Interaction with Touch-Sensitive Knitted Fabrics: User Perceptions and Everyday Use Experiments

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(a) (b) (c) (d)

Figure 1: Touch-sensitive knitted fabric and example applications used during our formative focus group study. *(a)*: A large multi-button knitted controller used with the *Whack-a-Mole* game. *(b)*: A knitted controller on which the touch-sensitive area is designed to capture sliding motions and gestures, used to control the *Brick-breaker* game. *(c)*: A knitted controller with one interactive button which controls a *Flappy Bird*-style game. *(d)*: The piano keyboard, volume slider, and media control button touchpad connected in a system. The sensing hardware is networked via I2C, with a single sensing controller directing communication between all three devices. The master I2C device connects to a MacBook Air via USB MIDI to interface with *GarageBand*.

ABSTRACT

Recent work has investigated the construction of touch-sensitive knitted fabrics, capable of being manufactured at scale, and having only two connections to external hardware. Additionally, several sensor design patterns and application prototypes have been introduced. Our aim is to start shaping the future of this technology according to user expectations. Through a formative focus group study, we explore users' views of using these fabrics in different contexts and discuss potential concerns and application areas. Subsequently, we take steps toward addressing relevant questions, by first providing design guidelines for application designers. Furthermore, in one user study, we demonstrate that it is possible to distinguish different swipe gestures and identify accidental contact with the sensor, a common occurrence in everyday life. We then present experiments investigating the effect of stretching and laundering of the sensors on their resistance, providing insights about considerations necessary to include in computational models.

CCS CONCEPTS

• **Human-centered computing** → **Ubiquitous computing**; **Interaction devices**; **User studies**; **Gestural input**.

KEYWORDS

knitted sensors, smart fabrics, touch sensors, formative study, focus groups, qualitative study, design guidelines, quantitative study, everyday use, gesture identification, distance metric, sensor laundering, sensor stretching

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1 INTRODUCTION

Fabric-based touch sensors, created through various techniques, such as embroidery [5, 20, 22, 23, 39, 51], weaving [4, 15, 24, 52, 59, 67], and knitting [16, 38, 49, 62, 63, 65], have shown great potential towards enabling interactive applications through flexible and durable interfaces. We focus on touch-sensitive knitted fabrics designed with one conductive carbon-coated yarn and only two connections to external hardware [38, 62, 63]. The conductive yarn is combined with non-conductive yarns during digital knitting, and after the sensor component production, electrodes are attached at the two yarn endpoints to connect to other hardware. The purpose of this design with minimal wiring is to make manufacturing at-scale easier, by reducing post-processing, and to create user-friendly and robust sensors. These sensors have a smaller chance of breaking at fabric-to-wire connection points compared to other alternatives, and they do not rely on several layers of electrodes.

In this paper, our aim is to explore the application space of these minimalistically-designed knitted sensors and their potential to be integrated into our everyday environments. We start by gaining a better understanding of end users, their general impression of touch-sensitive knitted fabrics, areas where they would like to see this technology incorporated, as well as any hesitations when interacting with these sensors. This investigation fills a gap in existing literature since qualitative user studies from existing work have been narrower in scope, primarily focusing on specific design aspects. Informed by the focus group study, we explore some technical aspects of these particular touch-sensitive fabrics. These explorations provide insights related to designing interactions and implementing applications relying on these sensors for user input. As mentioned, some of the findings of our work can be generalized to the broader field of smart textiles, while other considerations, particularly those related to technical evaluations, are more specific to the construction of sensors relying on this particular design process and philosophy [38, 62, 63]. The contributions of this work are the following:

1. We report on a qualitative formative user study with 32 participants, structured as 8 focus groups. During this study, we introduced users to the touch-sensitive knitted fabric technology and its basic working principles, presented them with several design samples and applications prototypes from prior work, and asked questions regarding their opinions and perceptions.
2. Through thematic analysis of the focus group data, we identify new research directions and create a basis for later building real-world applications relying on touch-sensitive knitted fabrics according to users' views. We also identify specific hesitations and expectations of potential end users from the formative focus group study. An underlying requirement to developing the desired applications was the ability to use gestures in addition to simple touch on the fabric. Furthermore, there were frequently mentioned concerns about safety and everyday use durability.
3. Informed by the focus group study, we investigate the capability of one of the fabric designs to differentiate among three different, but related swipe gestures, as well as simulated accidental touch events. We conduct a user study with 12 users, where each user performs each gesture several times on the sensor, to later compute the similarity between all captured samples using the *Euclidean Levenshtein Distance (ELD)* metric [62].
4. We demonstrate the durability and everyday use potential of the touch-sensitive knitted fabric technology. To do this, we conduct a washing and drying experiment on three different touch-enabled knitted fabrics. We explore the effect that this has on resistance, which is an important property of the sensing area, since it affects the signal output from it. Similarly, we test the effect that stretching, horizontally and vertically, has on other sensor samples' resistance values. These experiments are necessary for informing future high-fidelity computational models to characterize the behavior of knitted sensors of different designs during everyday use.

2 RELATED WORK

Many modern human–computer interfaces are designed with soft and deformable materials to enable a variety of applications [41, 42, 70]. A large subset of these incorporate fabrics [4, 6, 15, 20, 22–24, 37, 51, 59, 68]. Aligning touch–sensitive textile construction with industry manufacturing standards enables reproduction of textiles on machinery outside of a laboratory, an aspect addressed by many [13, 38, 52, 62, 63, 65]. Although smart fabrics include mixed technologies, such as pressure or pinch detection [58], we conduct our study focusing on touch–sensitive fabrics. Such fabric–based sensors are developed in a wide variety of technologies including resistive [18, 26, 45, 50, 58], capacitive [38, 51, 52, 62, 63, 69] and *inter–yarn contact sensing* [28, 30], and in a wide variety of fabric construction or embellishing techniques. While several considerations and user views of touch–sensitive fabrics are relevant across different implementation strategies, our focus for this work is knitted capacitive touch sensors, producible using digital weft–knitting and using one sensing yarn routed in different ways to form various patterns [38, 62, 63]. In this technology, one important goal is minimizing the number of connections to external hardware, to make manufacturing easier, and to improve usability and robustness. Additionally, the sensor design, construction, and integration process are not tailored to one particular application, but it is intended to be leveraged by different ones.

In this paper, we study fabric–sensing technologies through end users' perspectives to explore the possibilities for real–world applications. We continue this section with a summary of previous work on qualitative studies regarding smart fabrics, and then provide an overview of prior research on the implementation of fabric–based touch sensors which we use for our formative study.

2.1 Qualitative Studies of Fabric Sensors

In order to properly explore the interaction space of smart textiles, end users' views should also be considered: their overall perceptions, hesitations, and desired applications. Qualitative studies in previous work have started addressing some of these questions but

Figure 2: Knitted touch sensor design workflow: 1) Textile designers conceptualize sensor layouts while considering knitted circuit design guidelines. 2) The textile layouts are programmed using *Knit Paint* in the *Shima Seiki SDS–ONE APEX3* software suite, and compiled for the desired weft knitting machine. 3) The compiled programs are transferred to the configured knitting machine for assembly. 4) The completed sensors undergo testing and evaluation to assess performance. 5) The textile circuits are directly integrated into devices with no human intervention needed after assembly.

have mainly revolved around specific aspects of a technology or particular applications. The work in [29] has used participatory design methodology to develop applications with toolkits. Other research has explored user preferences for finger gestures on smartwatches [54], wrist gestures for in–vehicle application control [43], and force input on steering wheels [27].

Participatory design methodologies [56] are conducted to develop specific applications for new technologies in various fields, such as education [34], medical fields involving experts and physicians [17, 55, 71], and to understand the needs of special groups [60]. These methodologies have also been adopted for e–textiles and fabric–based sensors [29, 40]. One example is the work from Devendorf et al [16], which, through user studies, examines dynamic textile displays in relation to personal style, which is typically associated with complex personal and socio–cultural significance [21, 25]. That work, similarly to ours, is based on Gaver et al.'s [19] original descriptions of ambiguity as a resource in design. Other work from Davis et al. [14] explored the emotional impact of textiles' textures and materials on users. These studies, however, did not explicitly focus on users' desired application space for touch–sensitive textiles, or their concerns for everyday interaction. Our work aims to utilize user perspectives to guide design aspects of future interactions based on touch–sensing fabrics in general, and more particularly, those applications that would rely on fabrics knitted with one conductive yarn and minimal external connections. The study protocol aimed to allow diverse input on key interface aspects of look and feel, accessibility, and intuitiveness [57].

