Zippro: The Design and Implementation of an Interactive Zipper

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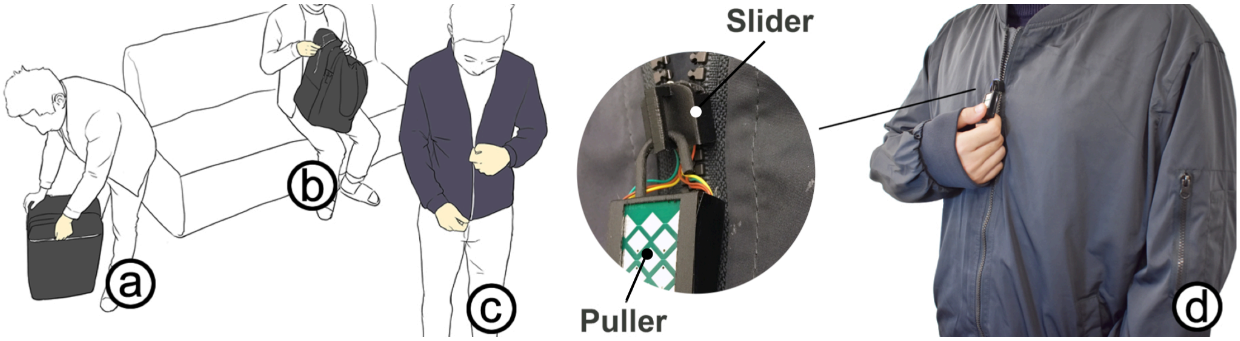

Figure 1. An interactive zipper brings interactivity to daily objects, such as (a) suitcase, (b) backpack, or (c) jacket. This is enabled through (d) our self-contained Zippro prototype, which senses (1) slider location, (2) slider movement (3) hand grips, (4) tapping and swiping on the puller; and the (5) identity of the operator.

ABSTRACT

Zippers are common in a wide variety of objects that we use daily. This work investigates how we can take advantage of such common daily activities to support seamless interaction with technology. We look beyond simple zipper-sliding interactions explored previously to determine how to weave foreground and background interactions into a vocabulary of natural usage patterns. We begin by conducting two user studies to understand how people typically interact with zippers. The findings identify several opportunities for zipper input and sensing, which inform the design of Zippro, a self-contained prototype zipper slider, which we evaluate with a standard jacket zipper. We conclude by demonstrating several applications that make use of the identified foreground and background input methods.

Author Keywords
Zipper, wearable, smart things

CSS Concepts
• **Human-centered computing~ ~Interaction devices**

INTRODUCTION

Computers are becoming smaller, more ubiquitous, and progressively "weave themselves into the fabric of everyday life", just like as Mark Weiser envisioned thirty years ago [47]. Concepts such as smart wearables [26, 33] and Internet-of-Things [4, 27] are no long considered as future technologies by today's standards. Research efforts never stop advancing computing technology to merge the digital world seamlessly into people's daily lives. Innovations like digital jewelries [12, 26], fabric displays [6, 11, 45], and textile sensors [30, 34] all exemplify such efforts.

In this paper, we extend this body of research by bringing interactivity to some of the daily objects that bear zippers, like clothing (jackets and jeans) or luggage (bags and suitcases). Zippers are found everywhere in our society, so are familiar to most people and are believed to have a great potential for ubiquitous computing [13, 43]. As a new input channel, the zipper has potential to widen the interaction bandwidth beyond the current capabilities of ordinary objects, such as touch input on the object's fabric surface [30, 34]. For example, by sensing whether the zipper is open or closed, a user can be notified if their backpack is left open when in a public setting. Alternatively, the zipper can be used as an eyes-free touch input device for subtle interactions in social scenarios [3]. Since it will not be obvious to observers whether someone is actively using technology or just fidgeting with their zipper, this type of interaction can avoid disruption in social settings or meetings. More generally, integrating input from common zipper usage can open a door to new interactions to support daily activities (Figure 1).

However, zipper-based interactions still present challenges for interaction designers due to the lack of insights in the existing literature regarding the best design practices. While one obvious potential usage scenario for an interactive zipper is to pull the slider for continuous input (as described briefly in [13] and [43]), many questions remain: does this meet the

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user's specific needs and goals? Will the user perform such a task say on a jacket with the side effect of the jacket being opened? The lack of knowledge in this space also means that engineers may also find it challenging to develop an interactive zipper for input as they do not know what sensing capabilities are needed to support the desired interactions.

We overcome these limits by taking a user centered design approach to understand sensing needs and potential applications that can benefit from using a zipper, based on the *foreground-background* model of interaction [15]. Through an observational study of over 400 online videos covering the daily use of the zipper on 15 objects, we report a rich vocabulary of natural hand behaviors occurring during the use of a zipper. The findings suggest a number of ways that zippers can be used for input for *background interactions*, where input to the zipper is carried out behind a user's conscious awareness (or implicit input) [15]. Through a second study with 28 participants, we further investigated user preferences of different types of zipper-based gestural input for *foreground interactions*, where input is carried out in the fore of the user's consciousness (or explicit input) [7]. The results of the two studies also allowed us to lay out several sensing requirements to guide the development of an interactive zipper.

To demonstrate technical feasibility and different usage scenarios, we implemented a self-contained proof-of-concept prototype, called Zippro (Figure 1). Our prototype is composed of a 3D printed slider and puller that can replace the slider of a standard size 5 zipper. The prototype is capable of: (1) tracking the location and movement of the slider, (2) distinguishing between two common types of hand grips on the puller, (3) identifying a user who operates the zipper, and (4) recognizing simple touch gestures on the puller, such as tapping and swiping. All were developed to satisfy the major interaction requirements suggested by the results of our studies. Finally, through a series of system evaluations, we demonstrated the effectiveness of our implementation in sensing hand gestures, users, and slider movements on various zippers with teeth of different types, color, and materials.

Our contributions from this work include: 1) the result of two studies to understand the foreground-background interaction and sensor design requirements of an interactive zipper; 2) a demonstration of its feasibility through an implementation of a self-contained proof-of-concept prototype, Zippro; and 3) a set of applications that demonstrate the unique benefits of an interactive zipper.

BACKGROUND AND RELATED WORK

The chronology of the zipper invention begins back in 1857, when a patent describing the method for continuous clothing closure was received by the sewing machine inventor Elias Howe [17]. However, a working zipper was not developed until 1893 by Whitcomb Judson, who developed a zipper-like device as a shoe fastener [18]. The modern zipper was invented by Gideon Sunback in 1917. Since then improvements are always underway, but innovations related to computing have not been a focus.

Among what exists, the work proposed by Gilliland, et al. [43] is inspiring in the sense that 1D continuous input to a computer can be carried out by pulling the slider. In the paper, the authors described a way to sense the linear movement of the slider along the teeth based on resistance. A prototype was developed to demonstrate technical feasibility by augmenting a regular zipper with conductive threads and electronic circuitry. A similar sensing technique was described in Sousa and Oakley's work [43]. The authors argued that the tangible nature of the zipper could potentially make it easier for the users to perform input through the zipper in mobile and wearable contexts.

Output on a zipper has also been discussed although not in an interaction sense. The robotic zipper developed by Baharom, et al. [5] is inspiring in the sense that it converts the zipper from something that needs to operate manually to a motorized device. The devices created by the authors can open and close the zipper automatically without the need for the user to pull the slider. The main application of a motorized zipper is for elderly or people with disability, who are lack of the ability to operate the zipper normally.

Amongst the existing work in the interactive zipper, insights were mainly given from an engineering perspective, which can be useful for developing future sensing or actuating techniques for the interactive zipper. However, little is known in terms of the usability of the zipper as a daily input device. There is also a missing knowledge in how and why an interactive zipper is useful, especially in the light of the rapid development of interactive fabrics. This can create a major barrier to exploit the full potential of the interactive zipper.

