FabriTouch: Exploring Flexible Touch Input on Textiles

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ABSTRACT
Touch-sensitive fabrics let users operate wearable devices unobtrusively and with rich input gestures similar to those on modern smartphones and tablets. While hardware prototypes exist in the DIY crafting community, HCI designers and researchers have little data about how well these devices actually work in realistic situations. *FabriTouch* is the first flexible touch-sensitive fabric that provides such scientifically validated information. We show that placing a FabriTouch pad onto clothing and the body instead of a rigid support surface significantly reduces input speed but still allows for basic gestures. We also show the impact of sitting, standing, and walking on horizontal and vertical swipe gesture performance in a menu navigation task. Finally, we provide the details necessary to replicate our FabriTouch pad, to enable both the DIY crafting community and HCI researchers and designers to build on our work.

Author Keywords
Wearable; fabric; touchpad; textiles

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): Input devices and strategies (e.g., mouse, touchscreen)

INTRODUCTION
Interactive textiles are a rapidly growing field at the crossroads of the interaction design and DIY crafting communities. Integrated into everyday clothing, they can detect user input to elegantly control key functions of modern portable devices, often eyes-free. They can remove the need to, e.g., take your smartphone out of your pocket to use its touchscreen, or locate and operate a cumbersome, timeout-riddled one-button headset interface, just to take a call or navigate a playlist. For richer, continuous 2D input, textile touchpads have been prototyped by the DIY community[1], bringing the touch-based interaction of tablets and smartphones to textiles. It is currently hard for designers and researchers, however, to adopt these designs with confidence, because they are rarely evaluated, documented to allow replication, or made from widely available materials. Moreover, so far we know little about how well such on-body continuous-touch interaction performs in different realistic usage situations.

[1]http://www.instructables.com/id/EJKTF3WGV490JGK

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Figure 1. Two FabriTouch pads integrated into a pair of trousers. Users tried both *parallel* (left) and *crossed* touch gestures (right).

To address this, we designed and prototyped *FabriTouch*, a fully flexible, wearable textile touchpad, and integrated it into a pair of trousers (Fig. 1). In the remainder of this paper, we review related work, describe our technical construction, and compare its performance on a rigid surface to a realistic, soft undergound such as the thigh in a target acquisition task. To assess its usability in different situations, we then report on a comparison of swipe gestures on FabriTouch while sitting, standing, or walking.

RELATED WORK
GesturePad [5] is an early prototype of a capacitive touchpad that can be integrated into clothing. While the concept looks promising, no further evaluation is presented. A re-calibrated capacitive touchscreen [6] can detect gestures through different fabrics. The result is a rich eyes-free input device to, e.g., write text messages on a phone that is in a pocket. However, this design is not bendable, making it unsuitable for integration into most clothing. It also needs electric insulation or distance to the body to work reliably.

Pinstripe [3] senses the size and movement of a fold of partly conductive cloth a user rolls between his fingers. Its continuous output can control, e.g., the volume of a portable audio player, or the brightness of night-vision goggles. The interaction is intuitive and eyes-free, but does not support more complex 2D input gestures.

Thomas et al. [8] studied the placement of a regular laptop touchpad on the body to control a wearable computer and head-mounted display. They found placing the touchpad on the front upper thigh to work best when sitting, kneeling, or standing.

Perner-Wilson et al. [4] described the construction of a textile touchpad, focusing on the DIY community. The textile touch surface by Schmeder and Freed [7] uses a similar architecture but is mounted and evaluated on a rigid surface.

In summary, while wearable touchpads are of great interest, the effects of integrating them into flexible clothing have not been evaluated yet.

TEXTILE TOUCHPADS

Before presenting our prototype and how it differs from other models, we introduce the general principle of most textile touchpads: A *spacing mesh* separates a *piezoresistive foil* from a layer of *conductive fabric* to prevent any touch detection when no finger is placed on the surface. The foil's electrical resistance varies depending on the force of a touch point and its distance to the points of measurement. If we apply a reference voltage to the conductive fabric and press on the surface, we create an electrical connection between the fabric layer and the foil. Measuring the relative voltages at the four corners of the foil gives us the position and pressure level of a touch.

The FabriTouch Prototype

Following the literature [2, 3, 8, 5, 9], we chose the upper thigh to place our FabriTouch pads. We determined the appropriate size and position of the input surface in a pilot study: 26 participants performed a series of simple gestures (e.g., circles, lines, crosses) with baking flour on a piece of fabric attached to their upper thigh. Averaging size and placement of these gestures showed that an 80×80 mm sized interaction surface was suitable. It should be placed parallel to the thigh, centered 285 mm down from the waist and 10 mm towards the outside from the top of the thigh (Fig. 1).