2.2 A Framework for Extensible Weft Knitted Capacitive Touch Sensors

In this paper, we use knitted capacitive touch sensors. These sensors are producible using digital weft–knitting and one sensing yarn routed in different ways to form various patterns while combining with non–sensing yarn. This creates a touch sensing circuit when connecting to external electronics. Weft–knitting is an industry–standard manufacturing process capable of producing intricate 3–dimensional fabrics [61]. This method enables easy mass production without the need of manual operations or human intervention. The loop structure can be specified and controlled programmatically. Figure 2 provides some insight into this textile production process. Designers can easily create different patters through rapid prototyping processes. Table 1 describes such example design patterns, which are also used in our formative study.

Since the sensors used in this work are constructed using one continuous sensing yarn, it is challenging to detect the exact location of touch. Previous work has shown that differential capacitive sensing can be used to detect human skin contact with the conductive yarn [38, 62]. Using this technique, we are able to detect discrete single position, amount of pressure applied or continuous swipes using a single finger. The conductive part of the textile sensors is made of carbon–infused nylon and the non–conductive part uses polyester yarn. All the sensors, irrespective of their design pattern, have two connection points.

Figure 3 illustrates how a serpentine conductive pathway can be adapted to form a multitude of shapes that can approximate conventional touch interfaces. Each circuit has two endpoints (A and B) with a cumulative linear resistance measured between them. The pathways do not branch or self–intersect and map a 2–dimensional area to a linear distance along each path. Touch localization is inferred by measuring a current differential induced at either end of the textile circuit when skin contact is made. The circuit's large resistance decreases current flow and increases the location sensitivity along the pathway. Supplementary sensing hardware connects to the circuit at either endpoint which generates, acquires, and processes voltage waveforms. The voltage measured at each endpoint is compared with the input voltage to yield the change in magnitude (gain). The gain is used to decouple the linear touch location and magnitude of capacitance. Additionally, the sensing hardware can be adjusted to account for variations in textile conductivity to effectively measure touch across a broad range of textile circuit designs.

The sensor prototypes described in Table 1 were all introduced in prior work [38, 62, 63]. They demonstrated diverse patterns and applications and their conductive components are illustrated in Figure 3. We use these prototypes as examples for our formative study and test their performance when exposed to potential real–world distortions, to subsequently determine our recommendations for application design with this technology. The fundamental circuit of all sensors (i.e., single–conductor and two endpoints) is similar. The conductive yarn forms a linear resistor which is separated into

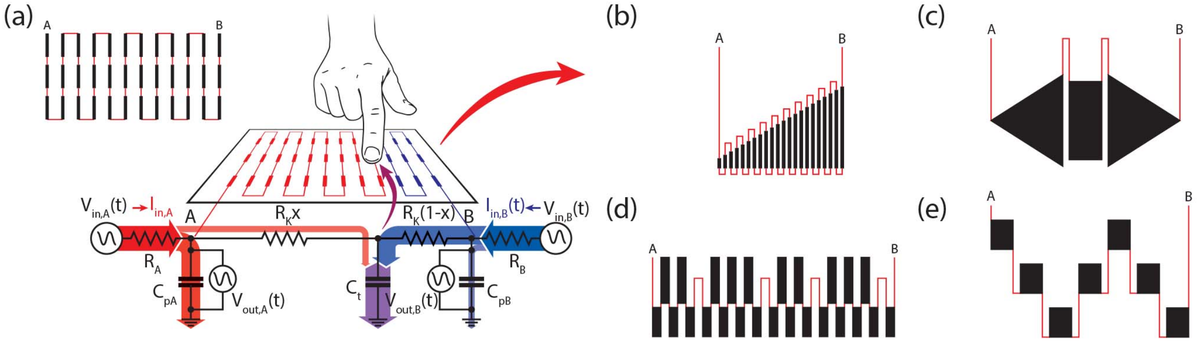


Figure 3: Extensibility of the knitted capacitive touch sensing circuit. The serpentine resistive sensing circuit *(a)* can be adapted to form a multitude of shapes approximating *(b)* a volume slider, *(c)* a 3–button media controller, *(d)* a piano keyboard, and *(e)* a multi–button game pad. The black polygons indicate exposed interface elements while the red lines indicate yarn interconnection pathways hidden within the textile structure.

two series–connected resistors at the location of capacitive touch. The physical routing of the yarn alters the resistance distribution along the linear path. The measured signals also depend on the current–limiting resistance and parasitic capacitance of the sensing hardware.

3 FORMATIVE FOCUS GROUP STUDY: USER INSIGHTS

With this set of diverse prototypes, we conducted a formative study to understand users' perceptions of incorporating interactivity in their environments and clothes, enabled by touch sensitive knitted fabrics. Participants were invited to interact with several textile sensors and applications to explore their potential benefits, as well as envision other possible forms. The objectives of this study were the following:

- To understand users' views and experiences regarding interaction with this technology
- To explore application areas into which users would want this technology integrated
- To identify potential concerns when engaging with this technology for further study
- To generate design guidelines for future interactive applications based on touch–sensitive fabrics

3.1 Participants

The study was structured as 8 focus groups of 2–5 participants each, with a total of 32 participants. Participants were undergraduate and graduate students of a median age of 24 years old, with 20 of them being male, 11 female, and 1 of non–binary gender. Each participant signed an informed consent form approved by our institutional review board before entering the study.

3.2 Procedure

During each focus group discussion, a facilitator moderated the discussion, asking a series of pre–defined questions and other follow–up ones as necessary, to ensure that the users' expressed ideas were understood. Each group discussion was conducted over a period of 60 minutes. An observer recorded the conversation and noted important ideas, themes, quotes, impressions, and body language [33]. Audio recordings were also taken for reference. Participants were first given a brief introduction to the touch–sensitive knitted fabric technology that is the focus of the study. In addition, the design philosophy behind it and its basic working principles, as discussed in Section 2.2, were explained. The discussion featured three main phases, described below:

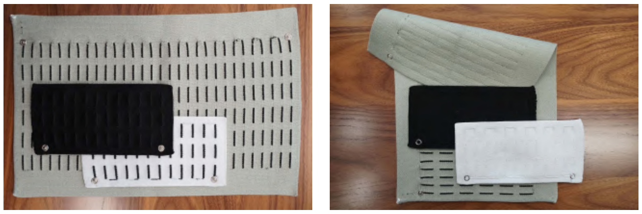

(a) (b)

Figure 4: Touch sensitive fabrics of varying sizes, knitted with conductive carbon–coated nylon and regular polyester yarns of different colors. They are all knitted in one piece with no electronic layers in between. *(a)*: Front of touchpads of varying sizes and colors. The noticeability of interactive components can vary with the non–conductive yarn choice: the black touchpad has subtle interactive areas, while the white one, prominent ones. *(b)*: Back of touchpads of varying sizes. The bigger sensor is knitted through the same process to be thicker.

3.2.1 Phase 1 – Design ideas and perceptions of knitted "Touchpad": During this phase, we explored the design ideas and perceptions related to the most generic sensor forms, the "*Touchpad*". Participants were shown three rectangular designs, with a set of evenly spaced touch–sensitive areas, or buttons: the *Small White Touchpad*, the *Small Black Touchpad*, and the *Large Touchpad*, whose size and specific characteristics are shown in Table 1, 4(a), and 4(b). This

Table 1: Characteristics of design form factor used in the formative focus group study.