In this work, we took a user-center design approach through an observational study and formative interview to understand the needs of an interactive zipper from the users' perspective and draw design requirements for input techniques and hardware sensing techniques for the zipper-based interactions.

Enable Interaction on Soft Fabric Objects

The zipper and fabric often coexist on objects with soft surfaces, such as garment, shoes, bag, toy, and furniture. Unlike the zipper, interactive fabric has been a topic widely studied in HCI to enable novel interactions on daily objects [19, 29, 32, 34, 36, 41, 45]. For example, touch input has been shown useful on garments (e.g., sleeve [32, 41], pockets [38], drawstrings [21, 29], fabric snap [10], pants [19, 30] and skirt [16]), soft parts of the electronic devices (e.g., headphone cord [29]), bags [30, 34], toys [34], and furniture [30, 34] for varying types of information tasks. Much of the knowledge gained form the conventional touch input devices, such as touchscreen, can be useful for guiding the development of interaction and sensing techniques on interactive fabrics. Taking sensing as an example, the existing touch sensing techniques for interactive fabrics, such as the one based on capacitance [16, 23, 25, 29, 33, 34, 42], optical [22, 36], and resistance [8, 30-32, 35, 48], have all been used on touch sensitive devices with a rigid body. This is not the case for the zipper.

In comparison to input, showing high resolution graphics using a soft fabric can be much more challenging. The existing approaches can be divided into the techniques using fiber optics [29], thermochromic paint [11, 45], and photonic bandgap fibers [6].

With this body of research in interactive fabric, an obvious question is where the zipper stands and what extra values can an interactive zipper bring to the table. In this paper, we show through studies that the zipper can reveal useful information about the zipper's hosting object, such as whether the zipper of a backpack is open, for background interactions like reminding the user to close it. We also show that an interactive zipper can enable small, subtle, and eyes-free input that is useful in varying social contexts.

OBSERVATIONS OF ZIPPER USAGE

Development of seamless interactions for interactive zippers requires knowledge of how users typically behave when using zippers. However, the existing literature provides little insight on such behavior. To improve our understanding, we conducted an observational study using online videos from YouTube, following an approach from Hillyer et al. [14]. By observing the many different ways zippers are used daily, we aimed to gain the insights needed to develop a wide range of interactions as well as identify hardware sensing requirements for developing an interactive zipper. While reliance on YouTube videos presents a risk of introducing social media bias [20] and unknown influences from YouTube's algorithms, we expect this sample to be adequate for this exploratory research.

Method

We brainstormed 11 objects that often have zippers and are found in a range of environments (e.g. indoor, outdoor, home, and mobile environments). These include garments (e.g., jacket, pants, dress), shoes (boots), containers (backpack, wallet, suitcase), bedding (pillow cover) and outdoor equipment (tent, sleeping bags, vehicle soft-tops).

We then searched YouTube using the name of these objects as keywords. We excluded the keyboard "zipper" in our search to provide results that focused more on interaction with the host objects rather than being limited to specific information about the zippers. We then used a snowballing technique to select more candidates from the recommendation list of each video in the search result.

Starting with 1299 candidate videos, we manually searched the events of each and removed 807 videos that did not involve any zipper operations. We removed an additional 48 videos for redundancy. This resulted in a total of 444 videos for analysis. These have an average number of views of 234,640 and average length of 9:43 minutes. We used an open coding process to categorize the zipper interactions we observed in the videos.

Observed Zipper Usage and Opportunities for Sensing

We observed several common zipper operations and states, such as static slider states, slider motions, various hand grip types, and grip locations. Our discussions below summarize our observations and potential opportunities enable foreground and background interactions (labeled **F*x*** or **B*x***, respectively, in the following sections).

Static States

Observations: Zippers have a number of possible *static states* when not being operated. These are *closed* (all teeth from the opposite rows are connected), *open* (all teeth are disconnected), and *partially open*.

We observed a consistency in the occurrence of the states under certain conditions. For example, the opening of a container is normally zipped closed when the container is in use, especially in public. Similarly, a zipper is closed when garments or shoes are being worn. Conversely, an open state may indicate that a container is in a private space or a garment is not being worn. However, some objects are used less consistently; for example, the front zipper of a jacket can be in any state regardless if it is worn depending on personal requirements or style preferences. Finally, static states *transition* from one to another, especially when the zipper's hosting object is in use. For example, people open and close a backpack when it is used in daily activities.

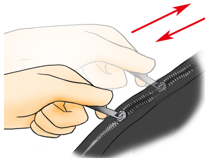
Opportunities for FG/BG interaction: Sensing the static state of a zipper can be used to enable background interaction with objects that have known consistency patterns. This allows the system to maintain an awareness of certain events or notify users of unwanted states (e.g., bag open in public) (**B1**).

Transitions between static states may reveal certain usage patterns of objects, for example to detect if a garment is not worn for an extended period (**B2**).

Users can slide open and close the zipper back and forth to trigger a certain action, however, this usage may potentially conflict with normal use of the object. Since the state of the zipper during this type of interaction may remain partially open, we call this type of foreground interaction *back-and-forth* in later analysis (**F1**).

Slider Motion

Observations: A zipper has two *states of motion*. *Moving*, when the zipper is in operation, or *stopped*. There are certain actions people may perform following a zipper operation. For example, before leaving home, a person may turn off the light after zipping close their jacket.



Opportunities for FG/BG interaction: Motion infers whether the zipper is currently in operation. This can be useful for triggering actions that coincide with zipper operation. Unlike detection of static states, slider motion is suitable for time-sensitive events that occur in response to a user's actions (**B3**).

As previous work suggests, sensing slider movement can be used in foreground interaction for controlling the value of a continuous valuable [13, 43] (**F2**).

Grip Locations

Observations: People generally pull the slider either by grabbing the *puller* fully or grabbing it partially by its *tip* (Figure 2). People occasionally grab the slider *body* when the puller is broken or missing. We did not see a clear consistency in how grip location differs in relation to the contexts of use.

Opportunities for FG/BG interaction: Gripping the zipper through different locations may trigger different actions for foreground interaction. Additionally, allowing the user to pull the slider from different locations enriches the input vocabulary of the slider motion (**F3**).

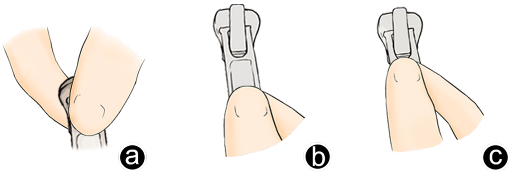


Figure 2. People generally pull the slider by (b) grabbing it partially by its tip or (c) grabbing the puller fully. People occasionally grab (a) the slider body.

Grips Types

Observations: In all of our observations, people used their thumb and index finger to *grip* the slider using a pinch gesture. However, a pinch may involve wither the *tip* or *side* of a finger against the thumb (Figure 3). There is not a clear usage pattern in how grip types differ in different use scenarios of a zipper.

Opportunities for FG/BG interaction: These two types of natural pinch gestures could be considered for triggering explicit actions for foreground interaction. As with grip location, allowing the use of different grip types enriches the input vocabulary of the slider motion (**F4**).

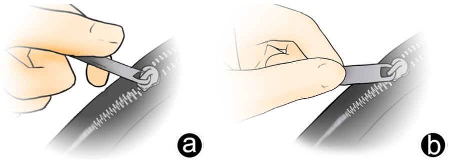


Figure 3. People usually use their thumb and index finger to grip the slider by pinching the thumb against (a) the side or (b) the tip of the index finger.

Operating Person

Observations: People primarily pull the zipper by themselves. However, in situations where the slider is out of reach (e.g., on the back of a dress), people find help by asking another person to pull the zipper on the user's behalf. In this regard, we learned that the access to the zipper even on a personal item may be given temporarily to another person.

