Base and Stitch: Evaluating eTextile Interfaces from a Material-Centric View

L. Vineetha Rallabandi
Sensorimotor Interaction,
Max Planck Institute for Informatics,
Saarland Informatics Campus
Saarbrücken, Germany
s8larall@stud.uni-saarland.de

Alice C. Haynes
Human Computer Interaction Lab
Saarland University,
Saarland Informatics Campus
Saarbrücken, Germany
ahaynes@cs.uni-saarland.de

Courtney N. Reed
Sensorimotor Interaction,
Max Planck Institute for Informatics,
Saarland Informatics Campus
Saarbrücken, Germany *and*
Biomedical Engineering & Imaging Sciences
King's College London
London, United Kingdom
creed@mpi-inf.mpg.de

Paul Strohmeier
Sensorimotor Interaction,
Max Planck Institute for Informatics,
Saarland Informatics Campus
Saarbrücken, Germany
paul.strohmeier@mpi-inf.mpg.de

Figure 1: Recreating an eTextile sensor, *Pinstripe*, on four different fabric swatches (A) for tabletop (B) and wearable (C) pinch and rolling gestures.

ABSTRACT

Fabrics are seen as the foundation for e-textile interfaces but contribute their own tactile properties to interaction. We examine the role of fabrics in gestural interaction from a novel, textile-focused view. We replicated an eTextile sensor and interface for rolling and pinching gestures on four different fabric swatches and invited 6 participants, including both designers and lay-users, to interact with them. Using a semi-structured interview, we examined their interaction with the materials and how they perceived movement and feedback from the textile sensor and a visual GUI. We analyzed participants' responses using a joint, reflexive thematic analysis and propose two key considerations for research in e-textile design: 1) Both sensor and fabric contribute their own, inseparable materiality and 2) Wearable sensing must be evaluated with respect to culturally situated bodies and orientation. Expanding on material-oriented design research, we proffer that the evaluation of eTextiles must also be material-led and cannot be decontextualized and must be grounded within a soma-aware and situated context.

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CCS CONCEPTS

• **Human-centered computing** → **Interaction design theory, concepts and paradigms**; **HCI design and evaluation methods**; *Gestural input*; *Interaction devices.*

KEYWORDS

materiality, eTextiles, gestural interaction, wearable sensing, design evaluation

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1 INTRODUCTION

Within the 2010s and now early 2020s, the availability and diversity of soft textile input devices has exploded. While early work on textile input often explored if such devices were possible at all and how they might be created [30], more contemporary work now explores methods to maximize the interactivity of such devices [29], examines novel manufacturing methods [16], or investigates the social implications of interacting with such devices [37]. A dimension that has only recently garnered attention is the effects of the materiality and material-driven design of sensors [11, 21]. Even though the differences between everyday textiles are frequently acknowledged, they are most often discussed from a technical standpoint [16]. We wish to draw attention to the experiential qualities of interacting with the materials that are integrated in textile sensors.

To address this, we chose to work with Pinstripe [23], a well understood sensor design specifically crafted to leverage the unique affordances of textiles. Pinstripe is designed to capture pinching gestures, an explicit interaction method that mimics the gesture we might use to explore the material properties of a fabric. However, neither Pinstripe nor its various subsequent explorations [13, 14] explore the effect of the textile's material properties on the resultant interaction. Our research aims to further the implementation and evaluation of the sensor to examine how properties of materials in the construction of eTextiles overlap and influence one another and how features of texture, feel, and pliability influence and guide gestural interaction.

To study the effect of material properties on interaction, we constructed a series of modified Pinstripe sensors exploring the entire eTextile interface, which are made of a **base** — that is, the supportive fabric upon which the sensor is built — and a **stitch** — the electrically conductive traces sewn into the base, enabling interactivity. We focus especially on the non-conductive base materials, which support the interaction and integration of the conductive material but are often not given as much attention as the conductive materials. With these sensors, we conducted a qualitative study exploring how the material properties of the base influenced the experience of interacting with the Pinstripe sensor. Specifically, we used a reflexive thematic analysis to examine how both the materiality of our sensors and the interaction with them is experienced. We then explored how features of the interaction relate to the perceived material properties of the sensors.

We found that the electrically functional elements – in our case the stitch – and elements which serve mechanical purposes – such as the base of our sensors – cannot be viewed as separate entities. The perceived interactive functionality is intertwined with the entirety of the design. Although not the central focus of our study, interviews also revealed that wearable sensing should be evaluated on the body, as the users' bodies provide context and semantic meaning. We propose that, in the evaluation of interactive eTextile devices, we as designers must consider materiality and ground our process within a body-based context. In this evaluation, we must consider both base and stitch — whatever those supportive and conductive materials might be — and how they work together to construct experiences through eTextiles interactions. Our work supports existing research examining materiality as a factor in design considerations and reiterates the presence of material properties in interaction. We expand ideas in material-driven design to look at material-driven evaluation and interaction. We found that materials, particularly the base fabric within which sensing materials were integrated, influence the gestures, feedback, and perceived comfort and usability of a contextualized interface. We expand on previous themes in research surrounding social acceptability and cultural influence on wearable interaction to demonstrate how material-led interaction reveals new insights into implementation of wearables.

2 RELATED WORK

eTextile interfaces, from their very conception, have been intertwined with aesthetics and materiality. Early eTextile devices in the 90s were featured at fashion shows in the context of the work of the Human Dynamics group at the MIT Media Lab, and often consisted of collaborations between tech-savy textile and fashion designers, such as the stitched capacitive sensors by Orth et al. [30]. Today, we have a plethora of fabrication approaches for building sensors, including functionalized fibres [31] and textiles [16], 3D printed [33] and woven materials [7], and knitted materials [32], as well as layered systems [24] and various patches [25, 36]. However, one of the most prominent methods used for adding sensing abilities to fabric remains stitching with conductive threads, both on fabrics in our environment [5, 15] and on clothing.

2.1 Material Influence

The affordances of textiles for intuitive gestural interactions such as with Pinstripe [23] are determined by the material properties of the base fabric and the interplay between fabric and sensor. For example, Hamdan et al. found that the physical properties of the base textile have a significant effect on the usability of the Grabrics interface [12, 13]. These affordances relate not only to functionality, but also user experience; for example, Jiang et al. found that the sensory engagement with GesFabri textures significantly impacted participants' affective responses to the interaction [19]. The complex role that materials play in interacting with and perceiving an interface needs to be taken into consideration throughout the design process. In *Material Driven Design*, Karana et al. focus on the importance of *The Material* not only in the context of what it is but also in how materials influence us and what kind of user experience we obtain from them [21]. This work provided *Materials Experience Vision*, with guiding questions to identify a material's contribution in its highest functionality and its unique experience when designed into an outcome.