Sensor	*Size (in)*	*Colors*	*Figures*	*Description*
Small Black Touchpad	8*x*4	black	4(a), 4(b)	A knitted sensor constructed by routing a conductive yarn through the fabric during the knitting process to create 36 interactive, button–like points across its surface [38, 62, 63]. The black carbon–coated yarn is less visible combined with the black polyester.
Small White Touchpad	8*x*4	white	4(a), 4(b)	A knitted sensor constructed by routing a conductive yarn through the fabric during the knitting process to create 36 interactive, button–like points across its surface [38, 63]. The black carbon–coated yarn is more prominent against the white polyester.
Large Touchpad	18*x*10	green	4(a), 4(b)	A knitted sensor constructed by routing a conductive yarn through the fabric during the knitting process to create 180 interactive, button–like points across its surface [38, 62, 63].
Keyboard	12*x*3	beige	5(b), 5(d)	The touch points of this sensor are knitted in the same serpentine structure as those in the touchpads, though the placement is staggered to mimic a alphanumeric QWERTY keyboard [62].
Single Button Controller	36*x*36	blue	9(a)	This prototype has a large circular sensing area in the middle. It can be used as a controller for applications that rely on pressing a button, as well as controlling pressure [38].
Multi–Button Controller	36*x*3	blue	1(a), 5(e)	This design is composed of several square–shape sensing areas, with the primary interaction modality being pressing one of the large sensing locations [38].
Slider Controller	36*x*3	blue	1(c)	This 32–row slider pattern is intended to capture continuous input, such as *swiping motion* [38].
Volume Slider	6*x*7	white	1(d), 6	A 22–row slider, which was knitted to control the volume in the *GarageBand* application. It relies on a swiping gesture used to control continuous input, similarly to the *Slider Game Controller* described above, but its proportions are smaller [38].
Piano Keyboard	15*x*5	white	1(d)	This prototype is a 25–button touch–pad, knitted to emulate a 2–octave piano instrument. The design and spacing of its keys follow those of a regular piano keyboard, and it can be used as a controller for the *GarageBand* application [38].
Media Control Buttons	7*x*6	white	1(d)	The button pad contains 3 buttons serving as discrete inputs to the *GarageBand* application as well, while graphically showing their functionalities in familiar forms: rewind, pause/play, and fast–forward [38].

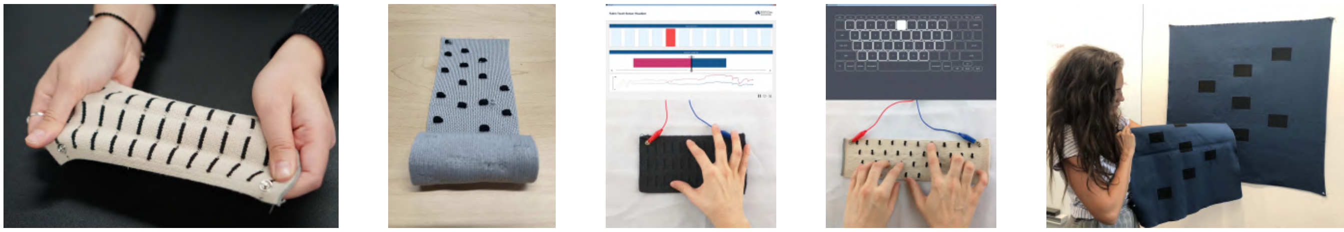
enabled participants to focus on understanding the potential interaction in a general sense, without a bias toward particular use cases, such as the *Piano Keyboard*, or the *Volume Controller* (Table 1), each of which have application–specific forms. The three knitted touchpads differed only in size, or color of the non–conductive yarn, highlighting the flexibility and scalability of the production process. Each of the introduced samples was connected through two electrical wires to a visualization application (5(c)), as described in [62]. After the users interacted with each of the forms, we asked them to share their thoughts on the technology, and potential uses of similar sensors relying on those same principles.

3.2.2 Phase 2 – Usability of specialized application prototypes: During this portion of the study, participants interacted with several specialized application prototypes, illustrated in Figure 1 and described in Table 1: the *Keyboard* (5(b)) together with an application prototype 5(d); the *Multi–Button Controller* (5(e)), with its associated *Whack–a–Mole*–style game application prototype, illustrated in 1(a); the *Slider Controller* and two game applications that can be controlled with it: *Brickbreaker* (1(c)) and *Flappy Bird*; the knitted MIDI controller system, demonstrated in 1(d), and composed of the *Piano Keyboard*, the *Volume Controller*, the *Media Control Buttons* (Table 1). These applications were selected as examples of potential use cases of capacitive knitted sensors, having real–time response, even though not fine touch location identification, which was developed in [38, 62]. They instead relied on sensing methods introduced in [63] and their purpose was to illustrate the potential of this technology to enable interactive applications. Participants were asked to assume, while answering, that the applications based on these touch–recognition sensors were working with high accuracy. As part of the inquiry of this phase of the study, participants were asked to think about the advantages and disadvantages of using existing technologies versus products based on the knitted prototypes. Moreover, they were asked to express whether a product based on these prototypes would be useful and usable to them and, if so, in what context.

3.2.3 Phase 3 – Reflections on technology and suggestions: At this stage, we wanted to understand the general impressions of participants after having been exposed to different uses of this technology. Our goal was also to realize if these interactions sparked any new application ideas for touch–sensitive knitted fabrics, and which uses mattered more to participants. Additionally, we were interested in understanding whether users would have any hesitations in interacting with these type of sensors; what they would like to see improved; what they would do differently if they were to design any of them from scratch.

3.3 Data Analysis

The recorded focus group audio files were transcribed using Otter.ai [3], a transcription software that converts speech to text. Following the automated transcription, we manually edited the files in two rounds for error correction. Subsequently, we coded the data using Atlas.ti [2], a tool which helps researchers conduct qualitative analysis of textual, graphical, audio, and video data. Because analysis is based on these transcripts, in a group context with identifiable information removed, we do not attribute quotations to a particular study participant below.



(a) (b) (c) (d) (e)

Figure 5: Properties and applications of touch–sensitive knitted fabrics *(a)*: Stretch–ability. *(b)*: Being able to roll the fabric. *(c)*: Visualization application of the approximate location of touch on a 36–button knitted fabric. *(d)*: An application using a knitted alphanumeric 36–key keyboard as an input. *(e):* Multi–button controller sensors with a similar design, but different sizes. The knitted components on each sensor are scaled versions of each–other.

Thematic Analysis (TA) [11] was selected to analyze our interview data. This approach provides the tools for a rich characterization of qualitative data, while not placing any requirements for theory development. We consider its scope appropriate for our purposes of understanding user response to this technology. Two researchers independently coded the data. Through later discussion, a consolidated and consistent list of codes and code groups was created that reduced redundancy and standardized the names. The two researchers each conducted a final round of analysis using those codes. A third researcher also reviewed the codes and data analysis for consistency.

We followed a pre–defined outward thematic structure of reporting findings, corresponding to our study objectives, with these three categories: the general perceptions, the potential for applications, and concerns and suggestions. In addition, there were two other major categories that emerged during the study: design aspects, and system and integration. The grouping of ideas, which was somewhat related to the three–phase design of our study, was performed this way for clarity of presentation and to respond to the study objectives more straightforwardly. However, this structure did not necessarily correspond to the way these insights emerged—for example, ideas mentioned in phase one, might be described in the section about concerns, if they are a better fit thematically.

While having previously defined major themes to explore might give the impression of a deductive analysis strategy, we argue that our approach is primarily an *inductive* one. First, our three major categories were defined by our research objectives and for clarity of presentation, not by existing literature. We did not have a codebook prior to analysing the data. More importantly, we analysed the information using a data–driven approach, assigning themes based on grouping similar concepts together. The process of determining themes was iterative and flexible. We aimed to create a thematic map which accurately reflected the dataset, and themes with internal homogeneity and external heterogeneity [7, 11, 48]. Not all themes had a similar number of data instances referring to them—the significance of themes was not necessarily dependent on a quantifiable prevalence measure, rather on whether each captured aspects of interest related to our research questions and objectives.

This analysis aims to provide *a rich description of the whole dataset*, rather than an in–depth account of one particular aspect, especially given the fact that this area has not been extensively explored before, and participant views are less clear [11]. However, ideas of integration or concerns expressed were followed with questions about details, to better understand them, and to ensure that participants had a clear mental picture of their suggestions. We employed a *realist theoretical approach*, which assumes that language maps to experience and opinion, rather than a constructionist one, in which context and society typically play a considerable role. We use *semantic themes*, with meaning assigned based on what the participants say, rather than looking beyond that aspect, and making inferences regarding any underlying ideas or conceptualizations. These choices were made since our purpose is not necessarily to deeply explore the psychology or social context behind the participants’ response. Instead, we are investigating the types of technological solutions that participants would be interested in using, based on our design principles and prototypes. This way, further research can be more purposely directed towards areas of interest to users.

