can be combined to send more complex messages. Lee et al. designed a wrist-worn device featuring three vibration motors that produced 24 distinguishable patterns [6]. Pasquero et al. [10] provided tactile feedback with a piezoelectric actuator that was built into a wrist-watch.

To communicate *spatial* messages to the user, researchers proposed 2D arrays of vibrotactile actuators. Tan and Pentland [13] proposed a 3 × 3 array of vibration motors to create a directional tactile display using apparent motion. Lee et al. [7] investigated sending directional and letter-like shapes (e.g. "L") to the user using a wrist-worn 4 × 4 array of vibrotactile units. More recently, Israr et al. [5] provided gamers with directional strokes produced by a 3 × 3 array of vibrotactile actuators mounted on the back of a chair.

Techniques that create tangential forces on the skin

Provancher et al. proposed providing stretching and pulling the skin to provide directional cues or rotary sensations on a small area of the skin, e.g. ⌀ 4 mm [4]. Bark et al. [1] compared skin stretch feedback with vibrotactile feedback in a cursor positioning task and found a significant performance benefit for skin stretch feedback. Their results confirm findings from physiology [9] that suggest the skin's directional sensitivity is higher (8 mm on the forearm) than its location acuity (30 mm–40 mm on the forearm).

Gesture output [11] ports the concept to displays that address the user's proprioceptive sense. They send eyes-free messages to users by dragging their thumb across a mobile device. Li et al. [8] proposed a device that "rubs" and "taps" the user's skin. Stanley and Kuchenbecker [12] wrapped the concept in wrist-worn form factor. We build on this work, extend it to 2D, and use it to encode tactile messages.

PROTOTYPE BASED ON A ROTATING DIAPHRAGM

Figure 1b shows our main prototype. Users wear it on their forearm. The device features a round actuation area of 40 mm diameter. It creates a tactile message by dragging the shown tactor across the wearer's skin.

As shown in Figure 3, our prototype is based on a rotating flexible disk or *diaphragm,* allowing it to respect the arm's curvature. The diaphragm is a 0.25 mm polycarbonate sheet which is compliant enough to rotate with reasonably low friction, yet stiff enough to mount the mechanics to it.

The diaphragm is held by a cylindrically curved 3D-printed frame with a groove along its inner circumference allowing it to rotate (Figure 3). Combined with a linear mechanism for in and out motion across the actuation area, this implements a "polar coordinate" design, i.e. it actuates the tactor in the form of rotation (azimuth) and distance from center (radius).

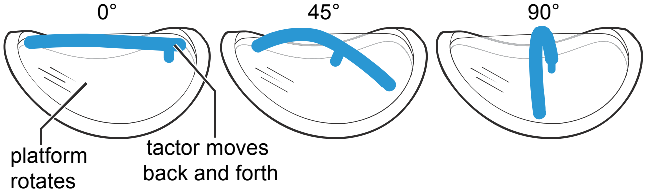

Figure 3: The rotating diaphragm is held by the cylindrically curved frame. The thick line illustrates the path of the tactor as it changes its curvature during rotation.

We chose this design because it enables us to place all mechanical and electronic components on the diaphragm, as shown in Figure 4, yielding a compact form factor (unlike designs based on an XY-tables).

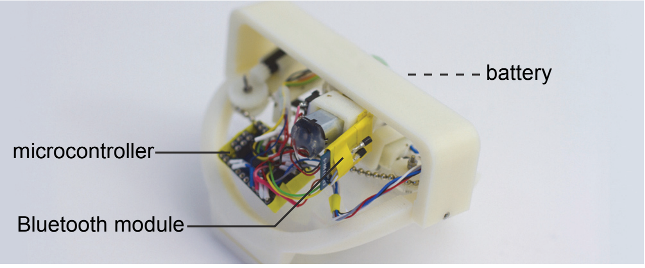

Figure 4: The rotary design allows placing all components on top of the actuation area. During operation, components move and bend with the diaphragm.

Rotation mechanism

Figure 5 shows the motor that rotates the diaphragm via a worm drive. The entire mechanism is mounted on and rotates with the diaphragm around a stationary gear mounted to the bar which is connected to the frame. A quadrature encoder (Alps EC05E1220401) provides position feedback with a resolution of 8°.