Focusing on the material in the design process is a stance also taken in posthumanist research, for instance by Barad [2] and Ingold [18]. Materials, as participatory agents of the design process, have no inherent meaning, but are given meaning based on the users lived experience and their position in the interactive context and all its sociocultural biases; an approach that Barad calls a *material-discursive practice* [1, 2]. Nordmoen et al. explore this in the context of traditional wood-working, commenting during the process that "it's only through interaction that this material can be known." Through the creation of a digital interactive system Nordmoen expounds that "matter and culture are inseparably entangled" [28], and foregrounds the vital and active role the materials play in the design and execution of the system. In this *Entanglement HCI* theory [10], the design process is not a matter of designing for certain interactions, but rather "creating configurations that enact certain phenomena". The actors (humans, devices, materials) in these configurations, are not "fixed representations of entities, but only exist in their situated intra-action" [10]. In the context of gestural eTextile sensors, this pertains to not only the material properties of the interface, but how these properties intra-act with a situated context; for example, Karrer et al. observe significant differences in the interaction afforded by Pinstripe when worn in different locations and orientations on the body [22]. They focus on feasibility of the gestures, but the *felt experience* of the materials, *tacit knowledge* of gestures, and *body awareness* of the interface also play important roles in experiencing and making meaning from the interaction. These are the basis of Soma Design theory [17], wherein meaning and understanding are made through bodies and our individual lived experiences of our bodies in interaction.

2.2 Operating Principles of Pinstripe-like Sensors

A class of particularly compelling sensors made by stitching are what we refer to as *pinstripe-like*, stemming largely from the Media Interaction Lab at the RWTH Aachen. These include the original Pinstripe designs by Karrer et al. [22, 23], which enable interaction through one-directional rolling and pinching gestures, explorations of omni-directional fold detection by Heller et al. [14], and multi-directional grabbing explorations by Hamdan et al [12, 13].

The working principle of pinstripe-like sensors is based around stitched conductors on a base fabric. When the fabric is manipulated, these conductors touch, and information on how the fabric is being held can be extracted. This makes pinstripe-like sensors somewhat unique; unlike many wearable designs, they do not copy sensing principles familiar from flat surfaces, but instead are a novel design based both around the material and interaction affordances of textiles. The interfaces thereby enable eyes-free, continuous input sensing that can be non-invasively integrated into items of clothing. They can be used in varied applications; for example, easily accessible phone or music player controls in mobile contexts.

Pinstripe-like sensors measure points of contact between conductive stitches. For the original Pinstripe design, these are long lines, hence the name. The rolling and pinching of the fabric interface creates contact points between the conductive stitches. By iteratively measuring contact between each pair of conductors and setting the remaining conductors to a high-impedence state, one can create a connection matrix in which each connection between stitches is provided a binary value, indicating if they are in contact or not (c.f. [13, 22]). The interface therefore exclusively supports gestures involving one-directional folding of the fabric, such as rolling and pinching, and is not activated by touch .

For the one-dimensional design of the original Pinstripe implementation, which we also explore in our study, the connection matrix can be constructed as a two-dimensional array of values. This can be visualized as a GUI, where the matrix is represented as a series of black and white areas, depending on the binary status of the lines being connected or not [23].[1] This array encodes both the position of a pinch (the pinch position being manipulated by rolling the sensor between index finger and thumb) as well as the size of the pinch (how much of the sensor the user has grabbed). For further details on this implementation, please refer to the paper by Karrer et al. [23].

These pinstripe-like sensors utilize the affordances of textiles as intuitive gestures like pinching, rolling, squeezing to interact with the textile interface [12–14, 23]. In addition to visualizations, such as the matrix GUI [23], the haptic feedback from the fabrics provides another feedback mode for interaction in the sensory engagement context [19]. The rolling and pinching gestures mimic the methods we use to understand and perceive the properties of fabrics in the wild; here, we use a pinstripe-like sensor in order to explore these material components in depth. In this work, we address the fabrics' tactile properties, such as haptic feedback, relating to gestural interaction and corresponding user experience. We focus specifically on the role and integration of not only the conductive elements of the sensor but all materials — the base *and* stitch — in a material-discursive way. Through this study, we examine the influence that fabrics and their material properties have in guiding gestures and interaction with eTextiles.

3 SWATCH IMPLEMENTATION

To study how the material properties of the base material affect interaction with a pinstripe-style sensor, we created a set of four sensor swatches each with a unique base fabric. The design closely follows the working principles of *Pinstripe* [23], as described in Section 2.2. Each physical sensor interface consists of 16 conductive embroidered lines (pinstripes) spaced 2 mm apart [23].

3.1 Materials

The conductive pinstripes on our eTextile sensors — our stitch — were sewn with the Adafruit 316L 3 ply Stainless Steel Medium Conductive Thread.[2] This thread was chosen as its weight is light enough to be suitable for machine embroidery, allowing us to accurately reproduce the same conductive traces on different materials. Our four examined base materials were chosen to have varied textures (Figure 2) and included woven cotton, a four-way stretch knit (elastane), moleskin, and cotton needlecord. These fabrics were selected due to their qualitatively distinct textures and common use in clothing and furnishings. The cotton (yellow swatch) uses a plain but heavy weave; while soft, the weave can still be felt and

[1] This GUI can be seen at the end of Karrer et al.'s supplemental material, https://doi.org/10.1145/1978942.1979137

[2] https://www.adafruit.com/product/641

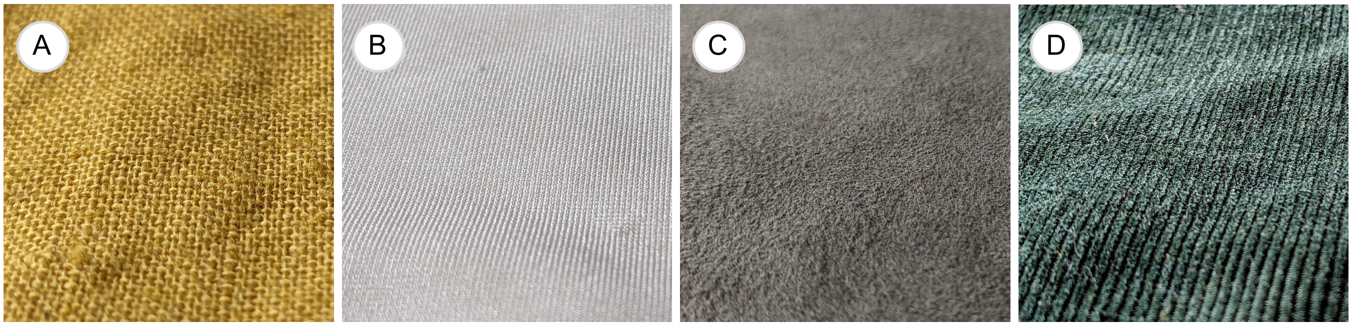

Figure 2: The base materials used in the study. We used a yellow cotton weave (A), a white elastane (B), a brown moleskin (C), and green cotton needlecord (D).

provides a subtle coarseness (Figure 2A). The elastane (white) is smooth and highly stretchable, and has no tactually detectable knit texture (Figure 2B). The moleskin (brown) has a typical napped texture, which makes it soft and fuzzy on the surface (Figure 2C). Finally, the cotton needlecord (green) — needlecord being lighter and having a finer rib than corduroy — has a high pile with distinct ribs (Figure 2D). We did not evaluate the relevance of the colors of the materials in interaction in this study, but rather reference them here to distinguish them in participant comments during the interview stage.