3.4 Results

In this section, we detail the study findings, starting with general perceptions of the technology, aiming to provide a holistic view of the users’ sentiments, and then moving to desired fields of applications. Further, we discuss aspects of the knitted sensors’ designs as they relate to functionality and style, continuing with system design and integration, also considering aspects such as device size, and interaction modalities. Finally, we describe areas of user concern and improvements for future iterations of this technology.

3.4.1 General Perceptions: This section discusses major themes that became apparent in the study, the participants’ general sentiments throughout the phases.

Fabric Texture: Participants were divided regarding their experiences of the fabric texture. Many were pleasantly surprised by the softness of the fabric. One participant said: *“The fabric was a bit softer than I was expecting, because I knit a lot. And yarn that I use to knit is more coarse than that. So I was kind of expecting that type of texture. But this was softer than what I use. It was much finer than I’d been expecting when you said ‘knitted’”*. Similarly, another mentioned: *“You did mention, right, the threading is made out of* *carbon fiber, see, and I expected it to be a little more sharp, a little more, [...] you know [...] the opposite of fabric. [...] It's actually pleasant to see that it's not too different from the conventional fabric. So that's a nice thing".* Other participants however, considered it rougher, with one saying: *"This seems less suitable for clothing to be honest. Because it's soft, but it's not as soft as like something you would wear, I think".* This sentiment was more prominent when participants were interacting with applications that required them to continuously run their fingers across it, such as using the *Slider Controller* with the "BrickBreaker" game [38]. Another participant, while identifying the interaction surface of that same controller as *"disconcerting"*, saw that as a positive aspect, potentially useful for her autistic son to get exposed to different textures while playing a game such as "BrickBreaker", which could shift his focus from the uncomfortable feeling.

Comfort and Approachability: Overall, the fabric softness, especially in comparison with typical electronic devices, inspired users to think of applications and environments offering a relaxed and comforting atmosphere, such as hammocks at resorts, or falling asleep with your fabric electronics on your lap without risking damage to them.

Additionally, it was mentioned that electronics may sometimes seem intimidating to interact with and understand, and the fabric form of the sensor might help break down the mental barrier. One participant commented: *"For me at least, fabric is just comforting in general, so especially in a hospital setting, where it's already an uncomfortable situation, maybe just introducing something to the patient that's more comfortable for them to access, would make them more prone to like alert a nurse if something's going wrong".* Children were also mentioned in this context, for example, potentially finding it easier to communicate their feelings by interacting with their toys rather than articulating them.

Robustness: Many participants mentioned robustness as a quality of the touch–sensitive fabrics introduced. *"I don't think this is going anywhere. I think this will outlive me,"* said one participant. The sensors' robustness was also considered an advantage over existing hard electronics, with one participant saying: *"But one thing definitely which beats the current keyboards is they are very delicate, but they will break [...] like manually. But this won't break".* This quality was also particularly mentioned for hard electronic applications related to children, who are more likely to damage them, or hurt themselves while interacting with electronics. Additionally, it inspired several participants to think about outdoor applications. One participant shared: *Yeah, so you know, put it down on the beach, and the kids can play on it, [...] can set up something that actually becomes a screen for.*

Portability: The portability potential of this technology was also a characteristic mentioned in the study. The fabric can be easily folded and brought to an outdoor gathering, in the form of a game board, or a knitted musical instrument. Its light weight and flexibility allow it to be rolled and put into a bag, for example, as a keyboard for one's phone or tablet. One participant mentioned that even though a typical iPad keyboard is very lightweight, it is fragile and uses more space. Another participant said: *"If you had a business that was in gaming, and you were doing different shows, [...] this would be quick: roll it up, throw it in the back of the car, roll it back out. Then you can set up your station, and people can interact".* In outdoor and traveling contexts, many participants would prefer applications based on these fabrics instead of existing hard electronic alternatives. For indoor environments, the answers varied by participant and situation. For example, as can be expected, instrument players would not choose fabric instruments over existing ones, even though many would use them as travelling alternatives. One participant said: *"Also, one thing to consider is that when you have a piano, it's super heavy. So, it's nice to have like something that's really light, portable. [...] you could use a keyboard, but definitely keyboard and piano are not the same, right?".* Regarding gaming, while some participants would not replace their existing controllers for indoor use with knitted alternatives, others were interested in that idea.

Affordability: Questions about cost of production were also common. Upon learning that the touch–sensitive knitted fabrics used in this study cost only a few dollars to manufacture at scale, many participants suggested several fabric–based applications as substitutes for traditional electronic ones, in cases where cost was a factor. This became especially relevant for education purposes, or for exploring different hobbies. Fabric electronics can be used for training and learning how to perform different interactive tasks, such as playing the piano. One participant said: *"It's available to everyone. A lot of people can't afford to buy such a big keyboard and keep it. So, if you're going to make something like this, you know, [...] if people have a hobby, they can learn it. And since this is fabric, it's going to cost way less than that."* For a fully functioning system, the cost of the electronic components needs to be considered as well, which is still substantially lower than most conventional instruments.

3.4.2 *Applications.*

Throughout the study, primarily in its second phase, many potential applications emerged as benefiting from the integration of touch–sensitive fabrics. The major areas are summarized below.

Wearables: Another major area that was discussed was clothing—in normal circumstances and specific occupational ones. Interactivity in controlling general functionalities such as changing music, making a phone call, or tracking physical activity were commonly suggested uses. A specific scenario that was mentioned in more than one instance was using the sensor in clothes as an inconspicuous call for help in dangerous circumstances, as expressed by one subject: *"...as a way to quick dial 911. Like you press it a certain number of times or in a certain pattern, because then if you're in an unsafe situation, you don't want to be obvious about something like that. You can do that. Even just [contact] your emergency contacts."* Other uses included producing special suits for first–responders, astronauts, and athletes, with functionality added to make their jobs more efficient and comfortable.

Smart environments: Incorporation of this sensing fabric technology into homes and vehicles for controlling temperature, lights, and music, was also an important theme. Such sensors would be able to be integrated into furniture, pillows, blankets, and car seats. One group of participants, however, expressed preference for voice over fabric for such functionality. Other similar uses were mentioned for artistic settings, including controlling effects in a theatre set. Another application area that was frequently mentioned in this context was monitoring with the purpose of activity recognition. Having a carpet composed of such fabric to detect human activity was a popular concept, especially related to security. One participant said: *"Yeah, for security, maybe if there are places that we do not want people to enter or you know, access. So, we can just place this fabric over the entire place, so that [...] if there is any sort of reading, maybe we know that someone who's not supposed to be there, is over there."* Another mentioned a similar idea, while adding that such a carpet could replace cameras due to the lower cost. Another participant saw this as an opportunity to study areas of interest in a store based on customers' movements: *"Another application could be [...] a carpet in stores where you want to find out the layout, [...] what movement do people move? Like from what aisle to which aisle"*. Another subject suggested passenger position detection in a car: *"So even [...] if it is in the car, the car seat might have this part [...] in case of any emergency like a hit or crashing into something, the airbags come out based on the sensors, [...] where the passengers were instead of coming out from everywhere"*. Environments that rely on user identification were also considered, for purposes of personalization or security.