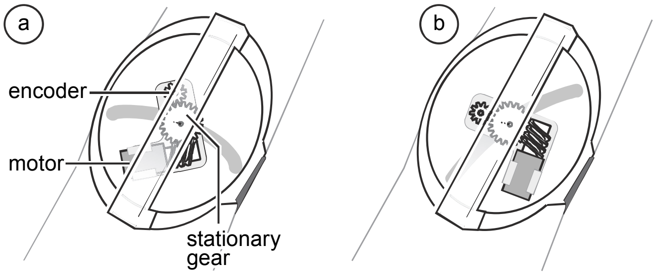

Figure 5: (a) A motor using a worm drive actuates the rotation of the diaphragm. (b) All components rotate with the diaphragm, e.g., 45° counterclockwise.

Linear mechanism

Figure 6 shows the ball chain drive that moves the tactor *across* the diaphragm. Unlike a timing belt, the ball chain is compliant in all directions, allowing it to follow the changing curvature of the diaphragm (Figure 3). A magnetic encoder (ams AS5304) attached to the tactor encodes the tactor's position with respect to a flexible multi-pole magnetic strip. We read 200 steps resulting in a resolution of 0.2 mm.

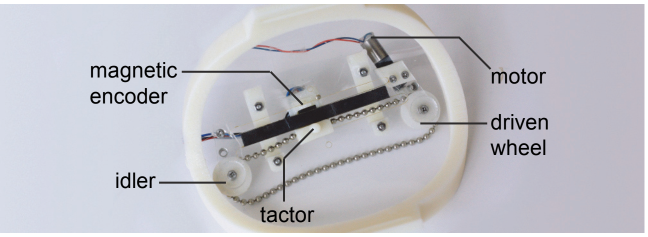

Figure 6: View onto the skin-facing side of the prototype. A chain drive moves the tactor across the diaphragm.

The tactor is a flexible to keep constant contact with the skin and compensate for varying distances.

Electronics & Software

A *baby orangutan* microcontroller board (pololu) mounted to the diaphragm controls the motors. Two li-ion batteries power the device. The device runs self-contained. In order to play back symbols, we send data from a notebook computer wirelessly via the RN42 Bluetooth module. The microcontroller interpolates between the control points of a symbol and controls the motors using a PID control loop to form the shape.

USER STUDY

In order to validate the concept of skin drag displays, we conducted a controlled experiment. In the study, participants interpreted shapes drawn onto their skin either by our skin drag display or a 4 × 4 vibrotactile array of comparable dimensions [7]. Since skin drag displays also stimulate skin stretch receptors, we hypothesized that they would lead to higher recognition rates.

Apparatus

There were two interface conditions. In the *skin drag* condition, we used our forearm-worn prototype. In the *vibrotactile* condition we drew symbols using a 4 × 4 vibrotactile display identical to Lee et al.'s [7].

Figure 7 shows how both devices were mounted on the dorsal side of participants' left forearms. Participants placed their arms orthogonal to the torso, as shown.

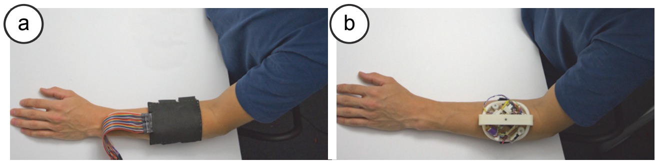

Figure 7: (a) Participant wearing the vibrotactile interface and, (b) the skin drag interface.

We implement the vibrotactile interface using the "tracing" method [15], running each actuator for 500 ms followed by 50 ms pause; during pilot testing, these values had performed best. Since the skin drag interface had continuous contact to the participant's skin, participants were indicated by the study software when the shape to be recognized was playing and when the device was merely homing.

Task and procedure

In each trial, the respective interface drew one of the 12 shapes shown in Figure 8 *once* onto the participant's skin. Participants responded with a forced-choice answer, i.e., they pointed to the shape they thought to have recognized on a computer display.

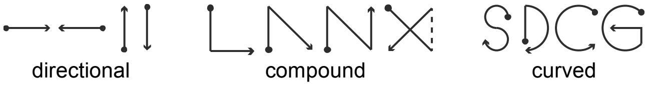

Figure 8: We tested a set of 12 shapes.