Opportunities for FG/BG interaction: For background interaction, user recognition can be helpful for maintaining an awareness of the identity of a zipper operator. This allows new applications such as access control to be enabled on the zipper's hosting object (**B5**). User identification is unsuitable for foreground interaction.

Summary

Our observations provided insights into the naturally occurring interactions with zippers, which present a hidden vocabulary that can be useful for enabling background interaction [15] on their hosting objects. Additionally, we learned about several nuances of the ways zippers are commonly operated. These include various grip types, grip locations, slider motions, and transitions of the zipper's static states. These attributes can provide a potentially rich vocabulary for foreground interactions to trigger actions. However, we still lack the understanding of user preferences needed to inform the successful design of foreground interactions [28]. In the next section, we report an interview study to fill this gap.

FORMATIVE INTERVIEWS

We conducted an interview study to improve our understanding of user preferences of *foreground* interaction using the zipper operations we identified in the initial observation study.

Participants

We recruited 28 participants between 19 and 24 years old.

Figure 4. An example of the tested zippers: (a) front zipper of a jacket, (b) pocket zipper on the side of a jacket, (c) zipper of a backpack, and (d) zipper of a wallet

Tested Items

We based our investigations on a few common items that typically feature zippers: jackets, backpacks and wallets. We asked our participants to bring their own items to the study to provide a variety of object designs and materials for testing. The study focused on the front zippers of jackets, pocket zippers on the jacket sides, and the zippers of the main openings of backpacks and wallets (Figure 4).

The tested interaction techniques were based on the findings of our observational study. In particular, we included two *Grip Types (**F4**)* (side pinch, tip pinch; Figure 3), three *Grip Locations (**F3**)* (slider, puller, tip; Figure 2) and two *Slider*

*Motions **(F2)*** (move, stop). We also included the *Back-and-Forth* motion ***(F1)**,* which required participants to quickly zip open and close (or vice versa) the zipper at least once.

To enrich the input vocabulary, we added two new touch techniques based on the physical affordance of the flat puller: *Tap Puller* ***(F5)*** and *Swipe Puller* ***(F6)*** (Figure 5). These techniques resemble familiar touchscreen gestures. Tap Puller required participants to use a finger (e.g., thumb) to tap the outward-facing side of the puller. Swipe Puller required participants to swipe along the length of the puller. We did not restrict handedness or how the gestures should be performed.

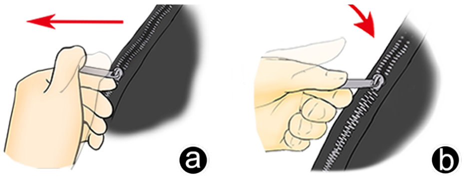


Figure 5. Additional techniques: (a) swipe, (b) tap the puller

For each of the four conditions, participants were asked to try one of each combination of Grip Type × Grip Location × Slider Motion. Since State Translation was a variation of Slider Motion, we allowed participants to try it using any choice of grip type and grip location. Finally, participants tried Tap Puller and Swipe Puller.

During the study, participants first tried each technique, then responded to the question "I see myself using the technique for input" using a 7-point Likert scale (with 1 being strongly disagree and 7 being strongly agree). Participants were encouraged to consider varying usage scenarios in their responses, including mobile and public environments as well as effort and comfort of use. They were asked to give scores without making comparisons between the techniques and tested objects. The zipper conditions were counter-balanced among participants.

Results and Discussion

We started our analysis by looking at the combination of Grip Type × Grip Location × Slider Motion. Analyses used Friedman signed-rank tests with Wilcoxon tests for pair-wise comparisons, with Bonferroni corrections.

Effect of Grip Location

Grip Location had a significant effect on preference scores ($\chi^2(482.6) = 2.2\text{e-}16$, $p < 0.01$). Generally, the techniques using the puller handle (not including the tip) received a preference score of 5 or above (mean: 5.7, SD: 1.6), regardless of grip type or slider motion. When using the puller tip, scores dropped to near neutral (4.2, SD: 1.7). Operating the zipper by holding the body of the slider was generally disliked (2.5, SD: 1.8; Figure 6).

Participants did not find it particularly difficult to grip the puller by its tip but were reluctant to spend effort finding it. Additionally, more effort has to be spent when pulling a puller by its tip: "*I had to hold the puller really hard when I pull the slider, especially when I passed through the curves"* (P11). As expected, such extra efforts became more pronounced on small pullers (e.g., jacket pocket).

Overall, participants found it difficult to operate a zipper by holding the body of the slider because it *"is hard to reach"* (P1). They also found it awkward with container objects: *"I can't close the zipper completely using this location because my thumb is stuck inside my jacket/bag"* (P5, P6) and *"it was very hard to pull it around the corner of my backpack and wallet"* (P7, P8).

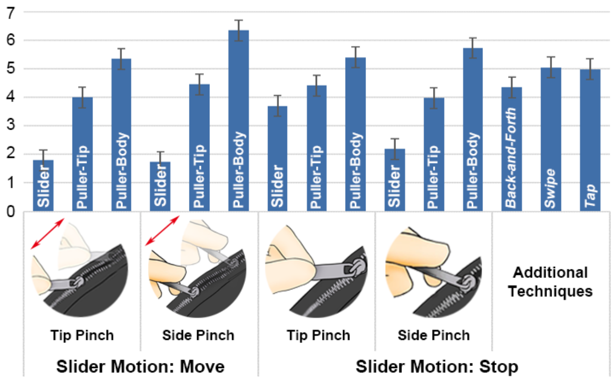


Figure 6. User preference scores shown by slider motion and grip type. Error bars show ±2 SE.

<u>Implications for FG interaction</u>: Techniques that involve holding the body of the slider should be avoided as it may burden user input. Holding the tip of the puller should only be considered if there is a strong need, for instance to allow a mode switch for a rarely-used interaction.

As gripping the slider body was strongly disliked by participants, we excluded this location from all following analyses to better understand the remaining options.

Effect of Grip Type

There was no significant effect of Grip Type on preference ($\chi^2(2.7) = 0.09$, $p = 0.1$). Grips using the thumb and tip of the index finger (tip pinch) received an average score of 4.9 (SD: 1.7), the thumb and side of the index finger (side pinch) received 5.0 (SD: 1.9). Both grips were considered "natural" (P2, P3) and "easy" (P5, P7, P8) to perform, despite situations where participants preferred one over the other, depending on comfort and puller location.

<u>Implications for FG interaction</u>*:* The two preferred grip types can be performed naturally, either by moving the slider for adjusting continuous value or without moving the slider for triggering discrete commands. An important benefit of the tangible pinch gestures is that users can perform them eyes-free without looking at their hand.

Another benefit is that they provide a subtle form of input which may improve social acceptability [3]. As one of our participants commented, *"such input is hardly noticeable, and I see myself using it when I do not want the others know that I am interacting with my device"* (P12).

Effect of Slider Motion

There was no significant effect of Slider Motion ($\chi^2(7.6) = 2.8$, p = 0.09) on preference. Scores for gripping the slider while moving and stopped were 4.4 (SD: 2.2) and 4.3 (SD: 2.1) respectively.

Implication for FG interaction: Participants were in general neutral about moving the slider as an input modality. Many of them mentioned that slider's travel distance has to be short. For example, a participant added *"it has to occur up high on my jacket when it is closed. This way sliding open or close the zipper does not interfere much of the normal use of my zipper, and I won't look awkward"* (P4). This indicates that the action is acceptable, but interaction designers have to be careful not to cause discomfort and social unease. If moving the slider has to be used for FG input, one possible solution to mitigate false positive is to design a gesture that can quickly trigger the sensing functionalities on the zipper. We see it an important future study to investigate the design parameters to minimize such impacts.

