Designing Skin-Dragging Haptic Motions for Wearables

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ABSTRACT
Skin-dragging is an emerging type of haptic feedback that coveys both precise spatial and temporal tactile cues through the motion of a small pin dragged across the skin. While past research focused on building skin-dragging wearable devices with different form-factors, and testing their feasibility, it is still unclear what the user's perception of such haptic stimuli is, and how designers should generate dragging motion-patterns for informative feedback to be presented on a finger. In this work, we attempt to answer these questions. We therefore asked designers to create dragging motions using changes of speed, direction and length. We then tested the generated skin-dragging motions with a haptic smart-ring, classified them and extracted guidelines that can be used to convey rich and informative feedback on the fingers.

Author Keywords
Haptics; skin-drag; wearable; smart-ring; emotional classification; motion design; eyes-free.

ACM CLASSIFICATION KEYWORDS
H.5.2. [Information interfaces and presentation]: User Interfaces – Haptic I/O.

INTRODUCTION
Skin-dragging is a type of haptic feedback that consists in dragging a small physical pin, or *tactor*, on the skin, in order to stimulate both the fast-adapting but coarse cutaneous receptors of vibrations (Paccinian corpuscles) and the slow-adapting and localized receptors of skin-stretch (SA1 and SA2) [6]. The benefit of this approach is that, by simultaneously involving different types of mechanoreceptors, the haptic stimuli can leverage both on the spatial and temporal resolution of the skin. For such reason, researchers are currently exploring different possible usages of skin-dragging displays in the form-factor of wearable devices, such as smart-watches [6], smart-rings [7] and finger pads [4]. As result, they achieved always-available, rich and accurate notifications for events and directions, with greater accuracy than simple vibration stimuli [7].

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While this research-field is still young, skin-dragging applications for wearables are rapidly emerging and haptic and HCI researchers have demonstrated the technical soundness and feasibility of this approach. For instance, Ion et al. [6] demonstrated that users can accurately distinguish directional, compound and curved dragging motions. However, there is a lack of knowledge about the users' perception and preferences for skin-dragging motions, and it is yet unclear whether users would actually choose to wear any smart-device with such haptic capabilities. What would be the perception of a user wearing a skin-dragging wearable device? What should be the criteria that a designer should use in order to create rich and informative skin-dragging motions that do not cause harm nor are annoying to users?

In this paper, we present a study that attempts to systematically answer these questions. We developed a simple skin-dragging ring prototype and we asked designers to create skin-dragging motions, which we then analyzed, implemented for our prototype, and tested with users. We then collected user's emotional perceptions using Ogwood et al.'s semantic differential scales [9], and, after a factor-analysis, we plotted and analyzed patterns of responses for the bespoke motions. We finally extracted three simple rules that describe how dragging-motion characteristics can directly influence users' perception and emotional responses.

SKIN-DRAGGING SMART-RING
Wearable devices provide the opportunity for always-available notifications and subtle input interaction. Smart-rings are especially fit for both input augmentation [1, 3, 8] and unobtrusive haptic notifications [7, 10], due to the direct contact with the finger's skin and their social acceptability [11]. It is therefore unsurprising that smart-ring technologies are attracting interest in the HCI community, and researchers have been exploring potential applications [11].

Following previous work [7], we built a simple skin dragging mechanical ring (Figure 1) capable of continuous movements around the finger in both the left and right direction. Like in Je et al.'s work [7], our ring has a small 5 mm tactor protruding from the inside of the ring, that can be dragged around the finger using a small DC motor (LCP06-A03V-0136 with torque 120gf-cm, 25 mA at 3V). The

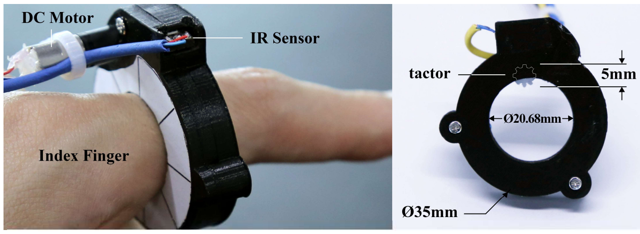

Figure 1. The skin-dragging ring used in the user studies.