Gaming and Entertainment: This area was of interest as well, with participants suggesting many uses. Indoor games were mentioned with interactivity integrated into larger areas like carpets, to enable dance and board games for example. One subject said: *"I was just thinking about fun – it could be set up almost like dance steps. Well, Dance Revolution or [...] dance schools. Brides sometimes will go and learn how to do a waltz or whatever, [...] do it at home"*. Outdoor activities were also mentioned as benefiting from these sensors' portability, with fabric versions of board games being a popular choice. Regarding gaming, some participants saw controllers based on these sensors as more desirable than existing ones, while others preferred the familiarity and functionality of current controllers and would use these only for simple games. One participant observed the fact that upon touch, the pressure was detected as well, noting that it could be used in game controllers to give more nuance to each key–press. In addition, VR environments were mentioned, with one participant saying: *"I'm thinking, [...] can we do something with VR? So, like [...], something [that's] not controllers. Well with fabric, it's [...] easier to put different shapes rather than monitors. And so, you can have more control over environment. And it feels more real."*

Education: Several participants mentioned potential benefits to education due to several qualities of the touch–sensitive fabric. One reason was the low cost of production of these sensors, compared to some electronic alternatives. They could be used to produce different electronic tools, such as keyboards, musical instruments, educational games, to be accessible to children in less affluent areas, or to anyone that wants to learn something new. One user said: *"You can have like a very simple piano. So just a quick question on thread itself, I would imagine it's not that expensive. So for instance, this thing is definitely a lot less cheaper than an actual keyboard. So, I would imagine it won't be that much of a leap to take the signal from this and turn into an actual interface that detects where your hand is for particular keys, and then having an application that can actually simulate a piano playing. Yeah. And so, this can then be, you know, for [...] school districts that don't have a lot of money, but you still want music lessons"*. Moreover, a few participants in one of the groups also considered these sensors to be more user–friendly than regular electronics, potentially making for more interesting lessons, and even drawing more people to engage with science and technology. One user said: *"Yeah. All in all, it definitely, you know, it's much more user friendly, and makes the learning or whatever you going to do more approachable compared to, [...] more technical devices, [which] are a little bit scary."*. Another agreed with: *"I think one of the challenges of science is that everyone just thinks about it, like, 'oh, how cool or how like, larger life it is'. And I'm like, 'No, we should find ways to get more approachable, you know, encourage more people to get into STEM."'*

Healthcare and Assistive Technologies: Many groups offered ideas related to medical and related fields. Assistive technologies were mentioned, such as developing a lightweight braille system. In physical therapy, suggested applications included helping people with disabilities walk, by using a sensitive insole within shoes or socks to identify gait abnormalities, or similarly, learning how to properly grip objects. Applications related to posture correction were also explored, implementable by having sensors on one's chair which could detect body placement and suggest adjustments to the users. Suggestions regarding medical use were also common, with some participants mentioning monitoring patients' movements on their hospital bed, while taking advantage of the pressure–sensing potential of this technology. One participant mentioned: *"But again, this goes back to [...] a patient wearing something like this. So let's just say you want to [...] get information on [...] maybe the joints, [...] because maybe the patient [is] suffering from [...] arthritis [...] or joint issue, right?"* In addition, usability scenarios were very focused on getting information from patients' vitals—biorhythm, temperature, galvanic skin response, blood sugar level.

3.4.3 Design Aspects: Another important area of interest during the focus group conversations was the sensor design, its flexibility, and its ability to be seamlessly integrated into clothing or environments.

Unintrusive Design: Participants described the sensor design as *"simple, predictable [...] in a good way,"* and *"blending in."*. They appreciated the subtlety of design, which would allow the sensor to be suitable for different applications, including clothing. One participant said: *"It [...] could detect touching a lot smaller, right, because I'm thinking of using this thread [...] inconspicuously on multiple surfaces, and then gather a lot of data there."* Another area mentioned as benefiting from this quality is medicine, as expressed by one participant: *"I think, these days, when it comes to medicine, a lot of people want to focus more on non–invasive, because it's less work and also less risk to the patient and the medical practitioners"*.

Design Flexibility: The fact that the yarn can be structured as required by the application was a point of interest and discussion, which enabled participants to think of different configurations for it, being aware of the flexibility of the design process. One participant mentioned: *"Currently it is [...] said [...] how it is supposed to move, but based on [...] which application we are using this for, we can change the way it has been designed so that it makes more sense"*. The scalability of the design came across from the ease with which participants would think of applications that could use a similar design but have different sizes. Participants inquired about the distance between the sensing components of the structure. One participant mentioned that in confined spaces, such as clothing, he would prefer them to be closer together, while in larger surfaces, such as furniture or carpets, he would find larger areas of touch more useful. Participants also inquired about the type and thickness of fabric, differentiating between use cases. One participant said regarding the *"Large Touchpad*: *"I feel like this is more like something I would sit on rather than something I would wear."* Personal style was also mentioned as a factor, with one participant saying: *"In the black one, I noticed that it's hard to see where you're supposed to be touching versus where the regular fabric is. [...] Yeah, I'd rather a design where you can see, where it's kind of like the white and black one, plus my aesthetic is kind of white and black."*

3.4.4 System and Integration: The hardware construction, system components, and the ability to integrate knitted sensors with existing technology were also important aspects of the discussions.

System Minimalism: Overall, participants appreciated the reduced wiring and electronics associated with the system. One participant saw this system as an alternative to some electronics for soft robotics due to having fewer wires: *"I was thinking in the lines of soft robotics. [...] There we need to [...] conduct the electrical signals, right. And the type of things which we're working on, are very soft, like flexible. So, [...] instead of using all these wires [...] we can use this flexible fiber fabric"*. The matching small hardware is also important for portability, in addition to the fabric component, as mentioned by participants as well. Another participant suggested adding a few more connection points to increase the touch detection accuracy: *"So, potentially having more than just two contacts would be able to improve that resolution, right and more accurately tell where it is, like, get two more contacts on this side"*.

Integration: An important point that was discussed during the study was how such sensors could be integrated with existing electronics, such as phones, laptops, Xbox, and PlayStation devices. One participant commented: *"You could probably hook that up to a phone easier than like a hard keyboard. So, if you're trying to [...] work from your phone, you can have this tiny fabric keyboard that can roll up easily and [...] write emails, because I know I prefer writing emails on a keyboard, not my phone's keyboard"*. Another described a use case with phone apps, which could open up many possibilities: *"An integration that could be possible with phones like [...] PokemonGo, as an accessory piece that you can [...] press buttons on, [...] maybe a bracelet or something that you could attach to your shirt, like cuff links almost, but with this fabric, to work with apps, so that you don't have to pull out your phone to [...] navigate on an app"*. In addition, participants were interested in the integration potential of several knitted fabrics with different touch–sensitive areas, mainly inspired by the Garage Band controller set. Smart environments were mentioned, where such sensors would need to be integrated for an immersive experience.

3.4.5 Concerns and Feasibility. One of the objectives of this study was understanding user concerns when interacting with this technology. The most prevalent ones are described below.

Touch Detection Accuracy: As expected, it became clear from almost every group that in order for users to adopt this technology, it had to work accurately and reliably, similarly to other objects and applications it would emulate. Questions of multi–touch detection were also raised, and suggestions were made to add more contact points, by adding another yarn. In addition, multi–touch functionality was mentioned as desired or expected.

Damage and Safety Concerns: Besides accuracy, safety was a concern in many cases, including the sensors' flammability, their electromagnetic field, and generally the participants' perception of having electronics so closely integrated into clothes. One participant asked: *"Is there like a chance, like any remote possibility of an electric shock?"*, and similar questions were not uncommon. Another participant was concerned about such issues caused due to interaction with water: *"Well, I worry about the wet. I throw it on the grass and my grass has dew on it, [...] and somebody's feet zapped, or their hands zapped. Or is it going to short out the electronics that it's connected?"* Others worried about maintaining the integrity of the electronics and any potential fires, with one participant inquiring about *"melting because the heat on a polyester material"*. Another reason for hesitation was also the potential for the sensor to easily malfunction, while offering no straightforward ways to troubleshoot, with one participant commenting: *"My question would be troubleshooting. [...] So usually [if] my electronics stop working, I can troubleshoot and kind of try and come down to the solution on my own [...] I'm not even sure how you would begin troubleshooting. [...] So kind of just like that idea of if something goes wrong, I don't know how to fix it"*. A few participants were also concerned about any potential waves emitted from the electronics, and their effects on their health, with one participant asking: *"If you are going to use it for clothing, [...] is there any kind of emissions [...] from the wires inside?"*

Everyday Use Reliability: *"What if it gets wet?"* was one of the most frequent questions, and related inquiries included *"spillages like coffee or hot water"*, and exposure to saltwater, sweat, and rain. One participant suggested coating the yarn with water–resistant material. Participants also asked about the sensor's capacity to only respond to intentional human touch. A related concern is that of false positives, with a similar effect to touch, possibly caused by any conductor in contact with the interactive areas of the sensors. They were also interested to know whether these sensors were robust enough to withstand differing conditions such as stretching, and laundering, while retaining their properties: *"Can I throw it in the washing machine and dryer, if it's a blanket? Or can I use industrial cleaner on it? If it's in my car?"*, inquired one participant. Another asked about the limits of their working and their breaking point: *"How about long term reliability? I don't really know that much about like, carbon fiber and its properties, but for instance, if you were to like fatigue test this and fold it many, many times, [...] eventually cause problems"*.