Participants wore a headset playing loud music to cancel out sounds made by the interfaces. For each interface condition, participants completed 2 blocks of 12 shapes in randomized order. The interface conditions were counterbalanced. In the beginning of each interface condition, participants received one block of training during which all shapes were shown once.

Participants

We recruited 8 participants (3 females) from our institution (age M = 22.12 years, SD = 3.22). They received a small compensation for their time.

Results & Discussion

Participants' error rate was significantly lower in the skin drag condition ($M = 23.96\%$, $SD = 43.23\%$) than in the vibrotactile condition ($M = 42.79\%$, $SD = 49.67\%$). A repeated-measures ANOVA ($\alpha = .05$) with 2 *interface conditions* × 2 *blocks* × 12 *shapes* revealed a significant main effect of interface condition ($F_{1,7} = 9.083$, $p = .020$). This confirms our main hypothesis.

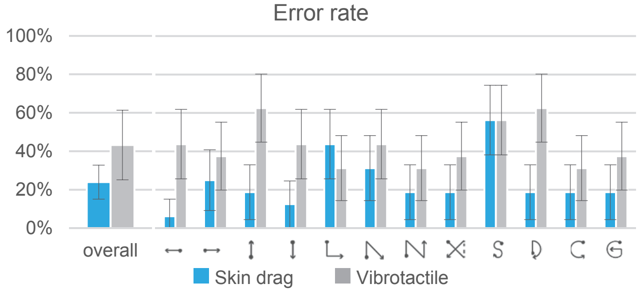

Figure 9: Overall, participants recognized shape significantly better in the skin drag condition. The error bars show the SE.

Our results show that there is no main effect of shape ($p = .325$). Pairwise comparisons show that for three shapes the error rates differed significantly depending on the interface condition: ↥ $p = .006$, ↧ $p = .049$, D $p < .001$. For these shapes the error rates where significantly lower in the skin drag condition, as shown in Figure 9. We did not find differences for other shapes.

Three participants mentioned during the study that shapes were "clearer" when displayed using the skin drag display.

In contrast, two participants reported that the strokes produced by the vibrotactile array "felt blurry".

CONCLUSION

In this paper, we presented the concept of skin drag displays. Skin drag displays are able to display simple spatial shapes on the user's skin. We have presented a prototype that implements our concept. The main benefit of skin drag is that communicates tactile messages more effectively than today's prevalent modality, i.e., vibrotactile.

To further illustrate our vision of skin drag displays in wearable use, we created the watch-style prototype shown in Figure 10. This design is also based on the polar coordinate design. Reducing the actuation area to 32 mm, however, allowed us to drop the flexible diaphragm, allowing for a very compact form-factor. Instead of a diaphragm, a rigid capsule rotates inside the casing. The capsule contains a small planetary gear motor (Precision Microdrives 206-110) that drives rotation, and a linear micro servo (Spektrum AS2000L) driving the radial motion. A microcontroller (ATtiny85) and battery are embedded within the capsule, making it a self-contained device.

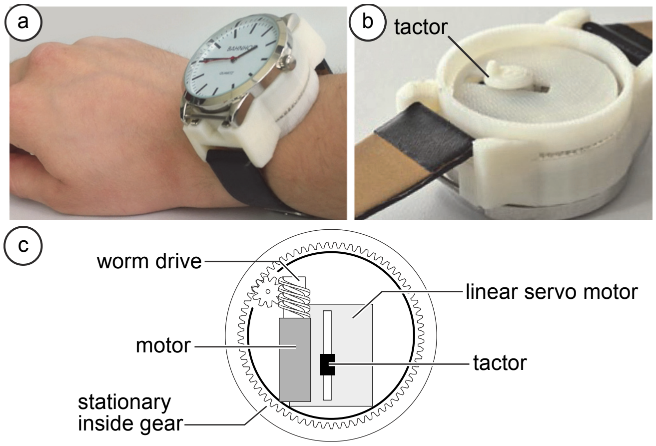

Figure 10: (a) Our wrist-worn device (b) actuates a 32 mm area in a 41 mm casing. (c) We use a worm drive with an inside gear for rotation and a linear servo for radial actuation.

In future work, we plan to use this prototype to study skin drag on smaller actuation areas and in long-term use.

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