Pinstripe: Eyes-free Continuous Input on Interactive Clothing

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ABSTRACT
We present Pinstripe, a textile user interface element for eyes-free, continuous value input on smart garments that uses pinching and rolling a piece of cloth between your fingers. The input granularity can be controlled in a natural way by varying the amount of cloth pinched. Pinstripe input elements physically consist of fields of parallel conductive lines sewn onto the fabric. This way, they can be invisible, and can be included across large areas of a garment. Pinstripe also addresses several problems previously identified in the placement and operation of textile UI elements on smart clothing. Two user studies evaluate ideal placement and orientation of Pinstripe elements on the users' garments as well as acceptance and perceived ease of use of this novel textile input technique.

Author Keywords
smart textiles, wearable computing, eyes-free interaction, continuous input.

ACM Classification Keywords
H5.2 Information interfaces and presentation: User Interfaces—*Haptic I/O*

General Terms
Experimentation

INTRODUCTION
'Smart clothing' incorporates electronic circuits in garments, whether to control devices, to take measurements, or to output information. It is often viewed as a branch of the more general 'wearable computing' characterized by the fact that the controls or even the complete systems are tightly integrated into fabrics or garments and more closely related to their functionality. One early example of smart clothing was introduced by Rantanen et al. in 2002; their arctic suit [17] incorporates a wearable computer with a control element that was designed specifically for the wearable context and integrated in the garment itself.

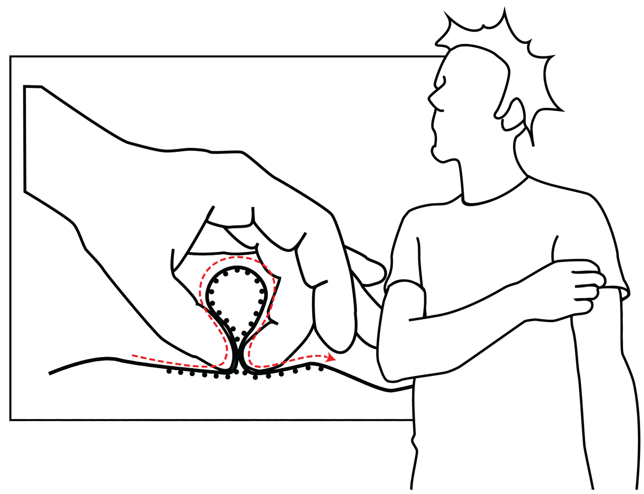

Figure 1. To use Pinstripe, you pinch and roll a fold of your garment between your fingers. This easy gesture allows you to control a linear value on a mobile device.

Closely related to Mark Weiser's vision of ubiquitous computing [21], smart clothing makes computing invisible and, in the very sense of the word, part of the fabric of everyday life [11]. Garments containing electronic circuits or controls can be made to be visually unobtrusive and interacting with them has a chance to be socially more acceptable than openly fiddling with the interface of mobile devices such as cell phones or music players [20]. Current smart clothing systems range from DIY approaches [1] to a small number of commercially available textile music player controls (e.g., Rosner mp3blue[1]) and specialized systems in the areas of health care or sports (e.g., the 'Nike + iPod' system[2][3]).

Still, designing user interface elements for such e-textiles is hard which may be one of the reasons for the relative absence of commercial success [10] (with the notable exception of the systems mentioned above). A multitude of challenges presents itself when trying to design, engineer, and manu-

[1] http://www.mp3blue.de
[2] http://nikerunning.nike.com/nikeplus
[3] http://www.apple.com/ipod/nike

facture smart clothing which can be roughly divided into the following four areas:

Wearability, although several definitions exist, commonly demands that the electronic component of smart clothing should not influence the main functionality of the clothing itself. This includes—but is not limited to—wearing comfort, body temperature distribution and insulation, or breathability of the fabric [11, 12, 13]. A more thorough discussion on wearability and a set of guidelines for the design of wearable systems is given by Gemperle et al. [2].

Fashion compatibility asks for the electronic and interactive components in clothes not to interfere with the visual aesthetics of the garment or, ideally, to be invisible altogether [4, 14, 11, 20].

Durability is another quality that is crucial for the success of smart clothing. Just as regular garments are engineered to withstand many cycles of staining, washing, and drying, smart clothes have to exhibit the same resilience towards this kind of regular use [10].

Most importantly though, the *interaction* with control elements on smart clothing poses a set of challenges by itself [12]. They should not activate involuntarily [9], and since their surface area is delimited, they need to be easy to detect on the clothing through visual or haptic cues [4]. Their position on the body frequently shifts with changing body posture and with movement, and users on the move often require eyes-free, one-handed operation [4]. Existing systems, however, mostly resemble buttons that activate on touch; as such they are difficult to operate eyes-free and support discrete input only.

We propose Pinstripe, a textile UI element that builds upon the natural affordances of cloth and textiles and which addresses these challenges. Pinstripe lets users pinch and roll a fold of their garment between their fingers to to input continuous values (Figure 1).

RELATED WORK

Holleis et al. [4] already identify many of the problems described above. The paper presents a valuable set of guidelines to the design of wearable control elements and is one of the relatively few works to include user studies. It emphasizes the need for eyes-free, one-handed interaction and methods to ensure that commands cannot be initiated accidentally. The paper also discusses the importance of where to place control elements across the body and that these positions may change with body posture. While these results are being supported by a number of studies, the paper only takes capacitive (textile) buttons as input elements into account. Thus, we conducted a similar user test to verify the findings in case of the Pinstripe UI element.