3.5 Summary and Discussion

The results of this formative study indicate considerable interest in furthering this technology, with participants proposing and being interested in a variety of usability scenarios. Participants' general perceptions of touch–sensitive knitted fabric were that this technology is comforting, portable, robust, and affordable. There were discussions regarding its texture, which was also a point of interest, and should be considered during application design.

Many applications were mentioned during the discussions, with the most major areas being: clothing, smart environments, gaming and entertainment, education, and healthcare and assistive technologies. Prior work has investigated applications of smart textiles in some of these areas, such as smart environments [46, 72], healthcare [8, 9, 32, 66], accessibility [12, 35, 64], wearable devices [68, 73], controllers [47], and entertainment [65]. While users in this study were presented with the basic working principles of this technology, they were not experts in the field, which led to them occasionally proposing applications that are not directly possible using this technology in its current state. Examples include medical applications of gathering information about patients' vitals, which was an idea suggested by several users. The functionality of these sensors is touch detection, and that is dependent on the type of yarn and circuit design. However, this tendency of the participants is worth noting for future developments, and for fabric–based sensing that might rely on other technology. Other work in fabric sensors has investigated such functionalities, such as heart monitoring [8], and joint moments [9] among others.

Similarly, many applications about monitoring were mentioned, which could be feasible, however it should be noted that these knitted sensors respond to the proximity of a conductor, which could be human skin, conductive shoes, or gloves. Another notable aspect of discussions regarding applications was that many of them would rely on the functionalities of pressure sensitivity and gesture recognition, among others. Section 4 of this work starts exploring this technology's potential for gesture recognition, since it is fundamental for developing many of the application desired by users. Pressure sensitivity should be investigated in future work, since it also holds considerable promise for enabling applications.

When asked, users noted several points of hesitation when interacting with this technology. As expected, touch detection accuracy was one of them, in addition to multi–touch detection. One user suggested adding more conductive yarn to increase the sensor's accuracy. In order to accomplish that however, circuit design compatible with digital knitting, and its current flow without shorting need to be ensured. Nevertheless, advancements in accurate touch detection and multi–touch are necessary for the proper functioning of the sensors, and previous work has started addressing accurate touch location identification [38, 62] on them. Future work should further those efforts, and should additionally, investigate multi–touch location identification.

Users also raised sensor damage and safety concerns. Presently, the touch sensing hardware operates at both a low voltage and low current and does not emit significant electromagnetic radiation. Cursory experiments involving moisture have shown a potential decrease in touch location accuracy, but no harm when touching the sensors. However further experiments should rigorously investigate those aspects. Additionally, users discussed everyday use robustness, such as the sensors' exposure to water, rain, sweat, or their ability to resist damage from stretching, washing, and drying. These are understandable concerns regarding the real–world scenarios to which such sensors would be exposed, if they were integrated in interactive applications. For comprehensive answers to these questions, specific applications and their needs should be considered as well. The sensors are expected to behave differently due to exposure to water, especially if it contains electrolytes, such as in the case of saltwater, sweat, and rain water. The level of moisture is also expected to impact the sensor's conductivity. Electrolyte solutions are conductive, and they can change the current flow within the circuit, therefore it is important for future work to thoroughly investigating those aspects. Section 5 starts addressing some of everyday use concerns, specifically related to normal laundering and stretching of the sensors.

3.6 Application Design Guidelines

Despite any hesitations or points of discussion, the participants' enthusiasm to interact with this technology and desire to use real–world applications based it, indicates great its potential in enabling interactions. Based on these results, we offer some guidelines regarding building interactive applications with touch–sensitive knitted fabric. Some of these aspects are specific to this technology, however, most of them can be generalized to many other smart fabrics technologies, irrespective of construction methods.

DG 1: Participants cared about the texture of the fabric, including the carbon–coated interactive components, especially when interacting with them to control an application. Some considered it soft, others not soft enough to use, and there were also views of it not being soft, but proper for some applications because of that quality. Therefore, when deciding the patterns of the fabric and related application functionalities, application designers should account for the sensation that the continuous contact with the interactive components generates. This consideration should be in accordance with the target user group. In addition, future research should explore new, softer conductive yarn materials to offer more flexibility in application design.

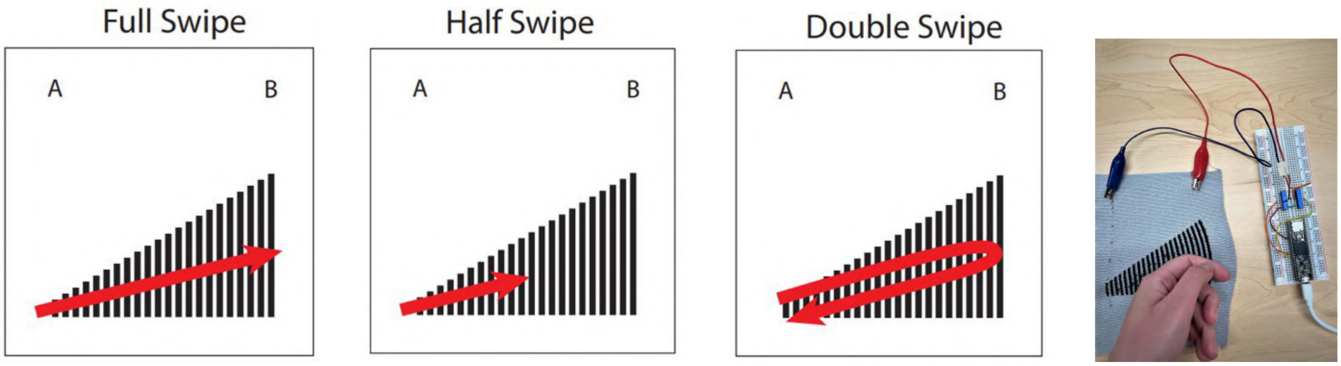
DG 2: Participants perceived touch–sensitive fabrics as compatible with relaxed environments, or capable of generating feelings of approachability and comfort. This psychological aspect should be leveraged when designing applications to add an extra dimension to the user experience. Since fabric is integrated into everyday objects, such sensors could be useful for creating inviting smart environments.

DG 3: The flexibility of the design process allows this technology to be suitable for a large variety of situations and use cases, about which users care. The importance of personal style was noted in this study, and it has already been established in literature [16, 21, 25]. Therefore, users should have a variety of choices, at least regarding colors, sizes, and patterns to match their preferences. Such choices can be easily accommodated through the streamlined manufacturing process that requires little–to–no human intervention.

DG 4: Other related considerations for application designers should be the fabric' size, its thickness, and the balance between flexibility and sturdiness, as they relate to the applications for which the sensor is designed. For example, users would probably prefer to wear fabrics that are flexible and choose sturdier ones for carpets. Similar considerations have also been investigated in prior work [39, 46].

DG 5: These sensors' low profile and unintrusive design could be an important aspect in applications that would benefit from discreet interactions.

DG 6: In addition to novel applications, or applications that replace existing technology, fabric sensors can be developed to be used alongside existing technology, but in different contexts. Examples include fabric musical instruments useful for travelling or practice, and relevant due to qualities such as portability or affordability, but not replacing those instruments.



(a) (b) (c) (d)

Figure 6: Experimental setup including the swipe gesture illustrations which participants were shown, corresponding to the gestures categories. An example of the last category, random contact, is shown in *(d)*, together with the data collecting hardware. Gestures varied for that category, since participants were not shown a particular motion trajectory, as in *(a)*, *(b)*, and *(c)* — some examples were mentioned to them, and they were informed of the types of situations that might generate accidental touch events.

DG 7: Virtual and augmented reality (VR/AR) applications are a direction which should also be explored, since touch–sensing knitted fabric can provide more control over the environment than regular controllers. Such fabrics can be the basis of constructing entire environments, since the shapes of both objects and their interactive components can be flexible, and easily modified. Due to the fabric softness compared to hard electronics, such an implementation could be a safer alternative, since in these settings, especially in VR, users might be less aware of their real environments.

DG 8: Additionally, children and the elderly could be particularly suitable target groups for interactions relying on this technology. The sensors' softness and robustness could offer protection from accidental harm. Previous work, for example, has explored playable surfaces for autistic children [12, 44, 64].