3.2 Fabrication

To examine the material contributions to the interaction, it was necessary to replicate a precise and identical interface on each of the base fabrics. For study purposes, to avoid any inconsistencies that might be introduced with hand sewing, we used a BERNINA B790 plus embroidery machine to replicate the pinstripe patterns. We created a digital outline for the stitches and spacing using KiCad to match the conductive traces to the footprint of a LilyPad Arduino micro-controller, as shown in Figure 3A. The exported PDF outline was edited in the BERNINA software to fit the machine's medium embroidery hoop, which has a maximum embroidery area of 100 x 130 mm. The pattern was sewn onto each fabric swatch (see Figure 3C), using a basic straight stitch and default settings on the BERNINA software.

Connecting the stitches to the LilyPad's castellated inputs required us to leave a loose end of conductive thread on each trace, as shown in Figure 3B, to be wrapped and secured around the input pin. To achieve this, the BERNINA's stitching was manually interrupted as the machine reached the end of each conductive line to avoid automatic thread cutting. In this way, 50 mm of loose conductive threads were left on each trace to connect to the LilyPad and to also prevent the LilyPad from shifting in use. After securing the traces to the LilyPad, the loose ends were insulated with a clear lacquer to prevent fraying and isolate them from the other traces. Figure 3D shows the four eTextile interface swatches produced using this method for the study.

4 EVALUATION

Our study examined material features of the eTextile sensor and their influence on the gestural and on-body interaction. We used a semi-structured interview during the study to gather perspectives and insight from the participants about the materials. The study was conducted in three parts involving exploration of the swatches, including both base and stitch, evaluation of the swatch as a controller with the GUI, and evaluation of the swatch in on-body use to probe wearable interaction.

4.1 Participants

Six participants, four female and two male, aged between 22 and 32 (M = 27, SD = 2.6), were recruited for the user study. The participants (P) were: P1 (F, 27), a bioinformatics doctoral student with little to no expertise in eTextiles; P2 (F, 23), a computer science doctoral student with expertise working with eTextiles and fabrics; P3 (F, 28), a computer science postdoctoral researcher with previous experience in fashion design and specifically with eTextile interaction; P4 (F, 27), a computer science student with little to no expertise in eTextiles; P5 (M, 31), a computer science postdoctoral researcher with limited experience in textile design but extensive experience in designing for gestural control and haptics-based interaction; P6 (M, 26), an education systems student with little to no expertise in eTextiles.

The study was conducted in English; all participants were fluent in English and were residents of Germany at the time of the study. Participants were compensated for their time following the study.

4.2 Apparatus

The study used the four distinct swatches outlined in Section 3.1. The swatches were attached to individual LilyPad Arduino micro-controllers connected to a Windows machine running the Arduino IDE for the LilyPad processing. The swatches were laid out at a workstation on a table in front of a Windows laptop computer so the seated participant could easily interact with them while referring to the GUI where instructed. Depending on the evaluation, the swatches were either placed on the table for interaction (Figure 1B) or affixed (one at a time) to the upper part of the user's sleeve, over the bicep, with safety pins (Figure 1C).

The visualization of the Pinstripe connection matrix, as outlined in Section 2.2 and shown in Figure 4, displays the real-time visual representation of the binary connection matrix; white is used to indicate connections between one line and another, while black indicates no connection. The middle white diagonal shows each

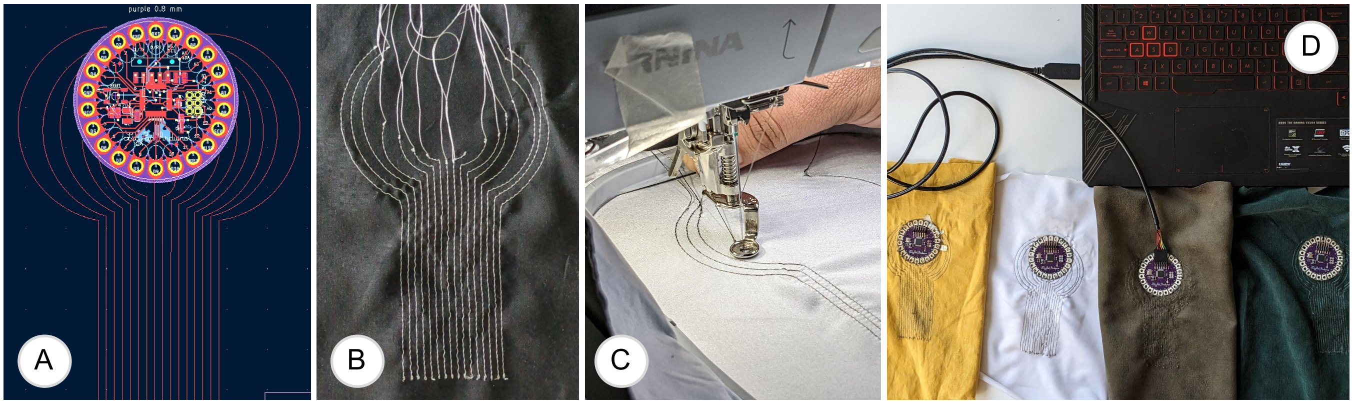

Figure 3: Constructing the swatches: Conductive traces and their connections are mapped out (A) and stitched onto a fabric base (B). The BERNINA sewing machine was used (C) to stitch the conductive traces onto the four interactive swatches (D).

line's connection to itself; the diagonal's adjacent shows connection between neighbors. As one moves away from the center, the black and white squares show connection information from lines with increasing distance. The GUI was displayed on the laptop at the workstation so participants could view the connections while rolling and pinching the fabric swatch.

We used a semi-structured interview to generate discussion about interaction with the materials; a full outline of the questions used can be found in Appendix A.