Schwarz et al. [18] use the headphone cord of an MP3 player as an input device that can be twisted and tugged. The design is also based on the deformation of a flexible piece worn on the user's body, making the interaction gesture similar to Pinstripe, although its location is constrained to the length of the cable. The paper also mentions the requirement of wearable systems to be suitable for eyes-free operation. The system, however, is not textile-based or designed as an invisible part of a garment.

Recently, Gilliland et al. [3] explored conductive embroidery for user input widgets, most notably the 'electronic pleat'. It consists of a row of folds in the textile which detect if bend to the left or right. Similar to Pinstripe, the user can give directional and continuous value input depending on the amount of pleats folded, but the pleats change the surface structure of the garment.

Komor et al. [9] propose a chording button interface to reduce involuntary activations of textile controls. While effective, it required a higher mental effort and was slower to use than standard textile buttons. Their paper also discusses the influence of body posture on the users' ability to locate and operate control elements and reports on the difficulties that arise from the observation that different locations of the interface on the garment may afford very different interaction gestures. Our first study tries to support and complement these observations with regard to Pinstripe.

Strachnan et al. [19] present BodySpace, a portable device to build a UI element that changes its control dimension according to which position on the body it is located at that moment. Holding the device at the hip and tilting it changes the volume of a music player; holding the device next to the ear that gesture is mapped to switching tracks. Although this method solves the problem of requiring the user to find and acquire an input element that is fixed to a potentially moving position on the body or garment, it requires an external control device. Pinstripe adopts the concept of mapping functionalities to coarser body areas and being laxer about precise control positioning. At the same time, similar to BodySpace, the control gesture itself has much more expressiveness than a button press.

Kim et al. [8] performed a Wizard-of-Oz study to explore the suitability of a plethora of wearable objects for controlling a music player. Participants were given free choice as to the location and precise nature of the control gestures they were applying to the different pieces of clothing. Apart from the inspiration that can be drawn from many of the observed interactions, one important result is the difficulties users had in differentiating between the directions of symmetric control mappings (e.g. volume up/down) where no natural mapping was evident. This problem also applies—to a lesser extent—to techniques like Pinstripe as we found out in our studies .

Jung et al. [6] built a working prototype of a wearable music player that is controlled via a textile keypad. The main focus of their work lies with the demonstration of the feasibility to engineer and build such a system. Together with the work done by Post et al. [15] and Quirk et al. [16] and the experiments by Linz et al. [10], they provide valuable insight into the process and caveats of manufacturing electronic components that are embedded into textiles.

An outline of this work has been accepted as a non-archival poster submission [7] for the ACM UIST 2010 conference.

SYSTEM DESIGN

The key idea of Pinstripe is to build upon two characteristic affordances of textiles: grasping and deforming. Most clothes exhibit loose folds in different areas when worn, and Pinstripe makes use of this fact: It lets wearers provide input by pinching a part of their clothing between their thumb and another finger, creating a fold in the garment, and then rolling this fold between their fingers (Figure 1). This rolling movement changes the relative displacement of the two sides of the fold, which is measured by conductive threads sewn into the fabric, and interpreted as a continuous change in value.

This design allows us to counter the *interaction* problems mentioned above: Pinstripe is operated one-handed, and since it is not necessary to create the fold at an exact location on the garment (control is *non-local*), Pinstripe is particularly well-suited for eyes-free operation. These non-local controls also make Pinstripe highly robust against the garment shifting relative to the body during movement. While a button implemented as a local capacitive touch sensor, for example, may change its position from the back of the wrist to its side when the sleeve of the garment twists, Pinstripe works equally well no matter which part of the general wrist area the input gesture is applied to. Also, Pinstripe does not directly activate when being touched, greatly reducing the problem of involuntary activation. The user first has to pinch a fold into the garment, a gesture which is quick and easy to perform but rarely done accidentally. Body areas like the joints, where involuntary garment folding is common or desired, are, of course, less suited for Pinstripe.

The active areas thus do not need to be highlighted on the garment, and since the conductive threads only run along the inside of the textile, their impact on *fashion* is minimal. The *wearability* of the garment is not impaired either; the sensor is flexible and the threads are spaced apart enough to allow breathability and preserve other engineered properties of the fabric. Running the conductive lines across the garment is possible, potentially allowing to house the necessary electronic components, a microcontroller and a power supply, inside a seam or button. Pinstripe can be constructed as a *durable* textile interface as modern conductive yarns and flexible printed circuit boards (PCBs) and interconnects between the two are becoming increasingly robust and can withstand aging and washing [10].

Continuous Value Input

Continuous value input elements usually exhibit an inherent problem of domain scaling. A GUI slider, e.g., can only produce as many distinct values as it occupies pixels on the screen. Zooming sliders as proposed by Hürst et al. [5] are often used to mitigate that problem, for example in the Apple iOS video player. Pinstripe implements a similar approach: pinching a large fold in the textile allows coarse control over a wide range of values. Pinching a smaller fold yields more fine-grained control (Figure 2).

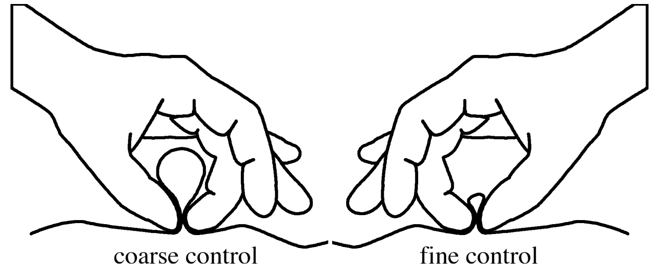

Figure 2. Pinching and rolling deeper or smaller folds of the textile provides different granularities of control.