Back-and-Forth, Tap Puller and Swipe Puller

Back-and-Forth received a near neutral score (4.4; SD: 1.9). Social awkwardness was the main concern as sliding back and forth is not considered normal. Another interesting source of social awkwardness is the relatively loud noise from the slider rubbing the teeth. Participants also expressed concerns about "*risking revealing or losing items inside the wallet*" (P15).

Tap Puller received an average score of 5.1 (SD: 1.8). Participants found it easy to perform on most items except the pocket zipper since participants found it uncomfortable to extend the elbow out to reach puller. Some participant preferred to take a two-step approach by grabbing the puller first and then use the thumb to tab, while others skipped the first step by tapping the puller directly.

Swipe Puller received an average score of 5.0 (SD: 1.9). Unlike Tap Puller, most participants griped the puller first and then use the thumb to swipe, this allowed them to stabilize the puller first before swipe. A participant commented that *"this is as natural as me fidgeting the puller"* (P21). Participants also found it a bit hard to swipe the puller on the side of the jacket.

Implications for FG interaction: Tapping or swiping the puller can be a good addition to the other input techniques. Unlike the technique requiring the slider movement, tapping and swiping the puller is subtle, thus suitable to be used in public social scenarios.

Summary

Tap, Swipe, and the combinations of Grip Type and Slider Motion (excluding gripping the zipper body) are suitable for foreground interaction using a zipper. These techniques are in general small and easy to perform. The tangible nature of the zipper puller also makes it possible for the users to perform eyes-free input, making the zipper-based foreground interaction suitable for different types of social scenarios. A preference for subtle interaction was shown in multiple cases where participants indicated that unusual interactions in public or interactions leading to unwanted object states may make them feel awkward. Table 1 summarizes the suitable BG and FG interactions (indicated by ✔) identified in our two studies for different zipper operations.

SENSING REQUIREMENTS

Based on the outcomes of our observations and formative studies, we can infer several sensing requirements needed to enable foreground and background interaction.

The *static state*s of a zipper can be sensed through the location of the slider. For example, an optical sensor inside the slider can be used to count the number of teeth the slider moves across. This information can be used to infer whether the zipper is in operation or the location of the slider if the total number of teeth is known. The same method can be used for sensing *slider motion*. Sensing *grip location* is possible using capacitive sensing, which can also be used to sense tap puller and swipe puller. Sensing *grip type* is possible using Swept Frequency Capacitive Sensing [39] or the images of the fingerprint or visual landscape of the finger skin. The sensing techniques were also shown effective in sensing *operating person* [40].

Zipper Operations	**Background Interaction**	**Foreground Interaction**	**Sensing Options**
Static States (close vs open vs partially open)	✔ **(B1)**	×	IR sensor
State Transition (BG) **Back-and-Forth (FG)**	✔ **(B2)**	× **(F1)**	IR sensor
Slider Motion (move vs stop)	✔ **(B3)**	✔ **(F2)**	IR sensor
Grip Location (slider vs puller tip vs entire puller)	×	× **(F3)**	Capacitive sensing
Grip Type (tip pinch vs side pinch)	×	✔ **(F4)**	SFCS; Vision
User Identification	✔	×	SFCS; Vision
Touch Input (Tap and Swipe Puller)	×	✔ **(F5, F6)**	Capacitive sensing

Table 1. The BG and FG interactions suggested by our studies and the corresponding sensing options. The highlighted cells are implemented in our current prototype.

ZIPPRO PROTOTYPE

We developed a self-contained prototype to enable some of the interactions suggested by our studies (Figure 7). By implementing a subset of the derived sensing options (discussed below and summarized in Table 1), our device can sense slider location, slider motion, hand grips, user identification, and touch input on the puller. Our goal was to show initial technical feasibility and demonstrate the use cases of an interactive zipper.

Our prototype is composed of a 3D printed slider and puller. The slider was created in size 5 (~5mm wide when teeth are closed) and can replace the existing slider on a standard zipper of the same size. The motion and travel distance of the slider was sensed by counting the number of teeth during its movement through two embedded IR reflectance sensors (QRE1113, ON Semiconductor). The IR sensors were positioned on top of each opposing row of teeth and were placed 8.5 mm apart relative to the slider's moving direction, allowing for the detection of moving direction based on the phase difference in sensor signal (Figure 8). Due to this simple structure, the slider does not know its absolute position. Therefore, a calibration has to be performed in a selected origin, serving as a reference to measure the slider's relative position. For example, the origin can be at the bottom stop and can be specified by the user (e.g., tapping the puller).

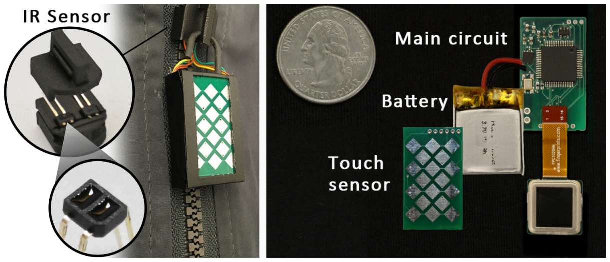


Figure 7. Zippro prototype, containing an IR sensor, capacitive sensor, fingerprint sensor, sensing board, and battery

Tapping and swiping the puller were sensed through a capacitive sensor, placed on the outward-facing side of the puller (Figure 7). Hand grip detection and user identification were implemented using a capacitive touch fingerprint sensor (FPC1020AM, FingerPrint) placed on the inward-facing side of the puller (Figure 7). The sensor has a resolution of 508 dpi and can capture images of 192 × 192 pixels with 8-bit depth for an area of 16.6 mm × 16.4 mm. The fingerprint sensor captures the skin landmarks, including the fingerprint of the index finger (Figure 9), allowing for the system to distinguish the two grip gestures and users. We used an open source software SourceAFIS [1] for user identification. When the system is not in use, the fingerprint sensor is kept in the deep sleep mode to save energy consumption. It wakes up upon a user touches the puller. It then captures an image of the contact area of the user's finger, which is sent to a laptop via Bluetooth for image processing and pattern recognition.

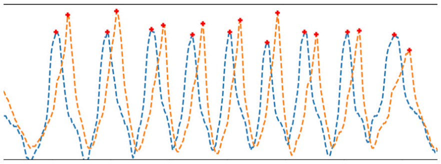


Figure 8 Raw signal from two IR proximity sensors. Peaks were used to count the teeth for calculating travel distance.

All the sensors and Bluetooth are handled by a Cortex M4 micro-controller (MK20DX256VLH7) powered by the Teensy 3.2 firmware, hosted on a custom-made PCB placed inside the puller of (18.5mm x 30.8mm x 5.5mm). The system is currently powered using a 150 mAh Lithium-Ion battery (19.8mm x 26.0mm x 3.8mm), also inside the puller. The power consumption of the entire system is 298.8 mW excluding the Bluetooth radio (99mW). As for sensing components, each IR sensor (QRE1113) has a power cost of 100mW and FPC1020 has a 10.8mW power cost. The rest of power is consumed by the Teensy framework. In a fully functioned mode, the current battery can sustain for about half of an hour use. However, all the sensing components are only activated when a touch event is detected, thus the device can remain functional for much longer without being charged. Power consumption can be significantly reduced using ultra-low power MCU and ADC, which we left for future work. Finally, software was implemented using Python running on a MacBook Pro.

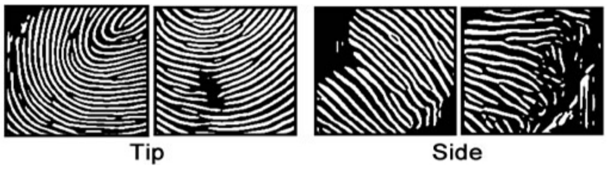


Figure 9. Raw image of the tip and side of the index finger captured by the fingertip sensor.