Based on these findings, we constructed a series of prototypes. Fig. 2 shows the final version[2]. We used .1mm thick Caplinq ESD protective sheet as piezoresistive foil. The conductive textile layer was made of Shieldex MedTex180 silver-plated nylon cloth. The spacing layer consists of tulle, a textile mesh, with a thickness of 0.45 mm and a hole diameter of 2.1 mm. Long strips of copper foil along the edges served as electrodes measuring the position along the two axes. Compared to small corner electrodes, these have the advantage that the measurements result in an undistorted image, thus providing higher resolution and simplifying calibration. We noticed that it is difficult to feel the borders of the sensing area, so we raised the border of the sensor surface by placing a rubber outline under the outer garment. An Arduino board collects the measurements and communicates (x, y) coordinates at a resolution of 100×100 points (31.75 ppi) at 30.3 Hz to the attached computer. There, we use the 1€ filter [1] to reduce sensor noise in software. The pressure signals were quantized into binary single-touch input.

STUDY 1: SUPPORT SURFACE RIGIDITY

While many sensors are demonstrated and tested on rigid surfaces such as tables, actually integrating them into clothing leaves them on top a flexible, nonplanar surface without firm support, and subject to body movements. We hypothesized that this would significantly impact touch input performance, and tested this in a study.

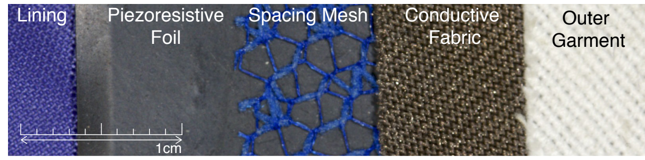

Figure 2. FabriTouch layer materials, placed side-by-side to show material structures.

Procedure: Users used the FabriTouch pad to manipulate a cursor and acquire circular targets (70 px diameter) that randomly appeared in a 5×5 grid on a desktop computer screen. To manipulate the cursor, users depressed the pad to generate input signals, which were mapped absolutely to 800×800 px on-screen. To acquire the target, users had to stay engaged in the target area for at least 2 seconds (a visual countdown was provided). Lifting the finger reset this engagement.

We performed a within-subject study; the touchpad was placed either on a table or on the upper thigh (counterbalanced order, 20 repetitions per condition). For the thigh condition, the touchpad was mounted on a large piece of cloth firmly attached to the users' trousers. Prior to each condition, users familiarized themselves with the touchpad until they felt comfortable. The dependent variable was task completion time. We log-transformed the data and used mixed-model ANOVA with USER as a random effect.

Participants: We recruited 26 volunteers (8 female, age 18–34, *M* = 25) from our campus. All had a computer science background and reported high familiarity with laptop touchpads (*Mdn* = 5 out of 5-point Likert scale).

Results: Users performed *twice* as fast on the table ($M = 5.90s$) as on the thigh (12.00), $F_{1,897} = 296.64, p < .001$, Cohen's d = 1.01 (Large effect size). The lack of statistical significance of repetitions ($F_{19,897} = 1.11, p = .3302$) and interaction effect ($F_{19,897} = 0.82, p = .6873$) indicates no learning effect.

We also observed that all users applied more pressure in the thigh condition. Even so, they perceived this condition as less stable (P10: *"It felt like writing on a sheet of paper on your thigh"*, P4,7: *"You should really hold your breath"*). Both increased pressure and perceived instability could be a cause of the slower performance in this condition. Even though the muscular nature of the upper thigh provides a rather firm base, finger pressure is still distributed over a larger area, reducing the sensitivity of the touchpad. These factors indicate that pointing input may not be suitable for fabric touchpads.

These results suggest stark differences of user behavior between the rigid support of the desk and the soft support of the thigh. Therefore, it seems crucial to assess and fine-tune wearable user interfaces with realistic sensor placement, on the body rather than conveniently on a lab desk.

[2] Build instructions at http://hci.rwth-aachen.de/fabritouch

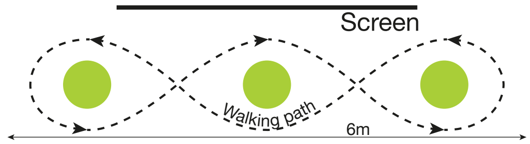

Figure 3. The path the users had to follow in the walking condition.