Menu Navigation

Pinstripe can also be used to navigate linear or nested menu structures, e.g., a music player's playlist. In this scenario, rolling the cloth between the fingers moves the current selection across the list. Feedback can be given by either an auxiliary display or by auditory icons. Different pinching depths let the user navigate the list by individual items (small pinch) or by some hierarchical semantic structure (large pinch) as, e.g., different albums in a list of songs. Several techniques to issue confirmation and cancellation commands without additional control elements are possible: 'dwell time', 'activate-on-release', and 'grab-and-crumple' are the ones most suitable for use with Pinstripe. 'Dwell time' confirms a selection if the current pinch is held for a time of a few seconds and cancel the current command if the fabric is released before reaching the confirmation dwell time. Although it is easy to implement, we chose not to utilize this approach because time based interfaces are well known to negatively affect usability. 'Activate-on-release' confirms a selection implicitly when the user releases the pinch. In this case, an explicit cancel item has to be included in the list of possible selections, preferably at either end. 'Grab-and-crumple' allows the user to grab the fold in the garment with her full hand, crumpling the textile in her fist, to issue an activation command; this is easy to distinguish from the normal Pinstripe navigation gesture, both for the sensor and for the user.

Applications

Possible applications of Pinstripe are situations where users want to control mobile devices without the need to take the device out of the pocket and without the need for eye contact. Music player and mobile phone controls that can be integrated into sports apparel or street fashion are not only more comfortable to use in mobile contexts but are also often socially more acceptable [20]. Safety-critical situations like road traffic or extreme sports are other examples, where eyes-free, one-handed controls like Pinstripe may be beneficial. Finally, since the Pinstripe sensor can be integrated to the inner layer of a garment it is well-suited for use in protective clothing that requires tight sealing.

PROTOTYPE

For our first Pinstripe prototype [7], we sewed 18 lines of *Statex 117/17* 2-ply conductive thread, spaced 2mm apart, to the inside of a T-shirt sleeve (Figure 3). For the outer (visible) counterthread, we used standard black cotton. Each line

Figure 3. Lines of conductive thread sewn into the sleeve of a T-shirt and connected to a microcontroller board (left: outside, right: inside). Lines are spaced approx. 2mm apart. On the outside, the lines are also painted on for demonstration purposes—normally the black outer cotton thread would be invisible.

was connected to a digital I/O pin of a LilyPad[4] Arduino microcontroller board. The Arduino was tethered to a computer to do the signal processing.

To determine which lines are connected to each other, the microcontroller pulls one line at a time to ground level voltage, connects all other lines to 5V via internal pull-up resistors, and then checks their voltage level. If any of those lines report a level near 0V, they are recorded into a binary matrix as having a connection to the current ground line at this time. Even though the inside conductive thread directly touches the skin, skin conductance is low enough to not impede our sensor readings. The process is then repeated using the next line as the ground line, thus yielding the next row of the connection matrix (Figure 4).

The complete matrix is sent via a serial connection to a computer, where it is filtered to remove noise before being searched for a connected area of positive entries. The location and size of this 'blob' along the secondary diagonal of the matrix indicates the size of the fold the user has pinched. When the user rolls the fold, the blob changes its position along the main diagonal (Figure 4).

This information can now be used, e.g., to change the volume of a mobile MP3 player, to adjust the temperature of a garment with built-in heating, or to navigate through graphical or auditory menus on a device. For this prototype, we implemented part of the processing chain on a desktop computer to facilitate rapid prototyping. Industrial microcontrollers, however, are already powerful enough to perform these computations directly, so that future versions of Pinstripe can run untethered.

INTERACTION WITH PINSTRIPE ACROSS THE BODY

To find out where a textile sensor like Pinstripe should ideally be placed on the users clothing we conducted a user study. The goal of the experiment was to find out, which of these areas are found to be most conveniently accessible and what position, angle, and direction the users would use for pinching and rolling the fabric of their clothing. While by design Pinstripe sensors do not require exact positional placement, it is crucial to know the *angle* at which users will perform the interaction gesture. If, for example, a Pinstripe element is used perpendicular to its intended operation angle, nothing is detected because the conductive threads just fold back on themselves and do not interconnect.

[4]http://www.arduino.cc/en/Main/ArduinoBoardLilyPad

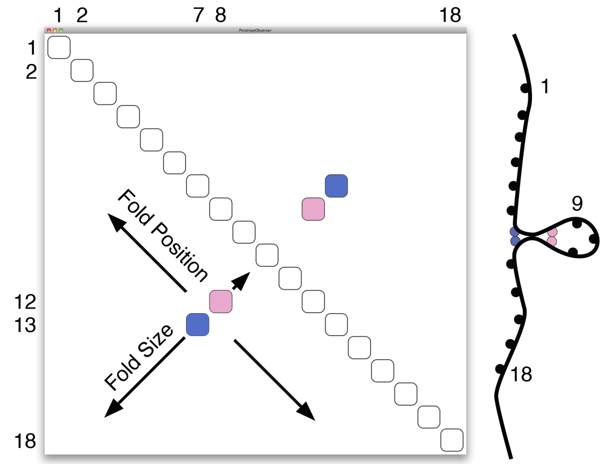

Figure 4. The connection matrix (filtered to remove outliers) and a corresponding fold. Entries in the connection matrix show which lines are currently connected through pinching. The 'blob' of all connection entries in the matrix indicates the size and placement of the fold across the conductive threads. Here, lines 7 and 13 (blue) as well as 8 and 12 (violet) are connected; the user has formed a small fold for fine-grained control. Note that the matrix is always symmetric.