ZIPPRO EXAMPLE APPLICATIONS

With our prototype, we were able to develop several demo applications to demonstrate the possibilities of zipper-based interactions.

Background Interaction

Personal Item Security

We implemented our prototype on a backpack. As shown in Figure 10, the system tracks the static state of the bag and notify the user through a smartphone notification if the zipper is left in the open state during the user's journey home on a bus (detected by the phone's GPS) (**B1**). The system keeps notifying the user until the zipper is kept in a closed state (Figure 10). The user's phone's alarm goes off if the system detects that someone is sliding the zipper open (**B3**). Unlike the existing anti-theft zipper systems [2], the alarm of our system only goes off upon detecting that the operator is not the user (**B5**) (Figure 11).

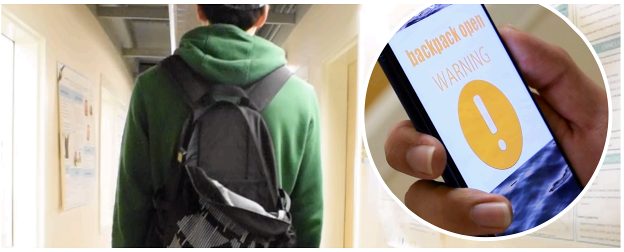


Figure 10. When a user's bag is accidentally left open, Zippro can notify the user on the phone.

Health Monitor

It is known that frequent urination can be a symptom of many health-related problems, such as kidney disease or diabetes [9, 44]. For example, frequent urination with an abnormally large amount of urine can be an early symptom of type 1 and type 2 diabetes [9]. Frequent urination could also be an indication of pregnancy in early weeks [44]. We developed our system on the fly front zipper of a pair of jeans to track urination frequency. The system monitors the zipper use through a day by counting the number of transitions between two static states (e.g., close → open or open → close) (**B2**). It notifies the user of any suspicious symptoms through the user's smartphone.

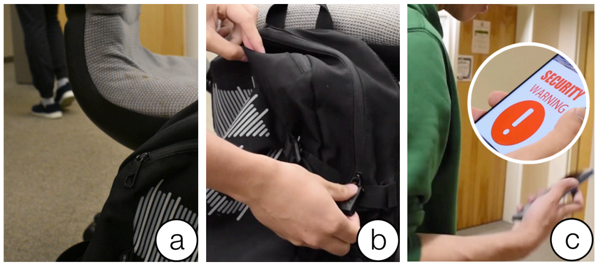


Figure 11. (a) A user leaves the bag behind in a public space; (b) a stranger tries to open the bag; (c) Zippro can notify the user.

Foreground Interaction

Facilitating Time-Sensitive Smartphone Use for BVI

Smartphones have become an important part of life for Blind and Visually Impaired (BVI) persons. However, in mobile scenarios, simple, frequent or time-sensitive actions (e.g., making/receiving calls or voice messages) can be very frustrating because interacting with the phone often necessitates both hands (e.g., pulling the phone out from a bag, unlocking the phone, and initiate voice input), which can be awkward when the user is holding a cane [46]. In this situation, Zippro can be an always-available interface to operate the phone. For example, a BVI user can listen to a voice message via wireless earphones by swiping on the puller (**F6**) (Figure 12), or use the tip pinch to make a call (**F4**). During the call, the user can swipe on the puller to adjust the volume of the sound. The user can hang up by tapping the puller (**F5**). We are working with the BVI community to study the usability of our approach.

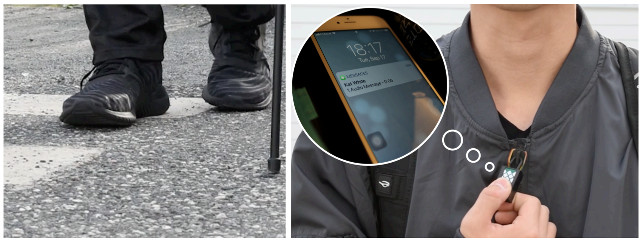


Figure 12. When there is a voice message coming, a BVI user can quickly listen to it using swipe without the need to reach the phone in the bag.

Subtle Interactions for Social Scenarios

We implemented our prototype on the zipper of the side pocket of a lightweight jacket. A user can use different pinch and touch gestures to interact with the puller to trigger simple commands, such as muting a smartphone (Figure 13), turning off/on the microphone of a home smart speaker, or listening to a voice message through wireless earphones (**F2, F5, F6**). Because the puller is tangible, it can be gripped without the user's visual attention. The benefit of such interaction is in social settings, such as in a meeting, where frequently performing these interactions can be considered inappropriate. Pinching or touching the puller does not reveal the user's interaction with a computing device because the action is ambiguous about whether the user is using technology or fidgeting the puller.

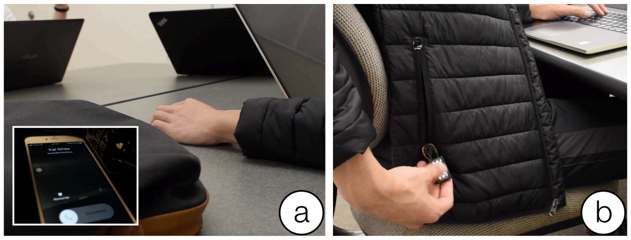


Figure 13. (a) A user's phone is ringing in a meeting; (b) the user can mute the phone unobtrusively by "fidgeting" the puller on the side of the jacket.

EVALUATION OF ZIPPRO PROTOTYPE

We conducted a series of experiments to evaluate our prototype. The first study measured the tracking accuracy of the slider movement. The second study measured the recognition accuracy of the touch gestures. Finally, the third study measured the recognition accuracy of grip gestures and user identification.

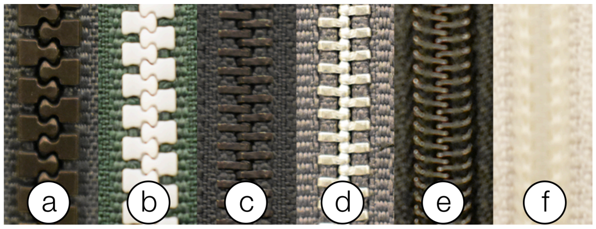


Figure 14. The tested types of teeth: (a-b) black and white vislon; (c-d) black and white metal; (e-f) black and white coil

Slider Movement

We conducted an initial experiment to evaluate the robustness of our system against teeth made of various materials of different colors. We included three common teeth variations: metal, coil, and vislon (Figure 14). We chose teeth colors with a wide variance in light reflectivity to test the robustness of our approach using IR. In particular, we chose black and silver for the metal teeth and black and white for the coil and vislon teeth. The width of teeth when closed are between 5-6 mm (e.g., size 5) across all the six tested zippers. The thickness and spacing of the teeth vary across different types of zippers. We sewed the zippers on six lightweight jackets. During the test, participants wore the jackets and operated the zippers in the vertical direction. This study was carried out with ten right-handed participants (average age: 20.8, 3 female).

Data Collection

The participants were asked to pull the slider to either open or close the zipper from its top or bottom stop. We also included three travel distances: short (12 cm), medium (24 cm), and long (36 cm) (Figure 15a). The start and end positions were marked using a tape. During the study, the order of the presentation of the teeth material and color was randomized. Participants were asked to pull the zipper in a normal and comfortable speed. In total, there are 3 Tooth Types (metal, coil, and vision) × 2 Colors (black and white) × 2 Directions (open and close) × 3 Distances (short, medium, and long) × 5 Repetitions = 180 data points.

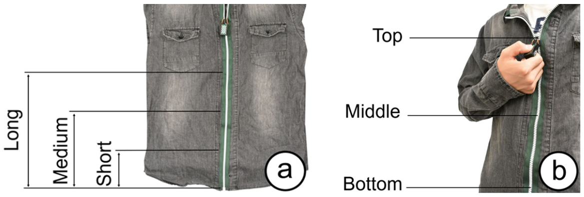


Figure 15 Demonstration of study conditions: (a) three travel distances and (b) three tested locations for the touch gestures.