4.3 Procedure

Participants completed the study at a workstation set up in a dedicated office space. Rallabandi, the study conductor, provided a general overview of the study procedure. Participants were informed that Rallabandi would conduct a semi-structured interview with them and that the flow of the study would be conversation-like as they interacted with the different materials. Participants gave written consent to the collection of their data and permission to record their voice and discussion during the study. After receiving consent, the recording and study began. Two initial questions were asked pertaining to the participants' 1) familiarity working with fabrics in their day-to-day lives and 2) experience with eTextiles. The study comprised of three evaluations:

Part 1: *Textile Evaluation.* Before introducing the interface or wearable aspects, this evaluation explored qualitative experiences of interacting with the base fabric in isolation. The participants were requested to close their eyes and each swatch was placed in their hand. They were asked to feel the fabric and its entire texture. After exploring each swatch, Rallabandi asked questions in a semi-structured interview about the tactile properties of the fabric, perceived texture, whether or not the participant could relate or compare the texture to other objects, and whether or not the fabric or similar had been utilized or worn previously in their life. See Appendix A for a full outline of the semi-structured interview.

This exploration and the questions were repeated for each subsequent swatch. Next, they were requested to open their eyes and were asked to compare their sense and perception of the fabric before and after visual contact for each swatch.

Part 2: *Controller Evaluation.* This evaluation examined the integration of the conductive stitch into the base and its use as an interactive controller through gesture exploration with the textile interface. The interactive swatches, now with conductive traces embroidered into the fabric, were connected to the computer using LilyPad Arduino and a serial USB cable. Rallabandi explained the gesture to the participant, demonstrating how the GUI changes rolling and pinching the swatch (Section 2.2). Participants were then asked to carry out the gestures themselves on all swatches, one at a time. Questions were asked relating to participants' perception of their sensory interaction with the textile interface. Rallabandi discussed with the participants about their experience of the gestures combined with the visualization in the GUI, the integration of the interface and the conductive stitches with the base fabrics, and the ease of use in operating each swatch as a controller.

Part 3: *Wearability Evaluation.* The final evaluation examined the controller as a wearable, as opposed to a standalone device in the previous evaluation. Each participant was asked to pick their two most preferred swatches to be attached via safety pins to their sleeve on the upper arm. This body location was selected based on the study findings with Pinstripe [23], which identified the upper arm, sternum, and forearm as best on-body locations for interacting with the interface. We used the upper arm only, as the sternum and forearm are not accessible when participants are wearing short-sleeved or low-neckline tops, as observed previously [23].

The participant was then asked to familiarize themselves with the interaction again, now as an on-body interaction. The final portion of the semi-structured interview was conducted; participants were first asked about the chosen swatches and why they were preferred (e.g., based on gesture control, the fabric qualities, etc.). They were then asked about the difference between the interaction on their body and the previous interaction on the table for the preferred swatches. Then, they were asked about the factors that influenced their lack of preference for the other remaining swatches. Rallabandi emphasized to participants to focus and comment on the feel and tactile quality of the swatches, rather than their visual

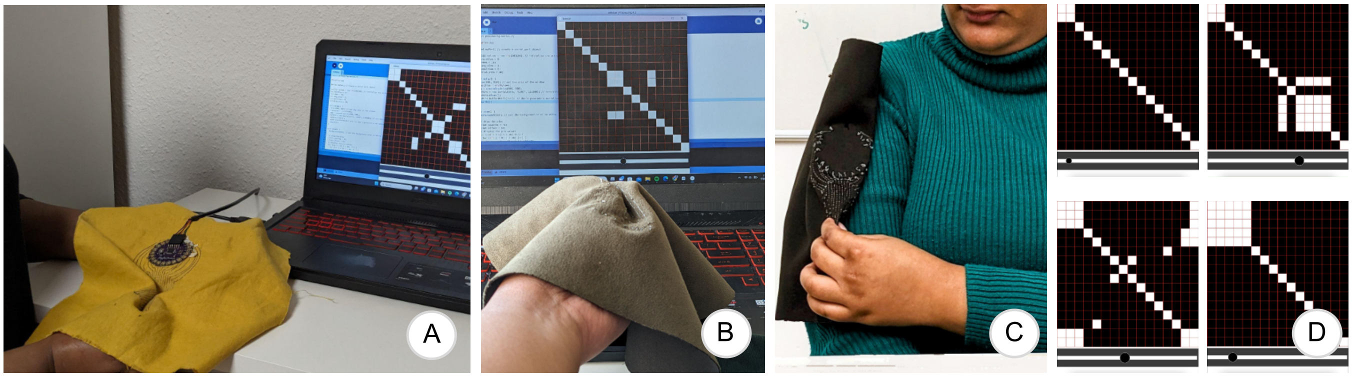

Figure 4: Interaction with the GUI. The fabric swatches can be rolled (A) and pinched (B). For on-body interactions, they are pinned to participants' sleeve on the upper arm (C). Connections between the conductive pinstripes are visualized as a dynamic, real-time matrix of black and white pixels, and a slider visualizes the position and size of pinching gestures (D).

appearance. Finally, the participants were asked to share their perspective on the social acceptability of the interfaces and the rolling- and pinching-based interaction in a wearable context.

Following this task, the voice recording was stopped and the study concluded. The duration of the study was, on average, 44.5 minutes and ranged between 32 to 50 minutes, depending on how much information the participant shared.

4.4 Thematic Analysis

Rallabandi, Haynes, and Reed conducted a joint, reflexive thematic analysis [4, 6]; respectively, our experiences as design and interaction student, textile and soft robotics designer, and haptics and gestural control designer contributed towards semantic meaning-making during the reflexive analysis [4]. We took an inductive approach, working together with the data and constructing themes based on our individual experiences with materiality in design.

Electronic transcriptions of the interviews were created by Rallabandi. We used a four stage process to conduct the analysis. First, we each spent two weeks in data familiarization [3], reviewing the interviews and transcripts. This stage was done without generating codes, rather focusing on noting points of participant discussion that resonated with the research questions, or areas in our respective experiences working with materiality in previous design research. In the next phase, initial codes were generated independently over a two week period. At the end of this phase, we met together to discuss the material and our initial codes; key areas of interest surrounding participants' relation to their lived experiences in assessing and understanding the fabrics, material considerations of requirements for different contexts of wear, and reflections on malleability and control over the different materials were discussed. In the next phase, we iteratively coded using these initial ideas to generate categories. At a final meeting, we each presented our coding and introduced candidate themes we had generated from our respective coding. In the final phase, a set of two overarching themes were jointly outlined and iterated again over the following week together, before finally being given names.