First Study

We identified 16 potentially suitable areas on the human body (Figure 5) where a Pinstripe element could be conveniently placed. The grayed out areas in Figure 5 were left out on purpose as they seem socially unsuited for Pinstripe interaction. Body areas that are usually not covered by normal clothing (head, hands) or otherwise difficult to reach (feet) were also excluded. Before each trial, the Pinstripe gesture of pinching and rolling was demonstrated by the experimenter on an 'off-body' pice of cloth. This was done to avoid influencing the participants in how they would perform the gesture on their garments. Since we only wanted to study the interaction gesture itself, we did not use an actual working Pinstripe system for the experiment.

The experiment was conducted under three distinct body posture conditions (between groups, 30 users each): sitting, standing still, or walking. In each trial, participants assumed the assigned posture—in the walking condition the experimenter walked with the user—and we asked them to perform the Pinstripe gesture on each of the 16 body areas respectively, using their own clothing. Users were free to choose which hand they used for each of the areas. If a user's clothing would not permit using Pinstripe in one ore more areas, these areas were excluded from the trial (e.g., forearm while wearing a t-shirt, sternum while wearing a shirt with a low neckline). Also, to get an idea of the social impact of using Pinstripe, we allowed participants to reject body areas for social or personal reasons. No further reason for rejecting the area had to be given by the participant in this case.

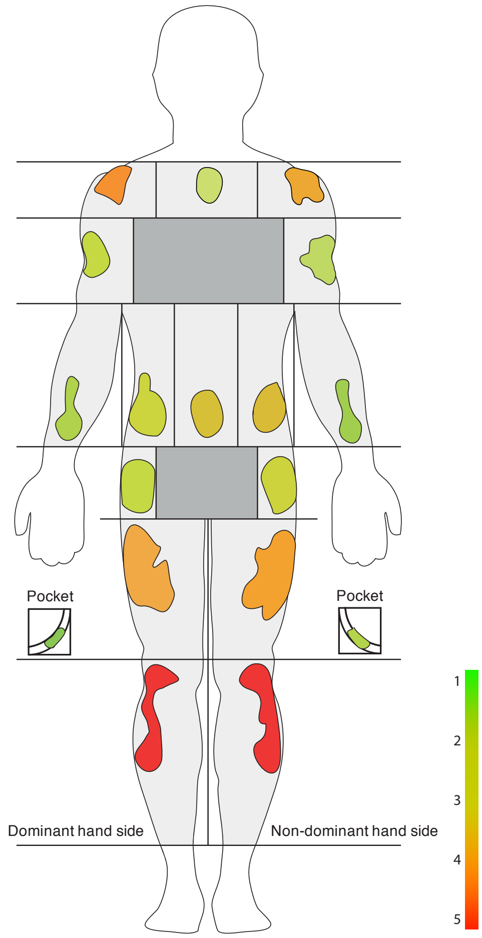

Figure 5. We selected 16 areas from the front of the human body where textile UI elements could be placed. Some areas were left out deliberately. The two 'pocket' areas were added after the study to account for an observation we made during the experiment. The 'blobs' outline the parts of each area where study participants grabbed a fold. Each 'blob' is colored according to the average grade given to the respective area.

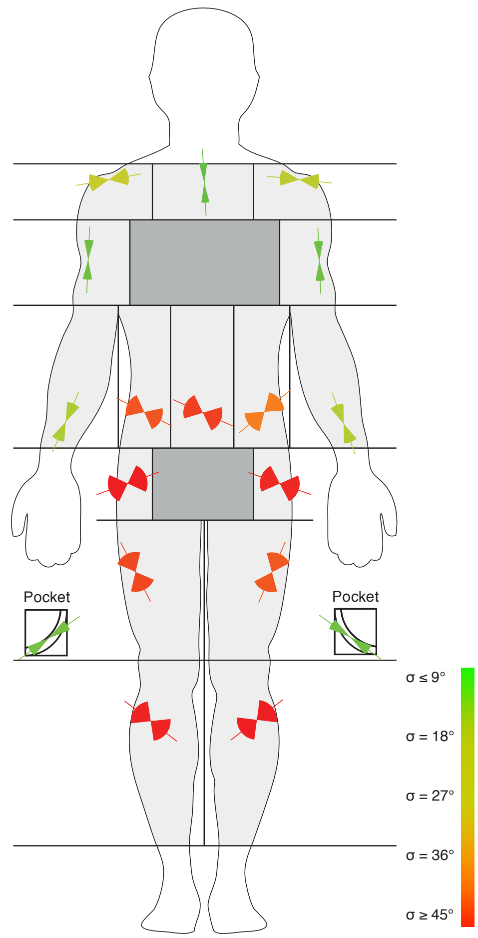

Figure 6. Visualization of the mean and standard deviation for the gesture angle distribution in each area. The colors correspond to the standard deviation; areas that are technically well suited for Pinstripe are shown in green, less suited areas are drawn in red.