Results

To determine the accuracy of our prototype, we calculated tracking error by comparing the detected number of teeth with a manual count of the actual teeth traveled. Data was analyzed using a repeated measured ANOVA considering that the tracking error was related to *Travel Distance*, and the *Color* and *Material* of zipper teeth.

	Metal (black)	**Metal (silver)**	**Vislon (black)**	**Vislon (white)**	**Coil (black)**	**Coil (white)**
Teeth length	2.36mm	2.46mm	3.07mm	3.04mm	1.47mm	1.43mm
Tracking Error	0.38%	0.33%	0.25%	0.47%	0.21%	0.62%

Table 2. Tracking errors in different teeth conditions.

Overall, data was collected for a moving distance of around 7.2 m for each tooth type. The average error is 0.067 cm for each zipper pull, or 0.38% (S.D. = 0.21%) of the total distance travelled across all the six tested tooth types. This is encouraging as the result shows that our sensing technique can track the slider movement with a high accuracy across common teeth types and colors. Details are shown in Table 2. ANOVA yielded no significant effect of *Material* ($F_{2,18} = 1.219,\ p = 0.3$) and *Travel Distance* ($F_{2,18} = 1.215,\ p = 0.32$) but a significant effect of *Color* ($F_{1,9} = 23.04,\ p < 0.001$). Pairwise post-hoc t-test adjust with Bonferroni method shows significantly more tracking errors on the white teeth than the black teeth ($p < 0.01$). We believe this is because white color surface is more reflective, which might lead to higher ratio of noise received by the proximity sensor. No error was found in detecting travel direction.

Touch Gestures

For the touch gesture recognition on the puller, we tested 3 gestures: tap, swipe up, and swipe down. A different group of ten right-handed participants (average age: 23, 1 female) were recruited to participate in this study.

Data Collection

Participants were asked to perform each of these gestures on the front zipper of a jacket worn on their body. To simulate different start positions of the slider before a zipper operation, participants performed each gesture 10 times on the puller with the slider located near the top, bottom, and middle of the zipper jacket (Figure 15b). They were asked to perform the tasks in a standing position using their dominant hand, as naturally as possible. The slider locations were counter-balanced among participants, and gesture type was presented in a random order. In total, there are 3 Gestures × 3 Locations × 10 Repetitions × 10 participants = 900 trials.

Results

All the three gestures, including tap, swipe up, and swipe down were successfully detected with an accuracy of 100%. This is unsurprising as capacitive sensing is known to be robust in sensing these simple gestures. However, the result serves as an evidence of the effectiveness of our implementation.

Grip Gestures and User Identification

We tested two grip gestures (i.e., pinch using the tip or side of the index finger) with the same 10 participants recruited in the touch gesture recognition study.

Data Collection

Labelled ground-truth data for user identification was collected the day before the study. During data collection, participants performed the two grip gestures (tip vs side pinch) 10 times each for the system to capture the skin landmark information on the tip and side of the index finger. Participants were not restricted to which part of the skin they had to present to the sensor.

Participants returned on the test day and repeated each grip gesture 10 times on the puller located near the top, bottom, and middle of the front zipper of a jacket worn on the body. The data was used for grip gesture recognition and user identification. Similar to the touch gesture study, the slider locations were counter-balanced among participants, and grip type was ordered randomly. In total, there were 2 Grips × 3 Locations × 10 Repetitions × 10 participants = 600 data points collected for analysis.

Results

Grip recognition. The collected data was first augmented by rotating and shearing the original images to ensure a better training performance. The data was then used to train a binary Convolution Neural Network (CNN) classifier. We conducted a leave-one-out cross validation, where data from 9 users was combined for 25 epochs of training and the single remaining user's data used for testing. The result yielded an average accuracy of 97.7% (s.e. = 1.3%).

User identification. The collected data was analyzed with the built-in classifier provided by SourceAFIS [1], using false accept rate (FAR) and false reject rate (FRR). FAR is the measure of the likelihood that our system incorrectly accepted an access attempt by an unauthorized user. It is calculated as the ratio of the number of false acceptances divided by the number of identification attempts. For each participant, we tested the system trained using their data collected in the first day against the data from the remaining nine participants collected in the second day. The final FAR is the average of the FARs for all the participants. FRR is the measure of the likelihood that our system incorrectly rejected an access attempt by an authorized user. It is the ratio of the number of false recognitions divided by the number of attempts. For each participant we tested the system trained using their data collected in the first day against their own data collected in the second day. The final FRR is the average of the FRRs for all the participants.

Depending on the choice of the classification threshold, the FRR increases with the decrease of FAR [24] , so a balance needs to be stroke based on the need of an application. To understand the relationship between FAR and FRR of our device, we calculated them by iterating all the thresholds defined by SourceAFIS (Figure 16). As shown in the figure, FAR and FRR for the side pinch are higher than those of the tip pinch. This is because there is less unique skin landmark on this part of the finger. Note that in SourceAFIS, threshold 20 was designed to have a FAR of 1%, which matches the result of our evaluation using the tip pinch (1%). Based on the result, we used a threshold of 26 for our system, which corresponds to the FRR and FAR of 10% and 0.1% respectively for the tip pinch and 37% and 1% respectively for the side pinch. We see this setting useful for security related applications.

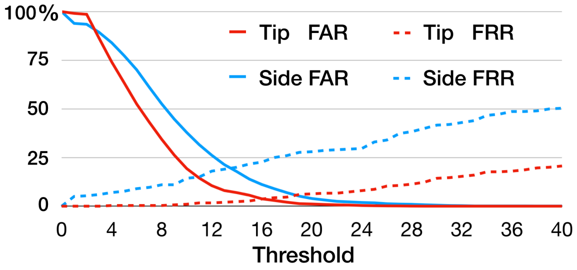


Figure 16. False reject rate (FRR) and false accept rate (FAR) of index tip and index side fingerprints across 10 participants.

LIMITATIONS AND FUTURE WORK

The user studies, prototype and demo scenarios show the opportunities for zipper input for foreground and background interactions and their feasibility in everyday usage scenarios. However, this exploratory work leaves many avenues for future exploration.

This work derived a set of possible operations and gestures from observations of YouTube videos. It is worth repeating here that this method is prone to potential biases of social media and proprietary algorithms, which may have caused some fruitful options to be missed. For instance, operations such as touching the zipper teeth with the fingers or contacting the zipper against other objects did not occur in our observations but could provide alternative interaction techniques. Our interviews also included only a small set of objects and the participant preferences do not generalize to the multitude of other everyday objects that contain zippers.

This work focused on the opportunities available for foreground and background interaction and did not investigate some important aspects such as the discoverability, memorability or learnability of particular gestures. Whereas background input may work well without any direct awareness of the users, the successful design of foreground interaction is dependent on the user's ability to know which operations are available at any given time and how to invoke them. Exploring the output of zipper (ex: adding vibro-tactile feedback, adding braking or lock to zipper) could be one of the possibilities to signal the users, and future work is needed to fill this gap.

Through our hardware implementation we demonstrated that a rich set of sensing capabilities can be implemented into a very small zipper form factor. However, the performance of the sensing techniques can be further improved. For example, our current prototype was only able to reliably identify the user when gripping the puller using the tip pinch. Efforts are currently underway to incorporate other sensing techniques, such as those based on impedance [40] to improve the performance of our system. Our current prototype needs further iterations to completely solve the practical issues. For washing, the current implementation can be easily removed for the cloth to be washed. For charging, a power management circuit can be integrated into our current design, allowing the battery to be charged via Micro USB interface.