mechanical structure inside the ring consists of three spur gears (8 teeth, 5mm face width) and one hollow gear (60 teeth, 2.5mm face width). The outer case was 3D printed with PolyLactic Acid (PLA). The tactor, designed as a rotating gear, is mounted on the hollow gear and protrudes from the ring by 1.5mm, guaranteeing contact with the skin at all times. The tactor position is sensed through an IR optical encoder and, similarly to [4], can be set to one of the four cardinal points. While prior work demonstrated that the spatial resolution of the skin around the proximal phalanx is about 5 mm and could therefore accommodate more locations [7], we simplified our design for the purpose of the study. Moreover, differently from tactoRing, we introduced three speeds for the dragging motions, by controlling the voltage supplied to the DC motor using Pulse Width Modulation (PWM). The ring is wired to an external Arduino, interfaced to a PC by USB. The controlling software written in Java runs on the PC. In practice, we created two identical rings with different sizes (US 8 and 11).

Our ring can therefore support two directions (left, right), four cardinal locations, and three motor speeds (slow = 160 rpm, medium = 180 rpm, and fast =200 rpm). Since we could not find any related work about optimal speed for skin-dragging displays, we first tested the three speed configurations with a pilot study. We recruited five participants (2 females, mean age: 31.2, SD: 14.2) without prior experience with smart-rings. Participants tested 80 random motions for each of the three speeds in fully balanced order, and were asked to identify them. Of the 240 trials, we excluded from our analysis 48 trials, considered as training. Participants showed an accuracy of 66%, 58% and 63% for the slow, medium and fast speed and in the post-hoc interview reported that the disambiguation was difficult. Therefore, we modified our prototype to support only two speeds (slow and fast).

SKIN-DRAGGING MOTION-DESIGN WORKSHOP

Using the hardware setup described in the previous section, we prepared a design workshop to investigate what kind of motion patterns designers would be interested in creating. We recruited eight design students (4 females, 4 males, with mean age: 24.2, SD: 3.45) with prior experience in interaction design, and motion graphics or animation skills. After an ice-breaking session and collecting demographics, we explained the purpose of the workshop and demonstrated our ring prototype (10 minutes). We then divided the participants in 4 pairs. We asked designers to create as many motion sequences as possible (30 minutes). After this

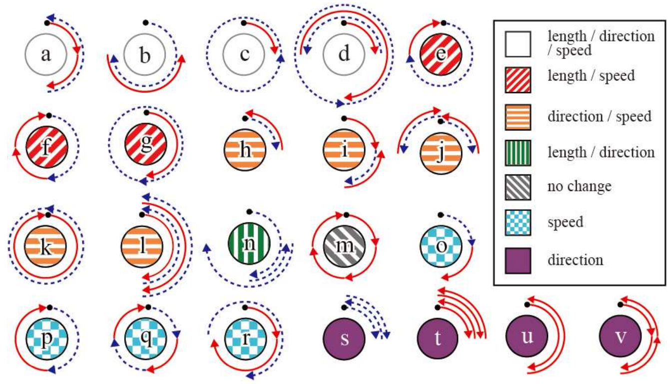

Figure 2. The 22 archetype motions generated through the design workshop clustered according to changes is speed, direction and length of motions. Motion starts at 0°. Different speeds are indicated using different colors.

creative work, we asked each team to present their motions to all the other designers, and to discuss them with everyone else (20 minutes). The workshop took approximatively 1 hour and participants received 15 USD in local currency for their time.

When creating motions, we instructed designers to follow only few rules. Motions can be simple or compound, starting from any cardinal point and with no pause between subsequent motion-steps. Motion speed can be either fast or slow, the direction left or right, and the length of a single step cannot be less than 90°. To support the creative activity, we provided participants with template sheets presenting images of two intersecting axis (a cross), and two colored pen (indicating slow and fast motions).

Results and Findings

In total, we collected 95 skin-dragging motions (team average: 23.7, SD: 3.3). In order to test them later with users, we grouped similar motions and normalized them with simple affinity transformations (rotations, horizontal and vertical reflections), so that all motions would start at 0°. We also considered only whether a change of speed, length or direction occurred, rather than the actual values: for example, a compound motion composed by a slow- followed by a fast-step is for our purpose identical to a motion composed by a fast- then slow-step. Similarly, a motion composed by a left step of 180° and a right step of 90° is equivalent to a motion with a left step of 90° and a right one of 180°, or even with a motion with a left/right step of 180° followed by a left/right step of 90°. In other words, we are interested in speed, direction, and length changes rather than the precise values of each parameter, or the specific order of presentation. Following these rules, we analyzed all the motions generated by the designers, and, using an affinity diagram, we synthetized them in 22 unique motion archetypes. These were clustered in seven groups, depending on which of the three parameters (speed, direction, and length) changed. The results are presented in Figure 2.