For each area, participants were asked to grade how conveniently they could perform the pinch-and-roll gesture. Grades were collected on a 5-point Likert scale (1 being 'very convenient' and 5 being 'very inconvenient'). The experimenter also recorded the position and angle of the fold by drawing a mark on a template sheet (similar to Figure 5) which was vectorized later, and he noted down the use of the dominant or non-dominant hand. After the trial, participants were asked to name the one single body area they would most prefer to use Pinstripe at. We also asked users for their preferred orientation of the control gesture, i.e. mapping an inwards motion of the thumb to an increase in the controlled value or a decrease. This information was only collected for the preferred body area the user had named.

Observations

We performed the study asking people on the campus of our university and around the city to participate. Of the 90 participants, 15 were female, 75 were male. 13 participants were left handed, the rest right handed. No ambidextrous person took part in this study. 8 persons wore tight fitting clothes, 9 wore loose clothing and the rest wore regular fitting clothes. Because we conducted the study during the summer, only 16 participants wore long sleeves.

Table 1 shows an overview of the tested areas. For each area, we calculated the median grade, lower and upper quartiles of the grade, and the standard deviation of the angle of the control gesture (Figures 5, 6). Five regions received a median grade of 2, six regions received a median grade of 3 and six regions received a grade of 4 or 5. The standard deviation of the angles reach from 11.7% at the sternum to 44.7% for the lower leg. The regions with the smallest spread in gesture angles are the sternum, the pockets, and the upper as well as the lower arms. These regions also show only one mode in the distribution of gesture angles. Most of the other areas show several modes, typically two, which correspond to different ways in which users held their hands when performing the gesture in these areas. Figure 7 shows the angular distribution of the middle waist area as an example where 23

area	combined			sitting			standing			walking		
	n	$M[Q]_{grade}$	σ_{angle}	n	$M[Q]_{grade}$	σ_{angle}	n	$M[Q]_{grade}$	σ_{angle}	n	$M[Q]_{grade}$	σ_{angle}
pocket (d)	17	2 [1, 2]	14.4°	3	2 [1, 4]	20.2°	4	2 [1, 3]	17.4°	10	2 [1, 2]	4.3°
forearm (nd)	16	2 [1, 2]	20.2°	4	3 [2, 3]	2.3°	7	1 [1, 2]	9.9°	5	2 [2, 2]	33.1°
upper arm (nd)	84	2 [2, 3]	13.6°	30	2 [1, 3]	16.3°	27	2 [1, 2]	1.5°	27	3 [2, 4]	16.3°
pocket (nd)	17	2 [2, 3]	13.9°	3	2 [1, 4]	18.3°	4	4 [3, 4]	15.6°	10	2 [2, 3]	3.6°
forearm (d)	16	2 [2, 3]	19.5°	4	2 [2, 3]	4.3°	7	2 [1, 3]	9.9°	5	3 [2, 3]	30.0°
sternum	77	2 [2, 3]	11.7°	26	2 [2, 3]	14.9°	26	3 [2, 3]	10.8°	25	2 [2, 3]	7.7°
hip (d)	74	3 [2, 4]	44.8°	27	3 [2, 4]	38.4°	26	3 [2, 4]	46.4°	21	2 [2, 3]	43.6°
upper arm (d)	84	3 [2, 4]	13.6°	30	3 [2, 3]	16.2°	27	3 [2, 4]	2.3°	27	3 [3, 4]	16.3°
waist (d)	88	3 [2, 4]	39.1°	28	3 [2, 4]	36.7°	30	3 [2, 4]	38.7°	30	3 [2, 4]	41.0°
hip (nd)	74	3 [2, 4]	43.2°	27	3 [2, 4]	34.9°	26	3 [2, 4]	46.6°	21	3 [2, 4]	44.6°
waist (center)	89	3 [3, 4]	40.7°	29	3 [2, 4]	38.7°	30	3 [3, 4]	43.7°	30	3 [2, 4]	37.8°
waist (nd)	88	3 [3, 4]	36.1°	28	3 [3, 4]	32.7°	30	3 [3, 4]	40.0°	30	4 [3, 4]	33.7°
shoulder (nd)	86	4 [3, 4]	23.5°	30	4 [2, 4]	28.8°	29	4 [3, 4]	21.1°	27	4 [3, 5]	16.6°
thigh (d)	82	4 [3, 5]	40.0°	28	3 [2, 4]	43.3°	28	5 [4, 5]	40.8°	26	5 [4, 5]	30.4°
thigh (nd)	82	4 [3, 5]	38.9°	28	3 [2, 4]	44.0°	28	5 [4, 5]	38.8°	26	5 [4, 5]	29.7°
shoulder (d)	86	4 [3, 5]	26.2°	30	4 [3, 4]	35.3°	29	4 [4, 5]	16.3°	27	5 [3, 5]	16.8°
lower leg (d)	37	5 [5, 5]	43.9°	15	5 [4, 5]	43.7°	12	5 [5, 5]	44.0°	10	5 [5, 5]	41.1°
lower leg (nd)	37	5 [5, 5]	44.7°	15	5 [4, 5]	45.6°	12	5 [5, 5]	44.3°	10	5 [5, 5]	41.0°

Table 1. Count (n), median and quartiles (M[Q]), and standard deviation of the angle (σ_{angle}) for all areas and conditions. Areas are subdivided by their position on the dominant (d) or non dominant (nd) hand side of the body. The rows printed in bold denote areas that were most often chosen by the users as their preferred area. The table is sorted by the combined median grade. Smaller values are better.