Our initial studies identified opportunities that our implementation was not able to detect. These include detection of the user's grip location, which could potentially be solved with a design that provides a finer resolution of a capacitive sensing on the puller. Another technical challenge left for future work is to distinguish a user's intentional touches from incidental touches to avoid false positives. Furthermore, it may be useful to explore potential gestures (e.g. a tap) to delineate the start of an intentional input sequence [37] to help the zipper differentiate between explicit foreground and implicit background interactions.

CONCLUSION

This paper explored the possibilities of interaction with ubiquitous zipper-bearing objects, with a focus on opportunities for foreground and background interactions. An observation study of YouTube videos containing everyday objects identified several zipper operations and potential vocabularies for foreground and background tasks. Formative interviews investigated user preferences for several foreground gestures when performed with different types of zippers. We then identified options for sensing various types of input and built a self-contained prototype, Zippro that can replace a common zipper slider. We evaluated Zippro when sown onto a jacket. Results show the feasibility of sensing several types of input we identified, including zipper location, gestures on the puller surface, grip type, and user identity. Finally, we demonstrate a number of potential applications that leverage the opportunities of foreground and background interaction with everyday objects.

REFERENCES

[1] Robert Važan. SourceAFIS. 2019. Retrieved August 01, 2019 from https://sourceafis.machinezoo.com/net

[2] Ti Ti Backpack. 2019. Retrieved August 03, 2019 from https://www.kickstarter.com/projects/1193270057/ti-ti-backpack-an-intelligent-zipper-alarm-backpac

[3] Fraser Anderson, Tovi Grossman, Daniel Wigdor and George Fitzmaurice. 2015. Supporting subtlety with deceptive devices and illusory interactions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing System* (CHI '15), 1489-1498. DOI: https://doi.org/10.1145/2702123.2702336

[4] Luigi Atziori, Antonio Iera and Giacomo Morabito. 2010. The Internet of Things: A Survey. DOI: https://doi.org/10.1016/j.comnet.2010.05.010

[5] Mohamad Zairi Baharom, Frank Delbressine and Loe Feijs. 2016. Kinematics analysis of A robotic zipper prototype for miniaturization. *Int. J. Mech. Eng. Robot. Res*, 5 (4). 305-310. DOI: https://doi.org/10.18178/ijmerr.5.4.305-310

[6] Joanna Berzowska and Maksim Skorobogatiy. 2010. Karma chameleon: bragg fiber jacquard-woven photonic textiles. In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction* (TEI '10), 297-298. DOI: https://doi.org/10.1145/1709886.1709950

[7] Bill Buxton. 1995. Integrating the Periphery & Context: A New Model of Telematics. In *Proceedings of graphic interface 1995* (GI '95), 239-239. DOI: https://doi.org/10.20380/GI1995.28

[8] Jingyuan Cheng, Mathias Sundholm, Bo Zhou, Marco Hirsch and Paul Lukowicz. 2016. Smart-surface: Large scale textile pressure sensors arrays for activity recognition. *Pervasive and Mobile Computing*, 30. 97-112. DOI: https://doi.org/10.1016/j.pmcj.2016.01.007

[9] Nathaniel G Clark, Kathleen M Fox and Susan Grandy. 2007. Symptoms of diabetes and their association with the risk and presence of diabetes: findings from the Study to Help Improve Early evaluation and management of risk factors Leading to Diabetes (SHIELD). *Diabetes Care*, 30 (11). 2868-2873. DOI: https://doi.org/10.2337/dc07-0816

[10] Artem Dementyev, Tomás Vega Gálvez and Alex Olwal. 2019. SensorSnaps: Integrating Wireless Sensor Nodes into Fabric Snap Fasteners for Textile Interfaces. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, 17-28. DOI: https://doi.org/10.1145/3332165.3347913

[11] Laura Devendorf, Joanne Lo, Noura Howell, Jung Lin Lee, Nan-Wei Gong, M Emre Karagozler, Shiho Fukuhara, Ivan Poupyrev, Eric Paulos and Kimiko Ryokai. 2016. I don't want to wear a screen: probing perceptions of and possibilities for dynamic displays on clothing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing System* (CHI '16), 6028-6039. DOI: https://doi.org/10.1145/2858036.2858192

[12] Barrett Ens, Tovi Grossman, Fraser Anderson, Justin Matejka and George Fitzmaurice. 2015. Candid interaction: Revealing hidden mobile and wearable computing activities. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, 467-476. DOI: https://doi.org/10.1145/2807442.2807449

[13] Scott Gilliland, Nicholas Komor, Thad Starner and Clint Zeagler. 2010. The Textile Interface Swatchbook: Creating graphical user interface-like widgets with conductive embroidery. in *International Symposium on Wearable Computers* (ISWC '10), IEEE, 1-8. DOI: https://doi.org/10.1109/ISWC.2010.5665876

[14] Grace Clarke Hillyer, Sarah A MacLean, Melissa Beauchemin, Corey H Basch, Karen M Schmitt, Leslie Segall, Moshe Kelsen, Frances L Brogan and Gary K Schwartz. 2018. YouTube Videos as a Source of Information About Clinical Trials: Observational Study. *JMIR cancer*, 4 (1). DOI: https://doi.org/10.2196/10060

[15] Ken Hinckley, Jeff Pierce, Eric Horvitz and Mike Sinclair. 2005. Foreground and background interaction with sensor-enhanced mobile devices. *ACM Transactions on Computer-Human Interaction* (TOCHI '05), 12 (1). 31-52. DOI: https://doi.org/10.1145/1057237.1057240

[16] Paul Holleis, Albrecht Schmidt, Susanna Paasovaara, Arto Puikkonen and Jonna Häkkilä. 2008. Evaluating capacitive touch input on clothes. In *Proceedings of the 10th international conference on Human computer interaction with mobile devices and services* (MobileHCI '08), 81-90. DOI: https://doi.org/10.1145/1409240.1409250

[17] Elias Howe. 1857. Improvement in Fastenings for Garments. U.S. Patent 8,540, issued November 25, 1851.

[18] Whitcomb Judson. 1893. Shoe-fastening. U.S. Patent 504,037, Filed August 17, 1892 issued July 29, 1893.

[19] Thorsten Karrer, Moritz Wittenhagen, Leonhard Lichtschlag, Florian Heller and Jan Borchers. 2011. Pinstripe: eyes-free continuous input on interactive clothing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing System* (CHI '11), 1313-1322. DOI: https://doi.org/10.1145/1978942.1979137

[20] M Laeeq Khan. 2017. Social media engagement: What motivates user participation and consumption on YouTube? *Computers in Human Behavior*, 66. 236-

247.
DOI: https://doi.org/10.1016/j.chb.2016.09.024

[21] Konstantin Klamka and Raimund Dachselt. 2018. ARCord: Visually Augmented Interactive Cords for Mobile Interaction. In *CHI '18 Extended Abstracts on Human Factors in Computing Systems* (CHI EA '18), LBW623.
DOI: https://doi.org/10.1145/3170427.3188456

[22] Tae Ho Lee, Eung Soo Kim, Tae Hoon Kim and Myung Yung Jeong. 2015. Simple pressure sensor for a vehicle seat using a woven polymer optical-fiber sheet. *Journal of the Korean Physical Society*, 67 (11). 1947-1951.
DOI: https://doi.org/10.3938/jkps.67.1947

[23] Diana Marculescu, Radu Marculescu, Nicholas H Zamora, Phillip Stanley-Marbell, Pradeep K Khosla, Sungmee Park, Sundaresan Jayaraman, Stefan Jung, Christl Lauterbach and Werner Weber. 2003. Electronic textiles: A platform for pervasive computing. *Proceedings of the IEEE*, 91 (12). 1995-2018.
DOI: https://doi.org/10.1109/JPROC.2003.819612

[24] Alvin Martin, George Doddington, Terri Kamm, Mark Ordowski and Mark Przybocki. 1997. The DET curve in assessment of detection task performance, National Inst of Standards and Technology Gaithersburg MD.