STUDY 2: USAGE POSTURE

Users' posture influences their performance in wearable UIs [8]. Additionally, the progress of each touch movement changes trackpad properties, such as its flatness, rigidity, or contact to the surface below. In this study, we investigated how these two factors influence gesturing performance. We chose horizontal and vertical swipe gestures for their simplicity and ubiquitous use in 2D touch UIs.

Procedure: In our within-subject study, users navigated a two-level hierarchical menu [10] using FabriTouch integrated into a pair of trousers (Fig. 1). Navigation on the top level was performed using horizontal swipes while the second level was navigated with vertical swipes. A rubber band ensured thight fitting of the trousers. The independent variables were POSTURE = {sitting, standing, walking} and swipe DIRECTION towards the user's {FEET, HEAD, non-dominant hand (NH), and dominant hand (DH)}. HEAD swipes mapped to moving the cursor downward (Fig. 4), as recommended by [8] and supported by our pilot study (6 users). Horizontal swipes were mapped like on a smartphone: Swiping towards the left moved the selection to the left.

As with a standard menu bar, the top level and the current submenu were always visible. A trial ended when the cursor reached the target item; the subsequent trial continued without resetting the position of the selection. The sequence of menu items was predetermined to balance the number of swipes across all directions. Users acquired five targets for training and seven for testing per POSTURE, resulting in M = 68.60 swipes per POSTURE (SD = 8.86).

In the WALKING condition, where users had to walk around a predefined path (Fig. 3) in the room, we projected the menu on a wall to ensure its visibility.

Data analysis: For each recognized swipe, we analyzed overall task completion TIME, DURATION of individual gestures, and the dimensions of the gesture bounding box: the LENGTH along the swipe direction and the DEVIATION orthogonal to the swipe direction. All variables were log-transformed before analysis with a mixed-model ANOVA with USER as a random effect, followed by a Tukey HSD for post-hoc tests. Descriptive statistics were calculated by inverse-transforming log statistics.

Participants: We recruited 17 volunteers (3 female, age 21–34, M = 26) from our campus. Six were ambidextrous[3], and two were left-handed. They all had a technical background and reported high familiarity with typical laptop touchpads (Mdn = 5 out of 5-point Likert scale).

[3]They scored less than 4[th] decile in Edinburgh laterality

Effects	df	DURATION F	DURATION p	LENGTH F	LENGTH p	DEVIATION F	DEVIATION p
Posture	2, 176	15.35	<.0001	2.86	.0602	0.32	.7251
Direction	3, 176	3.76	.0119	12.61	<.0001	14.37	<.0001
Posture * Direction	6, 176	0.43	.8597	0.83	.5502	1.86	.0904

Table 1. The effect of direction is significant across the board while posture has significant effect only on to duration.

Results and discussion

Posture: There was a significant effect of POSTURE on TIME $F_{2,32} = 3.44, p = .0442$. Post-hoc testing indicates that only walking (M = 470s) took significantly longer than sitting (351). Standing (409) did not significantly differ from both. Gesture duration while walking (M = 1.42s, 95% CI [1.35,1.50]) was significantly shorter than sitting (1.70, [1.60, 1.81]) and standing (1.71, [1.61, 1.82]) (cf. Table 1). The longer TIME and the shorter DURATION suggest that gesturing while walking was more difficult than in other postures.

Gesture directions: DIRECTION has a significant effect (Table 1).

NH swipes were slowest (1.73s [1.57, 1.92]) and were significantly different from FEET swipes (1.50 [1.41, 1.59]), which were fastest. Users were significantly less precise in performing horizontal swipes (DEVIATION M = 1.85mm [1.59, 2.16]) than vertical swipes (1.35 [1.24, 1.46]) (Fig. 4). NH swipes were significantly shorter (LENGTH M = 5.03mm [4.79, 5.28]) than other directions (5.68 [5.46, 5.91]).

Horizontal swipes (NH, DH) were harder than vertical ones. One reason was that horizontal swipes generated more wrinkles in the fabric while vertical swipes (especially FEET) stretched the cloth. The upward movement from the outside of the thigh towards the center in NH accentuated this effect, producing shorter swipes. The non-significant interaction effect indicates that the movements during walking did not make any particular DIRECTION harder.