DG 9: These sensors were specifically designed to have the smallest number of connections that could create a circuit, in order to increase their usability and robustness [38, 62, 63]. Further research should investigate the necessary number of connections per design pattern and application type. However, the ability of sensors produced using this technology with minimal wiring and connections, to easily connect to each–other, as well as external hardware, is an important feature which could facilitate their adoption. Future applications should keep easy integration and modularity at the forefront of their design strategies.

DG 10: Since damage and safety concerns were raised from the participants, once all have been properly investigated and addressed, they should also be clearly communicated to the end users. It is important not only for the technology itself to be safe, but also for users to perceive it as such and be able to trust it, in order for them to freely interact with it and integrate it as part of their everyday environments.

4 GESTURE REPRESENTATION

One of the main capabilities that needs to be investigated related to this technology is gesture recognition, which was also mentioned as expected or desired by the users in our formative study above. It is fundamental to enabling the full range of possible application that rely on the touch-sensitive knitted fabrics discussed in this work. In this section, we explore the representation of swipes on the volume controller sensor (Figure 6), designed to be intuitive for such gestures. We include three related swipe gestures, as well as a fourth class of gestures to represent accidental touch events during everyday use. In order to investigate the quality of the generated signal, we compute the similarity between different gesture representations by computing the pairwise distance between all samples, as in [62]. In order for this technology to show promise and feasibility, different samples of the same gesture type should be more similar to each-other than signal samples produced by different gestures. Additionally, the signal response of accidental touch events should be different from that of intentional gestures.

4.1 Experimental Procedure

To investigate if basic gestures can, in future iterations, be distinguished on this sensor, we collected data from 12 users, who were college students.

4.1.1 Study Tasks. Participants were asked to perform four different types of gestures: *full swipes*, *half swipes*, *double swipes*, and *random contact*. Each participant was asked to perform 20 repetitions of each of the first three gesture with a single finger, but with varying speeds (max 4 seconds) and pressure. These gestures are illustrated in Figure 6. For the random contact gesture class, participants were asked to imagine the sensor integrated into clothes or furniture, and perform gestures to depict accidental touch while interacting with them in daily life. In this case, multiple location and finger gestures were collected. Some examples of random contact gestures are multiple taps, brushing across the sensor, or resting

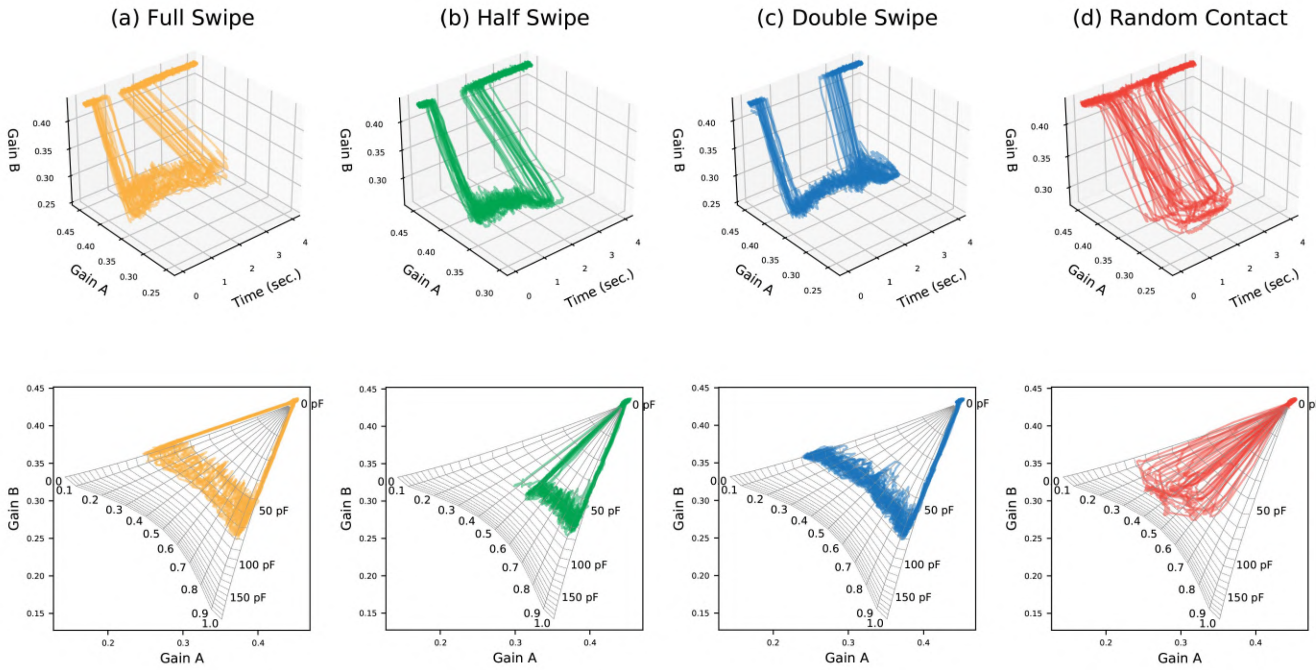


Figure 7: The representation of a swipe gesture using voltage gains from two signals over time. Each plot column contains 20 instances of swiping across the volume controller to perform the same gesture, obtained from one participant. The top row visualizes the A and B voltage gains over a 4 second duration. The bottom row contains a flattened view of the A and B voltage gains throughout the duration of each gesture overlaid on a grid depicting the linear location and capacitance mapping. These plots illustrate three similar but different swipe gestures and random contact gestures: *(a)* a single swipe across the volume controller *(b)* a swipe that stops halfway across the controller, *(c)* and a double swipe, starting by the swipe in (a) and then continuing in the reverse direction of it, *(d)* contact emulating accidental touch events.

one's palm, wrist or elbow on the sensor. A total of 240 samples were collected for each of the 4 classes from all participants.

4.1.2 Embedded Sensing Microprocessor. The sensing hardware and signal processing method are the same as the work in [38]. The hardware uses an NXP Kinetis® MK66 ARM® Cortex®-M4F 180 MHz microprocessor (PJRC Teensy 3.6 development board). Two connections lead the fabric circuit to the sensing hardware, which can connect to a computer via USB and transfer processed data at approximately 4.3 Mbaud, and 125 Hz to a Processing [53] application for data visualization. Bode analysis [10], a system identification approach used to characterize the behavior of an unknown system, given controlled inputs, is used for characterization of the signal.

Two 16-bit analog-to-digital converters (ADCs) synchronized with the DAC sample the output waveform at approximately 256k samples-per-second in 1024-point increments. Fast-Fourier Transforms of the samples were processed using the ARM CMSIS DSP library complex FFT function [31]. Ninety six frequencies between $f_0 = 2,000$ Hz and $f_1 = 26,000$ Hz were input for a duration of $t_0 = 0$ seconds to $t_1 = 0.004$ seconds. The swept-frequency range is chosen based on the locations of frequencies affected by additive distortion. The two significant sources of distortion are *power supply ripple*, contributed by the microprocessor's DC power source, and *electromagnetic interference* (EMI), induced by external power sources in proximity. The waveform uses the full range of the ADC's voltage output, between 0 V and 3.3 VDC, thus the amplitude A, and bias b, are 1.65 V and 1.65 V respectively. To characterize the system response during data analysis, we use the gain values of all recorded frequencies, for a total of 192 values per record window, which is 250 time-steps long.

4.2 Data Analysis

The plots in Figure 7 illustrate gesture signals captured as explained above. The data was collected from one participant performing the four different gesture types for 20 times each, and is meant to provide an intuitive understanding of the trajectory of the signal expressed as two gain values over time. We can see that samples of the same gesture type follow a very similar path, more clearly shown in the top plots. The bottom plots illustrate how different gestures follow distinct trajectories from each-other. Even random contact samples, emulating accidental touch events, seem to be more similar to each-other than to the swipe gestures.

Next, we perform a comprehensive analysis of all the samples in the dataset. In order to measure the similarity relationship of different gesture samples belonging to the gesture type, as compared to samples that belong to different gestures, we compute the distance for every sample pair in the dataset, similarly to [62]. We generate a 4 × 4 matrix, where both rows and columns indicate the type of gesture: *single full swipe, half swipe, double swipe, and random contact.* Each gesture sample is associated with its label, and when two samples are compared to each other, a scalar value that represents their distance is produced. That value is added to the matrix in position (m,n), where m and n denote the label of the first and second samples being compared, respectively. We use the Euclidean Levenenshtein Distance (*ELD*), summarized below, as a distance metric, in order to calculate the similarity between two gesture samples.