[25] Jan Meyer, Bert Arnrich, Johannes Schumm and Gerhard Troster. 2010. Design and modeling of a textile pressure sensor for sitting posture classification. *IEEE Sensors Journal*, 10 (8). 1391-1398.
DOI: https://doi.org/10.1109/JSEN.2009.2037330

[26] Cameron S. Miner, Denise M. Chan and Christopher Campbell. 2001. Digital jewelry: wearable technology for everyday life. In *CHI '01 Extended Abstracts on Human Factors in Computing Systems* (CHI EA '01), 45-46.
DOI: https://doi.org/10.1145/634067.634098

[27] Daniele Miorandi, Sabrina Sicari, Francesco De Pellegrini and Imrich Chlamtac. 2012. Internet of things: Vision, applications and research challenges. *Ad hoc networks*, 10 (7). 1497-1516.
DOI: https://doi.org/10.1016/j.adhoc.2012.02.016

[28] Donald A Norman and Stephen W Draper. 1986. *User centered system design: New perspectives on human-computer interaction*. CRC Press.

[29] Alex Olwal, Jon Moeller, Greg Priest-Dorman, Thad Starner and Ben Carroll. 2018. I/O Braid: Scalable Touch-Sensitive Lighted Cords Using Spiraling, Repeating Sensing Textiles and Fiber Optics. In *Proceedings of The 31st Annual ACM Symposium on User Interface Software and Technology*, 485-497.
DOI: https://doi.org/10.1145/3242587.3242638

[30] Patrick Parzer, Florian Perteneder, Kathrin Probst, Christian Rendl, Joanne Leong, Sarah Schuetz, Anita Vogl, Reinhard Schwoediauer, Martin Kaltenbrunner and Siegfried Bauer. 2018. RESi: A Highly Flexible, Pressure-Sensitive, Imperceptible Textile Interface Based on Resistive Yarns. In *Proceedings of The 31st Annual ACM Symposium on User Interface Software and Technology*, 745-756.
DOI: https://doi.org/10.1145/3242587.3242664

[31] Patrick Parzer, Kathrin Probst, Teo Babic, Christian Rendl, Anita Vogl, Alex Olwal and Michael Haller. 2016. FlexTiles: a flexible, stretchable, formable, pressure-sensitive, tactile input sensor. In *CHI '16 Extended Abstracts on Human Factors in Computing Systems* (CHI EA '16), 3754-3757.
DOI: https://doi.org/10.1145/2851581.2890253

[32] Patrick Parzer, Adwait Sharma, Anita Vogl, Jürgen Steimle, Alex Olwal and Michael Haller. 2017. SmartSleeve: real-time sensing of surface and deformation gestures on flexible, interactive textiles, using a hybrid gesture detection pipeline. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*, 565-577.
DOI: https://doi.org/10.1145/3126594.3126652

[33] E Rehmi Post, Maggie Orth, Peter R Russo and Neil Gershenfeld. 2000. E-broidery: Design and fabrication of textile-based computing. *IBM Systems journal*, 39 (3.4). 840-860.
DOI: https://doi.org/10.1147/sj.393.0840

[34] Ivan Poupyrev, Nan-Wei Gong, Shiho Fukuhara, Mustafa Emre Karagozler, Carsten Schwesig and Karen E Robinson. 2016. Project Jacquard: interactive digital textiles at scale. In *Proceedings of the SIGCHI Conference on Human Factors in Computing System* (CHI '16), 4216-4227.
DOI: https://doi.org/10.1145/2858036.2858176

[35] Mahsan Rofouei, Wenyao Xu and Majid Sarrafzadeh. 2010. Computing with uncertainty in a smart textile surface for object recognition. in *2010 IEEE Conference on Multisensor Fusion and Integration*, IEEE, 174-179.
DOI: https://doi.org/10.1109/MFI.2010.5604473

[36] Markus Rothmaier, Minh Luong and Frank Clemens. 2008. Textile pressure sensor made of flexible plastic optical fibers. *Sensors*, 8 (7). 4318-4329.
DOI: https://doi.org/10.3390/s8074318

[37] Jaime Ruiz and Yang Li. 2011. DoubleFlip: a motion gesture delimiter for mobile interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing System* (CHI '11), 2717-2720.
DOI: https://doi.org/10.1145/1978942.1979341

[38] T. Scott Saponas, Chris Harrison and Hrvoje Benko. 2011. PocketTouch: Through-Fabric Capacitive Touch Input. In *Proceedings of The 24st Annual ACM Symposium on User Interface Software and Technology*, 303-308.
DOI: https://doi.org/10.1145/2047196.2047235

[39] M. Sato, I. Poupyrev and C. Harrison. 2012. Touché: Enhancing Touch Interaction on Humans, Screens, Liquids, and EverydayObjects. In *Proceedings of the SIGCHI Conference on Human Factors in Computing System* (CHI '12), 483-492. DOI: https://doi.org/10.1145/2207676.2207743

[40] Munehiko Sato, Rohan S Puri, Alex Olwal, Yosuke Ushigome, Lukas Franciszkiewicz, Deepak Chandra, Ivan Poupyrev and Ramesh Raskar. 2017. Zensei: Embedded, multi-electrode bioimpedance sensing for implicit, ubiquitous user recognition. In *Proceedings of the SIGCHI Conference on Human Factors in Computing System* (CHI '17), 3972-3985. DOI: https://doi.org/10.1145/3025453.3025536

[41] Stefan Schneegass and Alexandra Voit. 2016. GestureSleeve: using touch sensitive fabrics for gestural input on the forearm for controlling smartwatches. In *Proceedings of the 2016 ACM International Symposium on Wearable Computers* (ISWC '16), 108-115. DOI: https://doi.org/10.1145/2971763.2971797

[42] M Sergio, N Manaresi, M Tartagni, R Guerrieri and R Canegallo. 2002. A textile based capacitive pressure sensor. in *SENSORS, 2002 IEEE*, IEEE, 1625-1630. DOI: https://doi.org/10.1109/ICSENS.2002.1037367

[43] Cátia Sousa and Ian Oakley. 2011. Integrating feedback into wearable controls. in *IFIP Conference on Human-Computer Interaction*, Springer, 556-559. DOI: https://doi.org/10.1007/978-3-642-23768-3_81

[44] L Viktrup, G Lose, M Rolf and K Barfoed. 1993. The frequency of urinary symptoms during pregnancy and puerperium in the primipara. *International Urogynecology Journal*, 4 (1). 27-30. DOI: https://doi.org/10.1007/BF00372807

[45] Akira Wakita and Midori Shibutani. 2006. Mosaic textile: wearable ambient display with non-emissive color-changing modules. In *Proceedings of the 2006 ACM SIGCHI international conference on Advances in computer entertainment technology* (ACE '06), 48. DOI: https://doi.org/10.1145/1178823.1178880

[46] Ruolin Wang, Chun Yu, Xing-Dong Yang, Weijie He and Yuanchun Shi. 2019. EarTouch: Facilitating Smartphone Use for Visually Impaired People in Public and Mobile Scenarios. In *Proceedings of the SIGCHI Conference on Human Factors in Computing System* (CHI '19). 1-13, DOI: https://doi.org/10.1145/3290605.3300254

[47] Mark Weiser. 1999. The computer for the 21st century. *SIGMOBILE Mob. Comput. Commun. Rev.*, 3 (3). 3-11. DOI: https://doi.org/10.1145/329124.329126

[48] Wenyao Xu, Ming-Chun Huang, Navid Amini, Lei He and Majid Sarrafzadeh. 2013. ecushion: A textile pressure sensor array design and calibration for sitting posture analysis. *IEEE Sensors Journal*, 13 (10). 3926-3934. DOI: *https://doi.org/10.1109/JSEN.2013.2259589*