5 RESULTS

We first identified different material features that impacted the interaction, as perceived by the participants. Participants noted different properties when interacting with the fabric on its own in the Textile Evaluation and when interacting with it as a controller in the other two parts of the study (Table 1). Although participants discussed textures in each case, the framing of these qualities shifted from associations to comfort in the Textile Evaluation to associations of control and graspability in the other evaluations. This demonstrated how the materials' perception changes based on context. Two material qualities were relevant in both situations: fabric density/thickness (light vs. heavy fabrics) and elasticity/stretch. As well, participants' ideas of use for the materials changed; in the evaluation of the textile itself, participants were more concerned with wearability features. For instance, P1 and P6 were interested in its absorbency, and all participants noted its thermal properties as a function of how it would be worn (e.g., good for summer heat or better suited for winter jackets). Comparatively, participants noted more control and movement affordances in the other evaluations, for example, the haptic feedback of finger movement over different ribbing and weave structures. This also related to participants' associations from other lived experiences. Compared to the textile and wearable associations when examining the material on its own, the introduction of control aspects saw participants relating the materials to other non-textile controllers they had used before.

5.1 Base Material Preference

In the interview, the participants were asked which materials they preferred for the pinching and rolling gestures. Four preferred the yellow cotton and two the brown moleskin. All participants preferred the green needlecord as their second choice, but no participants preferred the white elastane as a base for our pinstripe-like sensor. We did not endeavor to determine which material was "best" for this interaction; rather, the participants' preferences tell us about why the materials worked well in the design or not.

P1 and P2 preferred the brown moleskin. P1's preference lies in the material being "a little bit more sturdy for me to roll it around" and the general softness on the skin, while P2 compared

		Textile Evaluation	Controller & Wearability Evaluation
Fabric Features	Texture	roughness, softness, comfort	gripability, graspability, friction, coarseness, ribbing/structure
	Type	specific material, synthetic or natural	N/A
	Affordance	absorbency, thermal/heat-related properties	movement-coupled qualities, e.g., *tik tik* of needlecord, (P1, P3)
Associations		upholstery, clothing, decorative objects, tools (rags, micro-fibre cloths)	interactive controllers: Apple devices haptics, knobs

Table 1: Notable features and associations made from the participants' evaluation of the interactive swatches, focusing on the swatch just as a textile compared to the swatch as an interactive controller or wearable.

the moleskin to the haptic interaction of Apple products, being "very versatile and very seamless in a lot of circumstances." The napped texture was perceived to provide tactile feedback while still being easy to manipulate. On the other hand, P3, P4, P5, and P6 preferred the yellow cotton swatch for the interaction. The material was perceived to be both comfortable and easy to manipulate; P6 described how the ease of interaction "has something to do with the material, [the] cloth itself, because that enables the friction a bit more than [the other swatches]." The balance between having a larger textural structure, while still being soft: "[The swatch has] the best ratio of being flexible and I can actually feel the lines so I do get some haptic feedback. I feel like I have the most control." (P3). The preference between the cotton and moleskin seems down to individual preference on how rigid the material is. P2 and P3 liked that it was more sturdy and squishable, respectively, while P4, P5, and P6 cited this as the reason for *not* liking it, preferring a more flexible material for the gesture.

All of the participants liked the green needlecord as a second choice, stating that it still provided control but that the density of the material, likely with the more rigid high pile, was "restricting" (P1) to movement and less flexible than needed for the gesture (P3). P2 and P3 liked the haptic feedback of the ribbing but wanted it for a different interaction setting, for instance on an immobile material like a cushion or armchair.

P4 initially liked the while elastane but reasoned that it was unsuitable for interaction once the swatch was worn on the arm: "The experience is different on the table when compared to on-body. I felt [the] yellow one was much more comfortable on the body. I don't know, the white one, it's so slippery now." The other participants agreed the elastane was less controllable in their use; P1, P2, and P5 felt the swatch was getting away from them as they moved; P2 commented how they felt "paranoid about if [they] moved a lot or not because it's too stretchy, too smooth." P3 described that they "can actually barely roll it... I'm rolling my fingers and nothing's happening. Because it's hard to use it for the gesture, then I wouldn't want it, it would just annoy me."

In this overview of the participants' reactions to working with the materials, some are a factor of personal preference, for instance, preference for the more sturdy moleskin or the more flexible cotton. Others relate to the operability of the swatch as a controller, for instance, flexibility, gripability, and tactile feedback were important factors for achieving the gestures. Participants' responses demonstrate how materials matter for understanding gestures and control in eTextile interaction.

5.2 Themes of Material Interaction

Building on these preferences through our reflexive thematic analysis, we jointly formed two themes regarding work with and evaluation of materials in eTextile design. We derive these from analysing the participants' interactions with the different materials in the interface:

1) Textiles in an interface contribute their own, inseparable materiality to the interaction. Material-led practices should not occur in the design consideration alone, but must also be a key factor throughout implementation and evaluation of interaction. Reflecting on agency and Barad [1], we affirm that the textile components — the base material and the conductive stitch sensor, in this case — cannot be viewed as separate entities or as one having more or less influence in the interaction. The influence of materiality is well-known in design considerations and focus on craft practice [11, 21]. Similar examination of material entanglements in eTextiles [35] and other craft practices, including Nordmoen's examination of woodworking [9, 28], also support this. Participants' comments carry the importance of materiality in design considerations further to the evaluation of a sensor: The evaluation of eTextile sensors themselves often happens in a vacuum, giving full attention to the sensor. Whether sensor or housing, the fabric properties of the materials used and their integration impact the functionality of the interface and its use. Participant 2 (P2), an interaction and eTextile designer, nicely summarized this often missing perspective:

> "People talk about eTextiles as being like a ubiquitous computing kind of argument - like 'interaction everywhere you can.' It's very flexible. [But] I think about using the material property of the textile as to the usability of this interface as well. It's an aspect that people never see." (P2)

The observations from these interactions demonstrate the need to evaluate sensor use from this perspective, arguing that material-led discourse is appropriate not only from a design standpoint but also in the implementation. For instance, participants' interactions demonstrate how material properties, particularly of the base fabric, dictate not only the experience of the interaction but also the *gestural* use of the device. The materials, and especially their textures and elasticity, guide participants to being able to complete the specified gesture well or not. P5 described that "the yellow [cotton] and green [needlecord swatches] were easy... this coarser texture is maybe easier to keep it in between the fingers... sometimes [with the white elastane swatch] it was hard to not use the second hand." P2 also discussed the white elastane swatch's unsuitability for the given task and gesture, stating "it's not that I have like grudge towards this kind of fabric. It's just, it's not suitable for the rolling interaction." Rather, the white elastane swatch naturally suggests a stretching interaction just by being stretchable. Other materials provide different direction on what kind of gestures one should use while interacting with them. P3 mentioned that the brown moleskin swatch "gives the sense of being able to squeeze it," which distinguishes its gripability from the other materials: "All of them are similar for the grip except the brown [moleskin] one. It lets you squeeze more."