Gesture location: While users reported that the ridges allowed them to orient their finger (Mdn = 4 out of 5-point Likert scale), most gestures were performed in the middle third of the sensor (fig. 4). This indicates that users used the ridges to orient their finger initially but performed the swipes without relying on the ridges. Informal observations during our study and qualitative feedback indicated that users rarely looked at the touchpad during the test.

Handedness preference: Despite no explicit instructions, almost all users used the touchpad on the side of their dominant hand. Only P1, who was right-handed, used the left touchpad with his right hand to *"give it a try"* in the STANDING condition. His performance here did not differ from others'.

DESIGN IMPLICATIONS

Use vertical swipe gestures instead of horizontal ones: Users perform vertical swipes faster and in a smaller bounding box than horizontal swipes, which should be considered in the gesture recognition. Horizontal swipes from the outside of the thigh towards the center result in dragging upwards which requires a constant complex adaptation of pressure and should therefore be avoided. Due to the high touch pressure required, we do not recommend using this touchpad type for pointing.

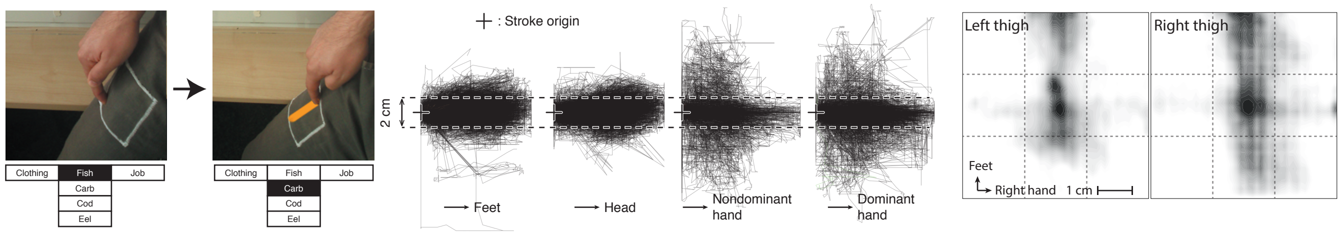

Figure 4. Left: Menu navigation mapping in Study 2. A swipe towards the user's head moves the menu selection downward. Middle: Gesture traces in different directions show high deviation of horizontal swipes towards the nondominant hand. Right: Contour plots show the density of touch locations from Study 2. Users perform gestures mostly in the center third of the touchpad.

Performing gestures on fabric touchpads while walking is harder: If activity detection is possible, e.g., via accelerometers, relaxing the gesture duration criteria of the gesture recognizer's tolerance during walking could reduce gesturing difficulties. Since the gesture duration is shorter, designers should avoid including both sliding and flicking in the gesture alphabet used while walking.

On-body and multi-posture tests are necessary: To cover the breadth of realistic user experiences, fabric touchpads need to be tested on-body in both static and dynamic postures. According to our study, we recommend testing with at least standing and walking postures.

EXTENDING INTERACTION

We integrated two flexible textile touchpads into a pair of trousers to allow users of both dexterities to use it in the same way. Extending this idea, one could have several sensor areas for different purposes [5], e.g., the outer thigh for the volume and the inner thigh to navigate a playlist.

Integrating the touchpad into the inner layer of a pocket enables invisible gestures for privacy-relevant input. When placed on the outer layer, the thumb could interact on the surface formed by the palm and the other four fingers. The active surface would be reduced to approximately the size of the hand, but the interaction between thumb and hand can be performed with high precision.

SUMMARY & FUTURE WORK

We built a simple and low-cost textile touchpad to gain empirical insights into its usability in realistic settings. The high availability of the materials used (apart from the conductive fabric, everything can be found in local shops) makes it an ideal construction for makers. With a soldering iron and sewing machine, crafting your own FabriTouch only takes about an hour. Our user studies show that user performance was influenced significantly by the rigidity of the underground, the posture, and the direction of the gesture. We used visual feedback in our experiments as this immediately reflects the input, however, in a real-world deployment this could be replaced by wearable displays or audio output.

We intend to reduce the pressure needed to register touches, to simplify pointing input, by improving our construction. We are looking into insulating liquids, gases, and special conductive foam[4] as spacing layer, and into using capacitive sensing.

[4]similar to EeonFoam http://www.eeonyx.com

This paper provides a step towards the scientific evaluation of touch input on fabrics. Further studies will need to investigate in more detail how users' real-time posture influences the shape of fabric and resulting touch signals. We hope our findings can enable better gesture recognizers and more robust gesture vocabularies for interactive fabrics.

ACKNOWLEDGMENTS

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