Although we also asked designers to label each motion pattern they drew, we were unable to clearly classify this data. In fact, the labels chosen by the different design teams greatly varied and were either too descriptive (e.g., one-cycle, rotation, swing, down…) or too generic (e.g., scratch, angry, blink…). We believe that this is a consequence for having left ambiguous the context and the application scenario for the ring, but we also did not want to constrain the creative process. Moreover, we also note that the design process greatly varied across teams, where some teams only relied on the visual cues on paper for generating motions, while others attempted to simulate the skin-dragging motion by scratching with the tip of a pen the skin of their fingers. However, we did not observe any variation of creativity (e.g., quality and number of motions generated) across teams.

HAPTIC EVALUATION WITH USERS

The second half of the study aims to measure the users' perception and attitudes about skin-dragging motions, following the procedure in prior related work [2]. For this part of the study we used the 22 archetypal motions generated in the design workshop, and created the software for our hardware ring that can reproduce the correct motion sequences. The goal of the study is to extract patterns and eventually criteria for designing skin-dragging motions.

We recruited 14 participants (7 females, aged 21-31, mean: 24.4, SD: 1.46) with finger sizes US 8 or 11. The study lasted 30 minutes and users were remunerated with 5 USD in local currency for their participation. After introducing the study and collecting demographics, we explained how the ring works and let users freely experience random skin-dragging motions. During the experiment, participants remained seated next to a supervisor, wearing the smart-ring on the index finger of their left hand. The hand was placed inside of a box to occlude any visual aid, and participants wore earmuffs to avoid sound cues.

Each of the 22 motions was presented in random order to the users, with at least five repetitions (more if the participants asked) and with a pause of 2 seconds between motions. Directly after each motion, the users filled a questionnaire based on the ten 7-point semantic differential scales (as in Ogwood et al. [9]). The scales present bipolar pairs of keywords: high arousal vs. sleepiness, pleasant vs. unpleasant, agreeable vs. disagreeable, nice vs. awful, harmonious vs. dissonant, positive vs. negative, like vs. dislike, useful vs. useless, important vs. unimportant, and meaningful vs. meaningless. In total, we collected 3080 responses (22 motions x 10 emotions x 14 participants).

Results and Findings

The questionnaire responses were analyzed using a factor analysis to reduce the number of variables and identify the major dimensions for the users' perception, as in Guest et al. [5]. We therefore performed a principal component analysis with a Varimax rotation. The adequacy test resulted in a Kaiser-Meyer-Oklin (KMO) value of 0.87, with a significant Bartlett's test (K-squared = 1867.1, df = 45, $p < 0.01$).

Through the factor analysis, we reduced the results from the 10 interrelated semantic scales to two compound factors, labelled "positive-negative" and "important-unimportant", following the convention of using the axis with highest factor loadings (Figure 3). Each axis ranges from -15 to +15 points, which represent the computed factor scores for each motion on the two axis. We then plotted each of the 22 motions on a graph (Figure 3.a), and subsequently the graphs exploiting individual motion trade-offs changes of speed, direction and length. Specifically, we plotted the motions with either directional or speed changes (Figure 3.b); speed or length changes (Figure 3.c); and directional or speed changes (Figure 3.d). Analyzing these graphs, we were able to identify main trends (though a statistical cluster analysis was not performed due to the limited data points).

Three main trends emerged. Users generally perceived changes in direction as more annoying than motions with no direction change. Figure 3.b shows that, except few outliers, motions were rated with positive connotations if no direction change happened. In addition, users regarded motions with no speed or length changes (i.e. only directional changes or no changes at all) more important than others, as shown in Figure 3.c. Finally, changes of speed were uniformly regarded positively, as shown in Figure 3.d.