As well, the materials also provide tactile feedback that confirm behavior and help users to access action-result paths when learning. When working with the textures of the green needlecord and yellow cotton swatches, P5 discussed how the base provided an indication of their position and that "[they] wouldn't mind [the material] to be evident because [they] don't want to look at it when trying to interact with it, it would be good to be able to feel how it is aligned so that [they] can use it without looking at it." Participants also discussed how the textures and "rib actually adds on details" (P2) and "fine grained" (P4) feedback to their gesture. P1 described this texture as acting like "some sort of dial;" both P1 and P3 described their motion over the fabric as producing a "tik, tik, tik" sensation of position. P6 likewise commented that "friction obviously helps any day, at least in my personal preference. I would prefer to have friction so that I can exactly control what I'm doing." This physical material influence mirrors findings in haptic feedback and digital materiality and the design of digital haptics [34]. The participants' comments here demonstrate how this materiality manifests and influences their use and sense of control, based on feedback, from an evaluation standpoint.

The integration of the base material and conductive stitch also matters, impacting participants' interaction of each material and also functionality of the garment as a whole. Although the white elastane was not favored for the gesture, P6 noted that "the white [elastane] didn't have a huge difference [from the stitch]. I couldn't sense the difference between this [thread] and the material itself, it felt better." However, P1 observed that "the white [elastane] feels heavy only over the stitches, so my I might have felt it or it might have change the way my clothes might look" in a wearable implementation. Similarly, P3 discussed how the stitch in the brown moleskin swatch did not lie flat and formed "bubbles" as the fabric puckered under it. In a wearable, this integration between base and stitch would be undesirable, potentially that "the knots at the end and the bubbles on the brown [moleskin] one may be more annoying on the skin" (P3). To summarize, the users' perspectives and behaviors were influenced by the material properties of the swatches, namely through texture and elasticity, which provided grippability and a sense of control. This theme expands on previous research from craft and design to demonstrate how materiality also influenced gesture, tactile feedback, and wearability from the users' point of view.

2) Wearable sensing must be evaluated with respect to culturally situated bodies, orientation on the body, and specific use-cases, which create context and semantic meaning. Our second theme again objects to the idea of eTextile interfaces as independent entities; in addition to material influence on the interaction, we here highlight how materials and bodies align, and how this influences wearability and comfort for the end-user. Rather than evaluating these interfaces alone, as nonpartisan devices, we must evaluate them as they are understood through bodies and our lived experience. Previous research explores the cultural and contextual influences on interaction, for instance how privacy and social norms influence interaction with wearables [8, 20, 26]. The participants here reiterated that meaning-making in interaction with eTextile interfaces relies on existing relationships with textiles. In novel findings, we see that body-contextualization also influences spatial organization on the body, and innate directionality in tactile interaction.

Meaning-making in interacting with fabrics relates to the above point about materials suggesting their own gestures for interaction; our bodies and the orientation and spatialization of the sensor provides context on their use. This is apparent in the participants' comparisons between interacting with the sensor swatches flat on the table or placed onto the body:

> "On the table I'm looking at two different things, maybe. But right now, since it's on me, I'm not even looking at where it's going. But I know it's going left or right now so it feels more natural on my body." (P1)

We often evaluate sensors in controlled environments, away from their intended place of use — in this case, on the body or as a part of worn clothing, where the interaction is contextualized by our knowledge of our bodies. The locus of interaction, either embodied or in situated externally, changes the interaction. After placing the swatches on their body, we see as above in Table 1 how attention changes depending on context. Participants described how this awareness changed when using embodied understanding of gestures: "Using [the sensor] like this on my shoulder, I can feel the [conductive] lines a lot more, maybe because I'm not looking at it," (P3) and "I feel less conscious because I'm not actively looking for [the sensor], it's just there" (P6). Position on the body also provides a sense of natural orientation to the gesture, often being "much more comfortable [to use] on the body" (P4). P4 goes on describe how "Now I feel it is a little difficult [on the table]. The experience is different on the table when compared to on body... Maybe this angle is much more better. I can feel. I feel it good now, like I'm able to move [the swatch]." P1, P3, P5, and P6 also stated that the interaction became "easier" and more "under control" (P1). As well, placement on the body dictates use and what kind of gestures are possible or easily accessible. P6 described that "On [my] body it feels lot more comfortable... depending on the place you're placing it. Since I chose my hands it feels very easy and reachable... I think it's easier to navigate."

We also see how participants understand eTextiles as they would feel on their bodies to predict or make judgments about sensors' usability. Previous experience with fabrics allowed participants to assess the sensors. All participants discussed comfort in wearability specifically as a factor of whether or not the sensor would work well. Integration of the stitch into different bases created unpleasant sensations on the skin; P1 noted that the stitch on the yellow cotton and white elastane swatches were less embedded than they were in the brown moleskin swatch. This reminded P1 of the stitches in Indian blouses, which evoked prior experience from memory and led her to worry that the sensor "would really be prickly and annoying and give [her] rashes" within a wearable in skin-contact. P5 also commented that the integration of conductive threads might be itchy, particularly around the neck, making the sensor only suitable in certain places. These evaluations were not made in-situ, with the sensor actually on the skin, but reveal necessary further examination that otherwise might not have been addressed by someone with different previous experience. Similarly, certain base fabrics had associations to clothing to be used in different weather or for certain events. Experience also helps to suggest uses for the interaction in design. Although the sensors functionally worked the same way, fabrics were viewed as being more "decorative" (P4, about the brown moleskin) than functional or better used in a non-clothing interaction, like the green needlecord being used on an armchair or pillow (P1, P5).

Similarly, the social context of the wear impacted the participants' evaluation of the sensors; this affirms previous work into design within culturally-situated contexts [11]. Participants were divided about how others would perceive their use of the sensor; P6 described how "If I'm going on a metro I don't mind it. If I'm in a socially important event, I wouldn't like to have [my clothing] being touched so much. I think the context and the personal choices matter." They go on to say that they "wouldn't want to be [seen as] scratching in public." As a wearable, some would not want the sensor to be so large or obvious; P1 and P5 were concerned with how visible the sensor might be in their clothing, with P5 commenting "it does feel odd to have such a big thing To wear. I would want it to be smallish [and] if it was the same color of my shirt then it could just feel very natural." as well, P5 commented about the Arduino being used: "Right now the microcontroller is not apparent, but I would think [about] how would I hide it so that it doesn't show," demonstrating how the entire setup, even beyond the sensor itself is present in wearability. P3 remarked that, for the brown moleskin swatch, they "would want it to be more as a feature of the clothing," to not alter the texture or clothing itself. Additionally, expectations of clothing on bodies and how they change our appearance also matter. P1's concern about the white elastane swatch's heavy stitching was that "[the sensor] might change the way my clothes might look." This sensitivity to the position of sensors was discussed within the development of Pinstripe [22, 23] with placement on low cut shirts. Participants in our investigation also demonstrate how cultural acceptability and sensitivity of touching oneself in public can factor into deployment. Considerations of materiality in the evaluation by the end-user lead to such new insights beyond the initial design considerations.