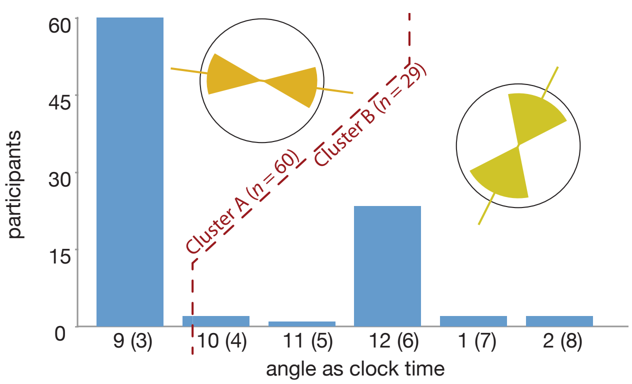

Figure 7. Histogram of angles used for the Pinstripe control gesture at the waist and visualization of two clusters obtained by k-means clustering.

people grasped a vertical fold, holding their hands horizontally, and 59 participants grasped a horizontal fold, holding their hands with the fingers pointing downwards.

Note that, since the procedure to capture the angles involved visual judgement on the side of the experimenter, we can expect the data to contain measurement noise up to ±7.5° determined by the performance of human angular perception. Even so, the current implementation of Pinstripe starts reporting wrong positions or fold sizes only when the control gesture deviates from the axis by more than ±19.8° allowing us to base out design decision on the presented data.

Participants rejected areas for social or personal reasons in 36 cases. The areas most often rejected were the lower legs (6 participants), thighs and waist (4 participants each). Some users commented that they felt uncomfortable bending down (lower leg) or touching their belly (waist) while potentially being watched by others.

Figure 5 shows the positions of the Pinstripe gesture on the garments. Positional spread is largest at the thigh area and the lower leg. The areas above and including the waist exhibit a smaller spread in position. Most of the participants (67) preferred a mapping of an outward motion of the thumb (Figure 8) to an increase in values.

As table 1 shows, the grades and angles vary with the different body postures, like we expected. While the upper arm is a rated very highly for standing and sitting, was only graded with a median of 3 for the walking condition. The forearms display the smallest spread in the sitting and standing conditions but exhibit a high increase in the walking condition.

When asked for the area with the highest preference after the test, the upper arm of the non dominant hand was mentioned most frequently (27.8%) followed by dominant hip (13.3%), pocket (12.2%) and sternum (10.0%). Only 16 people wore long sleeves allowing them to perform the gesture on the forearm, but seven chose it as the best position. Of the people who wore long sleeves 43% preferred the forearm of the non dominant hand and 25% preferred the upper arm of the non dominant hand.

Unexpected observations

When asked to perform the gesture on their hip or thigh 18 participants chose to perform the gesture using their trousers' pockets, placing their thumb inside the pocket and the fingers outside the pocket pointing down their leg. We had not foreseen Pinstripe to be used in this manner; nevertheless, twelve (≈ 67%) of these users rated it as the best position to use Pinstripe (in contrast to [20]). This is especially no-

Figure 8. Typical Pinstripe gesture. Most users associate moving the thumb in the 'out' direction with an increase in value.

ticeable in the walking condition where 'pocket' even is the strongest preference. Because of this, we decided to add the pockets as areas 17 and 18 (see Figures 5 and 6) to our evaluation.

Conclusions

The study reveals several feasible positions for the Pinstripe input technique. Since Pinstripe works best when the variations in angle stay small, an area is only feasible for Pinstripe when the respective σ_{angle} is small. This is especially important for mass production of Pinstripe enabled shirts since the position of the control element has to be fixed for a larger population. In that regard, the best positions for Pinstripe are the upper arm, the sternum, and the forearm.

The overall best suited areas are the upper arms. The dominant upper arm is highly preferred and the standard deviation of angles stay consistently low. For our next prototype we chose to use the right arm to accommodate for the larger part of right handed people in the population.

The forearm seems to be a good solution for with long sleeved garments. Most people are already used to interact with watches in that area and the forearm is usually easily reachable.

The sternum received high marks by the study participants and shows the lowest standard deviation in the angle used. However, 73% of the female participants in our study wore clothes with a low neckline that would not allow interaction in that area. Additionally, two participants flagged it as an area that is socially unacceptable for interaction. We still believe that the sternum is a promising area when only looking at a part of the population. Especially in the walking condition the area was received very well which we attribute to the fact that it, compared to the arms, exhibits less movement while walking. It is likely that we would observe similar results while running. This would make the sternum well suited for a textile control to be used during sports, e.g., to control a music player during jogging.

Hips, waist, and thighs seem to be less suitable for Pinstripe. Besides some mentions of social unacceptability, the area is less restrictive in terms of hand position which increases the spread in angles used in these areas. This reduces the applicability of Pinstripe since the system can only work in one direction.

Although the shoulders show a lower spread in angle the area is harder to reach, and thus received worse grades. Additionally, seven participants complained that it would not be possible to use the system in that area when wearing a backpack.

Our study results differ from the results of the study conducted by Holleis et al. [4]. Especially the thigh was highly preferred by users in their study while receiving bad grades in our study. We think that these differences are related to the input devices evaluated in the two studies. It is more comfortable to press a button located on the thigh than trying to grasp a fold and moving it. In that regard, the grading results presented in our study are not necessarily generalizable to other input devices. However, our results regarding the social acceptance and the positions that are used for interaction may be applicable to other devices.