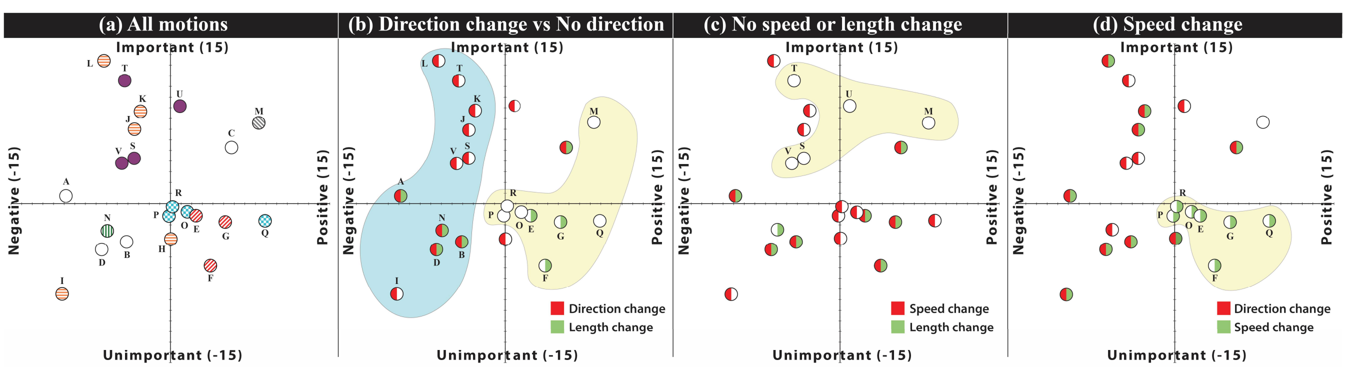

Figure 3. The 22 archetype motions plotted according to their factor scores on two axes (important vs. unimportant, positive vs. negative). The graph presenting "all motions" (a) is color-coded to reflect the groups in Figure 2. The other graphs show individual trade-offs: direction/length (b), speed/length(c), and direction/speed (d).

DISCUSSION

While past researchers [4, 6, 7] were able to demonstrate the feasibility of skin-dragging haptic motions for information presentation on wearable devices, these attempts lacked a discussion about the users' perception of motions and of how designers can explicitly create skin-dragging feedback that are informative, yet acceptable. Inspired by previous work [7], we developed a skin-dragging display in the form of a smart-ring, and asked designers to create compound motions using three possible changing elements: the length of a single motion, its speed and direction. We classified these motions as archetypes, presented them to users, and asked users to evaluate them using multiple semantic scales [9]. Then, we factored these variables in two dominant vectors, and plotted motions according to their factor scores.

Our analysis reveals that different types of changes affect the user's perception about the quality or meaning of specific motions. In details, we found that speed plays an important role to determine the motion connotations. In fact, we found that motions with alternating speed are generally perceived with positive meaning, while monotonic motions, altogether with the absence of direction changes, convey the meaning of importance. On the other side, direction can signify either a positive meaning (when there are no changes) or a negative meaning (when direction changes). We speculate that this result is simply due to how users associate directional changes with the act of "shaking the head", but further investigations are needed to validate this claim.

Perhaps the most important finding in this study is that, contrary to common wisdom, presenting motions with changes for all the three criteria (speed, direction, length) is not necessarily a good strategy for conveying clear messages. As shown in Figure 3.a, no distinguishable patterns are visible when all three motion-elements are combined together. Indeed, a designer might find that communication through motions is more effective if only one or two motion parameters are used in the same sequence. Although further work is needed to verify this claim, we expect that similar findings may apply to motion patterns with more than three varying parameters. In sums, different motions parameters are associated with different meanings, and the usage of more than two parameters for a single motion can deteriorate the overall user experience.

CONCLUSIONS, LIMITATIONS AND FUTURE WORK

This paper presents a study that attempts to describe which criteria should be used to design skin-dragging motions. Through a design workshop and an evaluation with users, we describe how changes in speed, length and direction can affect communication of different meanings through motion, and how the usage of the variables can enhance or diminish the clarity of the intended message. This research is limited by the quality of our ring-prototype and by the fact that the experiments were conducted in a lab with only 22 participants. Environmental conditions such as humidity and temperature could also impact the performance of the ring in real settings, and future work will investigate these issues. We also acknowledge that our findings could be biased by the ring form-factor used in the study, and the different characteristics of users' skins (e.g., the presence of callus and the thickness of the skin). Future work should investigate whether other skin-dragging wearable interfaces (e.g., watches, bracelets...) lead to similar results with a variety of users. Finally, while in this paper we were interested in investigating how changes in motion speed, direction, and length affect users' perception, we made the assumptions that the order of presentation of such parameters and their absolute values are irrelevant. We acknowledge that this assumption should be verified in future studies.

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