6 DISCUSSION

Reflecting on these themes and participants' experiences demonstrates how the material aspects and interactions between the physical components in a sensor used cannot be decontextualized from each other, their use case, or the lived experience of the user. We propose that, in both the design *and* evaluation of eTextiles and wearable interaction, we as designers and HCI researchers must instead work in situated context, where the eTextile is not just an object but rather a composition of the materials in its construction, the way in which it is worn, and the lived experience and body of the wearer. We must be grounded within an awareness of different bodies and somatic experiences, which form interaction and meaning making. Our work furthers the findings of Hamdan et al. [12] to examine how material influence is present in interaction with eTextiles and Karrer et al.'s findings from deploying Pinstripe on the body [23]. Our findings reiterate that sensor design cannot be separated from the materials used [2, 28]; when we evaluate sensors, we must also evaluate material-led use to evaluate how they are deployed. Evaluation must involve all of the sensor's components, not just the conductive ones. In our case with eTextiles, both the base and stitch materials guide the interaction.

Materials Influence Gestural Affordances: Hamdan et al. previously highlighted that the friction behavior of the fabric influences if a pinch-roll gesture can be performed [12]. We highlight that the influence of fabric on interaction goes even deeper, as the materials themselves can influence and guide gestures. Participants discussed how different materials implied different behaviors. Materials may provide additional direction to the gesture, such as the directionality of the provided by the needlecord or the squishability of the rolling gesture suggested by the brown moleskin. On the opposite side, the white elastane was seen as unsuitable because it suggested an entirely separate gesture of stretch, rather than rolling or pinching. We argue that these gestures are inferred by the haptic qualities of the material. The slippery elastane provided no feedback for having a sense of position or control over the interaction. The other materials, for instance the preferred yellow cotton weave swatch, provided feedback to play with and inferred a resolution to the interaction that could be explored. The description of the ribbing on the green needlecord as providing a "tik tik tik" sensation suggests that the properties of the fabric lend inherent markers over particular distance. Materials in this way can provide an indication of this control and guide gestures over spaces. This has broader implications for the design of tangible user interfaces; in choosing materials for pre-defined gestures or interactions, we may miss opportunities for gestures and control that are more intuitive and ergonomic when guided by the unique affordances inherent in the materials themselves.

Functional Augmentations influence Materiality: While previous explorations of material properties often used non-functional samples [13, 23], our work highlights that using the fully functional device is important, as the stitches of the pinstripe-style sensor in fact influence the perceived materiality. Participants' perception of the stitch demonstrated the inseparability of stitch from base (and vice versa) and aesthetic value. The conductive stitches are integrated into the base fabric and they therefore alter the base material's properties – in particular, for more bulky stitches such as those used by Heller et al. [14] and Hamdan et al. [13]. Participants were concerned with the way the conductive lines modified the shape of the fabric or a possible garment implementation. This extends to an aesthetic appearance — the integration impacts the wear in terms of both comfort and different feelings on the body, as well as appearance. The integration of the stitch into some fabrics was subtle and unnoticeable; for instance, existing alongside the ribbing of the green needlecord. In other cases, such as in the moleskin, the stitch was too much at a contrast and gave sensations of being itchy or scratchy.

This supports the idea that eTextile design and use cannot operate solely on the creation of sensors, assuming separation between the stitch (here extending beyond just conductive stitches to all sensing materials, such as resistive foam, integrated circuits, etc.) and the fabric base which supports and houses them. Both base and stitch have their own unique material qualities and the combination of these must be accounted for; design perspectives benefit from accounting for this integration and discussing the sensor in the context of materials and base, rather than the sensor on its own.

On-Body Deployments Provide Rich Opportunities: Karrer et al. [23] previously provided an initial exploration of Pinstripe on the body, suggesting issues such as user agreement on sensor orientation and social acceptability as design constraints. Our study expands upon this by highlighting how tacit knowledge of one's own body and the garments one wears positively influence the interaction, which means that on-body deployment offers many opportunities. For one, while the pinching gesture feels unusual for a tabletop device, it felt natural and comfortable on the body. The body also provides additional proprioceptive and tactile feedback, making it easier to locate and use the sensor without visual guidance. The body also provides a natural directionality to the sensor, providing gestures with a natural embodied semantic, which can be drawn on during gesture design. Generally, we observed participants started to fully appreciate the sensor design once placed on the body, highlighting the strength of the concept behind the original Pinstripe design [23].

Social Norms Shape Sensor Use: Participants' experiences of the materials highlighted not only functional and aesthetic properties of the fabric and sensor but also how the sensor would change the look and feel of clothing, which exist in well-established cultural and social norms. For example, the sensor stitches altering properties such as stiffness, stretch and texture were discussed in relation not only to their wearability but also their appropriacy in different types of clothing. For example, one participant did not want to have the sensor integrated into formal clothing and felt that the gestures would be inappropriate in the setting of a formal event. P6 described the social acceptablility in how "again this culture matters. I mean wearing headphones are okay right now. But back then, like five years back it was not okay to talk to people while having headphones." This reflects the complexity of personal style and perceptions of social acceptability, which are influenced by the materiality as well as behavior and use of the interface, as discussed by Devendorf et al. [8]. Material influences not only functional properties but also fundamentally changes the look and feel of clothing, which exist in well-established cultural and social norms. Our work expands on previous pinstripe-like implementations to demonstrate the importance of materiality and of context. Participants' interactions show that sensors are factors of their composition and the participants' lived experiences. The sensor does not just exist; rather, its meaning and use are products of the materials which guide gesture, cultural and experiential understanding, and the context of use [1, 2, 27]. Throughout the interview, participants related their experience of the materials back to previous encounters with clothing and other interactive devices, as well as the social settings in which they were worn. Even without particular vocabulary to describe what they felt, participants related through their lived experience.

Understanding of the sensor is also dependent on the users' tacit knowledge and understanding of the body, particularly with regard to with materials and their placement. There is an inherent directionality that is introduced when moving the eTextile placement from the tabletop to a wearable setting. On the table, the sensor does not have a relevant directionality, although the fabrics can provide a sense of orientation; for instance, via the ribbing on the green needlecord. On the body, there is spatial and orientational awareness that can be accessed. Including participants' bodies in the interaction integrates tactile properties of feeling the fabric to feel the body underneath. This provides rich feedback in control, playing with the tacit understanding of touch on the body and incorporation of feedback from the materials' tactile properties. Interaction with sensors and their evaluation cannot be decontextualized from bodies and individual lived experience formed through them [17].