USING PINSTRIPE IN A REAL-WORLD SCENARIO

Based on our experience with the first prototype and our findings from the first study we created a second Pinstripe prototype. We created a larger Pinstripe sensor patch (24 threads) in the left upper arm region of another shirt; this region was identified as highly preferred in our first study for right handed people. In contrast to the first prototype, we slightly changed the position of the sensor on the sleeve from the front of the arm to its side to better match our observations of how people typically pinched their shirts in that area during the first study.

We also further reduced the noise in the detected connections by modifying the low pass filtering. A simple median-of-three filter removes outliers and the mean position and loop size are smoothed using an exponential filter. This already greatly reduces the effect of a jittering connection between two threads. Instead of the original LiliPad Arduino, we used an AVR ATmega1280[5] micro controller which has a higher clock speed (16 MHz instead of 8 MHz), thus allowing for a higher sample rate (¿5 KHz instead of 2.6 KHz for the cross-connection matrix entries) to reduce the lag caused by the filtering.

As a real-world example, we implemented a simple music player application that utilizes Pinstripe to either control volume or the current track in a playlist. We also implemented a mode unrelated to music playback where users can navigate through a graphical menu and select items from it to test the systems viability as a more general input device.

When interacting with the system, each new pinching gesture resets the origin of Pinstripe's internal coordinate system. Subsequent rolling of the fabric then applies the result-

[5] http://www.atmel.com/products/avr/

ing change in position as a relative offset to the value that is currently controlled (selected menu item, track number, or volume level). To allow coarse and fine grained control, the size of the grasped fold is used as a scaling factor for these offsets. Creating the smallest detectable fold in our implementation means pinching off a length of 2mm on the fabric (only two neighboring conductive threads connect), the largest fold is detected when the outermost conductive threads connect (cf. Figure 2). For volume control, moving the fold 2mm (distance between two threads) changes the volume by 1% for the smallest and 33% for the largest fold size. When switching through the list of tracks, 'next track' and 'previous track' commands are issued every time a threshold is crossed which happens approximately every 4mm.

Many portable music players apply volume changes directly while for track changes they first give audio feedback in the form of a beep before they switch over. In the music player mode, our system copies this behavior and additionally plays a different sound when reaching either end of the playlist. In the graphical menu mode, moving the selection mark inside the graphical menu works similar to changing tracks but no audio feedback is given. To activate the selected menu item we adopted the 'grab-and-crumple' technique described earlier. This gesture is detected when 35% of all possible thread connections are active. All of these settings were derived in a small pilot study performed beforehand with members of our lab.

Second Study

Using this second prototype, we conducted a short user test where the participants used the Pinstripe UI element to control our test application in three modes: graphical menu, music player volume, and playlist controls. We wanted to get a qualitative impression on how well people would understand the interaction and be able to use the control in a series of real-world tasks. For this experiment the participants wore the prototype Pinstripe shirt over their own short-sleeved garments. The playback software was running on a small notebook computer carried in a backpack.[6]

Before the tests, the interviewer gave a brief introduction to the Pinstripe input method and demonstrated it on his own shirt. Afterwards, people had five minutes to become familiar with the system where we asked them to think aloud. During the main part of the study, testers were asked to perform several tasks using Pinstripe (Table 2): changing tracks in a playlist of 15 songs, adjusting the volume, and navigating through the graphical menu which was displayed on an iPod touch. At the end of the trial we conducted an informal interview where we encouraged the users to share their general thoughts about Pinstripe.

Observations and Lessons Learned

From the 14 people that participated in this second study 12 were male, 2 were female. Their ages ranged from 21 to 31; only one participant was left handed. When being introduced to the Pinstripe garment most users expected touch functionality—similar to touchpads or interactive surfaces—at first. After being shown by the experimenter and a short initial learning phase, however, all participants were able to successfully use Pinstripe.

menu mode	1	move to the next item in the menu
	2	move back to the previous item
	3	move ahead 3 items in the menu
	4	skip to the last item in the menu
	5	go back to the first item in the menu
	6	select the item "flower" in the menu
	7	deselect the item "lightning" in the menu
volume mode	8	adjust the volume to a suitable value
	9	adjust the volume to minimum
	10	adjust the volume to maximum
	11	adjust the volume to a suitable value
playlist mode	12	move to the next item in the playlist
	13	move back to the previous item
	14	move ahead 3 items in the playlist
	15	go back to the first item in the playlist

Table 2. Tasks to be performed during the qualitative study

Sensor location and angle

In accord with our findings from the first study, the angle at which people pinched the sleeve was in alignment with the sensor lines and very consistent across all participants. At the same time, the absolute location of the interaction on the shirt sleeve could be observed to vary strongly between different users. Some pinched the cloth on the outside of the arm, others performed the control gesture on the inside. This supports our argument that non-local controls like Pinstripe have an advantage over capacitive buttons and similar designs. However, since our prototype was technically limited in the number of conductive lines and thus the size of the sensor patch, some participants still happened to 'slip off' the Pinstripe sensor during the interaction. This can be easily remedied, though, by using a larger flexible PCB as a breakout board for the microcontroller, allowing for a full-size sensor which spans the full circumference of the sleeve.

Ease of use

All participants felt that navigating the graphical menu using Pinstripe was easy. Activating menu items by grabbing the fold with the full hand and crumpling the textile was also immediately understood and performed without difficulty. Most people felt more at ease when using the menu condition—which was the only condition with graphical feedback—than using the music player controls that only gave auditory feedback.