Collectively, these findings highlight the interconnectedness between the materials, sensor, gestures, physical context, and social context of eTextile sensors — factors that, *in combination*, contribute to overall user experience and preferences. As designers and HCI researchers, we must continue to develop and critique our design and evaluation methodologies, to move towards practices that recognize these interfaces as holistic compositions of materials and situated context. For example, practices that foreground materials [28] and bodies [17] within the design process.

6.1 Limitations and Future Work

This is a qualitative exploration of a small sample of fabrics. We make no claims towards having covered all possible effects any fabric might have on interaction, but rather we reveal the type of structural effects one might expect. However, we do not make claims towards the generalizability or exhaustiveness of the present work. As observed through this exploration, ours and similar analyses in HCI should continue to be aware and note the subjectivity of individual users and bodies in interaction with eTextiles.

The current work focuses on the Pinstripe sensor [23], exploring a single type of gesture (rolling and pinching) and a consistent stitching pattern (straight stitch, 2 mm spacing) in accordance with the original sensor design. Participants engaged with the interfaces in an abstract context (the GUI provided feedback but was not task-oriented) and in a lab setting. These factors enabled us to control the scope of the study and focus specifically on how the material properties of the base fabric influence interaction with this pinstripe-like sensor. However, they might also limit the scope of our results. Our findings suggest that factors such as stitch style, stitch density, and the conductive thread used will affect the textile preferences of participants, since they influence the tactile properties and aesthetics of the interfaces. This opens up an opportunity in future work to investigate how different stitch properties (e.g., decorative stitches, variably spaced stitches, etc.) and materials (e.g., different conductive threads) in combination with the base fabric affect the interaction. Modifying these variables will additionally influence the sensor's functionality, so further study will be necessary to investigate these effects. Another avenue for further investigation is sensors that enable varied gesture types beyond rolling and pinching. Our study highlighted that some materials, which did not perform well for the pinstripe-like sensor, might perform well with other interaction modalities, such as stretch-input for the elastane.

The on-body interactions explored in this study were limited to the upper arm. This was a conscious decision of scope, based on the findings from the Pinstripe study [23], but it would be of interest to explore perceptions of the materials, interaction, and social context with other body locations and garment types, or with other locations in the built environment. It is expected that these varied contexts will elicit different associations and perceptions of the materials, extending the findings presented here. Particularly, it will be essential to explore participants' comments regarding social and culture contextualization, which would expand on similar work by Muehlhaus et al. [26].

Color and visual aesthetic are additional important factors to comment on, especially with respect to cultural and social acceptability. In this study, participants initially interacted with the swatches with closed eyes to focus on their haptic experience. Still, throughout the rest of the study and interview, the participants could see the swatches. We emphasized to participants to focus and comment on the feel and tactile quality of the materials rather than visual qualities throughout the study. However, the color of the swatches may have influenced their preferences and commentary on social context. Indeed, several participants mentioned swatch colors during the interviews and were reminded to focus on the tactile properties; this indicates a prospective area for future research.

Finally, this study was designed for embroidered eTextiles with a distinction between Base and Stitch. Since other types of eTextile sensor will have unique configurations of sensing and base materials, often with less distinction between the two (e.g., in knitted, felted, or crotched sensors, the conductive materials are more deeply integrated into the base material), this limits the generalizability of the observations presented in this work. However, the themes raised in Base and Stitch still present factors applicable to diversely available eTextiles. Future work may want to explore fabric sensor affordances in a more systematic, bottom up manner, starting with the raw materials and techniques.

7 CONCLUSION

In this paper, we presented a re-implementation of an eTextile interface, *Pinstripe*, on four distinct swatches to determine the impact of materials on rolling and pinching gestural interaction. We used four materials, woven cotton, elastane, moleskin, and needlecord to address different fabric structure, tactile qualities, and textures in the interaction. We evaluated the textile sensors in a user study, conducting semi-structured interviews with six participants. Participants interacted with the fabrics and the eTextile sensors, drawing from their previous experiences to describe the materials and evaluating each swatch according to a combination of their aesthetic preference and ability to achieve the gesture. We found that fabrics and their properties indirectly provide certain information relating to suitable/unsuitable interaction. The fabrics guided interaction according to their material properties and situated context; the participants' interaction experiences differed when interacting with the fabric on its own, compared to interacting with it as a wearable sensor on the body. The participant interview responses were analyzed using a joint, reflexive thematic analysis. From this analysis, our key thematic contributions regarding design and interaction with eTextiles were that 1) Both sensor and fabric contribute to their own materiality and meaning to the interaction and resulting gesture, and 2) Wearable sensing cannot happen in an isolated manner and must be evaluated with respect to culturally situated bodies, orientation on the body, and context of use.

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A SEMI-STRUCTURED INTERVIEW QUESTIONS

Are you familiar with eTextiles?
How much experience do you have with materials?

Part 1: Textile Exploration

- Now I request you to close your eyes. I will give you each swatch and feel free to touch it and get the feel of the fabric. You can start talking about your experience right away or take some time. Once you think you've given enough input you can let me know by saying "I don't have anything extra to add here or I'm done".
- Now open your eyes. Do you notice any differences for the textures and feel of the fabric with and without the visual contact. Would you like to add anything here?

Part 2: Controller Evaluation

- How easy is the gesture to learn?
- Are you facing problems while performing the gesture?
- This textile interface, how does it feel against your skin? Would you feel comfortable wearing it?
- Lets talk about the texture, does the texture feel same or different with the interface? When rolling back and forth, there's friction between fingers as well as the fabric, Are these textures causing a friction or the interface?
- In what ways is the slider enhancing your experience with the swatch? Is it enhancing your experience?

- Is the slider enhancing the experience of the gesture by taking away from the fact you are rolling the fabric between fingers?

Part 3: Wearability Evaluation

- Choose one from the set of swatches, why did you select this one specifically?
- What factors contribute to reject the remaining swatches?
- How natural does it feel when placed on your clothing?
- How is the experience of the gesture on your body and on the table?
- How would you feel to interact with it multiple times in a single scenario?
- Do you think frequently holding the fabric can be lead to misinterpretation?
- We discussed about the features of the fabrics, Do you notice these features of fabrics with the interaction?
- Pick a swatch that is your least preference. How would you feel to perform the gesture if this swatch is used for interaction in a social situation?Would you feel confident? If not, how would you feel and why?