Variations in gesture

Interestingly, none of the participants experienced problems to switch to the next track or turn the volume up but some struggled with the opposite direction. We found that, on

[6] A version of the control circuit currently under development will be able to directly control an iPod portable music player, making the computer unnecessary.

closer observation, these users performed the Pinstripe gesture in a way that resulted in asymmetric forward and backward finger motions. They would hold the thumb against the index finger when performing the forward gesture, and then move the fold by bending and stretching the index finger while holding the thumb steady. This is similar to the way the instructor performed the demonstration gesture (Figure 9 left). When going backward they would do the opposite and bend the thumb against the steady index or middle finger. This latter movement is restricted by the smaller angular range of the thumb joint. Users performing the gestures in this way usually felt that reaching the threshold for, e.g., skipping to the previous song required a larger movement of the thumb in contrast to the index finger although the threshold is currently equal in both cases. Some participants, however, made the gesture in a totally different way: such that the thumb and fingers were parallel to the cloth fold (Figure 9 right). Instead of bending the fingers, they would form a flat surface with their fingers and then slide the thumb sideways across it. These users perceived no difference in the amount of movement required to issue forward and backward commands, presumably because the thumb can be slid sideways in both directions equally well. However, they generally felt that the distance they had to move their thumb to reach the next piece or menu item was too large.

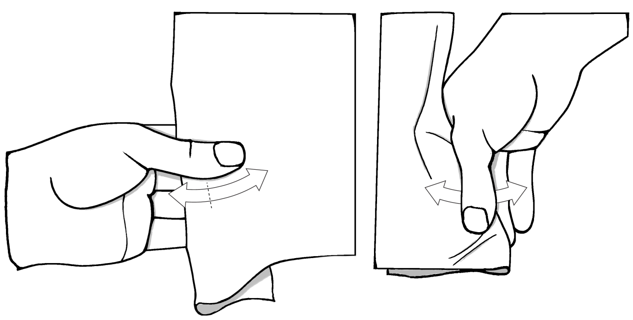

Figure 9. Alternative Pinstripe gestures. Left: This Pinstripe gesture is commonly used and has an asymmetric range. Right: This allows moving the thumb in both directions equally well but has less total range than the first gesture.

The movement direction that users expected to be associated with 'forward' commands was consistent with our predictions based on the first study. For 79% of the participants, the system's behavior matched their expectations, the rest found the mapping to be more natural the other way around.

The observations related to gesture and preferred directions indicate that Pinstripe should either allow some amount of personalization or adapt to the user. Both approaches seem feasible as clothes usually are personal items that are not commonly shared between people. A future version of our algorithm will implement this technique.

Different granularities of control

When controlling the music volume, all testers understood the domain scaling feature of Pinstripe and were able to change the volume in different levels of granularity by using smaller or deeper folds. However, some participants performed the gesture in a way that rolling the cloth between their fingers to change the position of the fold also resulted in a change of its size. This problem, which we had not not encountered in our pilot tests, made controlling the volume more difficult for these users. A possible solution would be to determine the size of the fold only when it is initially formed by the pinching gesture. This, however, would then require two interactions when a user wanted to change the scale for more fine grained navigation, e.g. first selecting a music album and then a specific song in it.

SUMMARY

Pinstripe is a continuous value input technique for smart garments that utilizes the affordances of cloth—grasping and deforming—instead of adopting known input techniques, like touch buttons, to the textile domain. This way, Pinstripe can address many of the challenges that UI elements for smart garments face: it can be operated quickly and easily in an eyes-free fashion, it is robust against involuntary activation and garment shift, and it implicitly allows to input values in different granularities. The design of Pinstripe facilitates its wearability, durability, and fashion compatibility—all important considerations when creating smart clothes.

In a first user study we identify locations on users' clothes that are suitable for Pinstripe interaction, both from the viewpoint of the system (low variance in gesture angle) and the user (acceptance and preference). We also discuss how and to what extent other textile input methods may benefit from the results of this study.

To demonstrate the applicability of our approach, we report the results of a qualitative second user study where participants interact with a Pinstripe prototype in a real-world scenario. Users were able to use Pinstripe to control the volume of a music player application in different granularities and to change tracks, as well as navigate through a graphical menu on a mobile device. From our observations during the test, we got valuable insights into how users experience the interaction with Pinstripe. Also, we learned that different users interact with Pinstripe using different gestures; a fact we will account for in future iterations of our prototype.

FUTURE WORK

For our current prototypes we are sewing each sensor line individually into the shirts. This process is laborious and prone to inaccuracies that limit the sensor's performance. Conductive lines that are directly woven into the fabric of clothes may provide a much more consistent line spacing, higher density, and larger sensor surfaces while at the same time boosting durability and manufacturability. Also we are creating an untethered, self-contained version of a Pinstripe shirt that can directly control, and is powered by, an iPod mobile music player.

Apart from the sensor locations on the upper and lower arms, we will investigate the promising concept of placing textile input elements inside the pockets as users commented positively on the perceived convenience and the low negative social impact of that position. This, of course, requires a modification of the algorithm because the two sides of the 'fold' always touch; the system would only look at deviations from a default pattern in the cross-connection matrix.

Further experiments are needed to verify the consistency of Pinstripe gestures for single users over a larger timeframe, not only for a population of users over a single trial as we did in this paper. Also, we are planning to perform a more detailed analysis of the influence of different cuts and fabrics of clothing on the applicability of Pinstripe.

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