4.2.1 *Euclidean Levenshtein Distance.*

ELD is a distance metric which is a modified version of Levenshtein Distance [36] and uses a similar concept to it in that it performs a pairwise comparison of two sequences, in this case consisting of gain values in a gesture sample. Within a gesture sample, the gain values are temporally related and the voltage discharge during touch is a process with a relatively pre-defined trajectory, therefore each gesture sample can be considered a sequence.

$$e_{k_1,k_2}(i,j) = \begin{cases} \max(\|k_{1i}\|_2, \|k_{2j}\|_2) & \text{if } min(i,j) = 0, \\ \min \begin{cases} e_{k_1,k_2}(i-1,j) + \|k_{1i}\|_2 \\ e_{k_1,k_2}(i,j-1) + \|k_{2j}\|_2 \\ e_{k_1,k_2}(i-1,j-1) + \|k_{1i} - k_{2j}\|_2 \end{cases} & \text{otherwise.} \end{cases}$$

Instead of using a binary 0 or 1 cost to denote a match or mismatch, as in the Levenshtein Distance with string characters, the Euclidean distance is computed between two time instances—each belonging to one of the gesture samples in the pairwise comparison. The total cost of converting a gesture sample k_1 up to its time instance values k_{1i} to the other gesture sample k_2 up to its time instance gain values k_{2j} is computed by adding the distance between k_{1i} and k_{2j}, or the vanishing costs of k_{1i} or k_{2j} to the minimum of value of the previous step, according to Section 4.2.1.

At every step of the algorithm, either one of the two time step gain values is kept and the other is discarded, or one is transformed to the other—whichever action has the minimum cost. This process is analogous to deletion, insertion, or character conversion when comparing two strings. In the minimum clause, from k_1 to k_2, the first case corresponds to deletion of the current time-step values (k_{1i}), the second to insertion, and the third to conversion from k_{1i} to k_{2j}. If two gesture samples are compared sample-by-sample, the resulting *ELD* is a measure of similarity between them. A smaller distance indicates higher levels of similarity, since converting one gesture sample into the other would cost less.

4.2.2 *Sample Similarity Results.*

The generated heatmap, illustrated in Figure 8, has a size of 4×4, where each cell in either direction corresponds to a gesture type. Each element of the heatmaps' diagonals is composed of the sum of such distances of different samples of gestures of the same class, while the rest of the elements result from sums of distances of gestures of different classes. It can be noted that the diagonal, which reflects distances of gesture samples of the same type, is composed of lower values compared to distances of samples of different swipe gestures. It can be noticed that there is less similarity among different-type gesture samples and more for samples belonging to the same gesture. Additionally, we compute some statistical measures on the resulting distance matrix to gain more insight into what the data means. We investigate two groups:

(1) The distances between same-type samples, encoded in the heatmap diagonal.
(2) The distances between different-type samples, encoded in the rest of the heatmap.

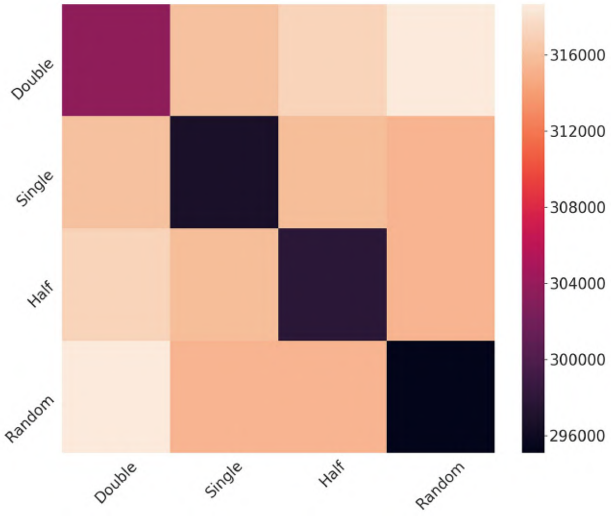


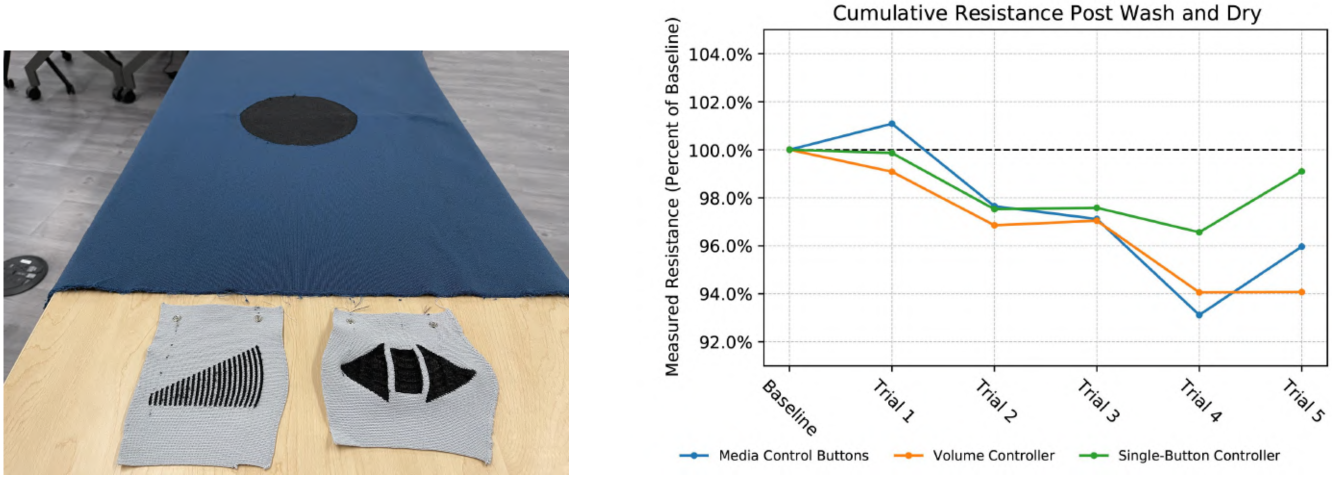
Figure 8: Heatmap indicating gesture distances, computed using the sum of *Euclidean Levenshtein Distance* of all gesture sample pairwise comparisons. Gesture samples of the same type are more similar to each-other than samples from different gesture types.

Table 2: Statistical significance of similarity matrix results. These values suggest that the difference between group *(1)* and group *(2)* comparisons is significant.

$f-stat$	p_f	$z-score$	p_z
231.81	0.00	-15.23	0.00

We record the *f-statistic* and its associated *p-value*, p_f, resulting from a *one-way ANOVA*, as well as the *z-score*, and its associated *p-value*, p_z. These inferential statistical tests measure separability of groups. The lower each *p-value* is, the more significant are the group differences considered. A *p-value* ≤ 0.05 is generally accepted to mean that the difference between the groups in the data is statistically significant. Results in Table 2 show that both p_f and p_z are equal to 0.00, which means that there is an estimated 0% probability of the differences between our two groups having occurred by chance. These values, together with the heatmap in Figure 8, suggest that the gesture representations of the same type are similar to each-other and different from samples produced by gestures of different types.

These results are encouraging since it seems, it is not only possible to distinguish among different types of swipes, which are



(a)

(b)

Figure 9: In *(a)*, we can see the samples that underwent 5 cycles of washing and drying. In *(b)*, the change in resistance values of those sensors across all cycles is shown. The y-axis values are calculated as the rate between the trial and baseline resistance values. These results demonstrate that there is only a slight decrease in the resistance values after undergoing washing and drying.

Table 3: The percent change in resistance $\%\Delta R$ between the baseline b and each test d_n is reported. The resistance is measured between the two yarn endpoints of each sensor. These results show that the resistance values after each washing and drying cycle are within 7% of the baseline.

	$\%\Delta R_{(b,d_1)}$	$\%\Delta R_{(b,d_2)}$	$\%\Delta R_{(b,d_3)}$	$\%\Delta R_{(b,d_4)}$	$\%\Delta R_{(b,d_5)}$
Single-Button Controller	-0.14%	-2.48%	-2.42%	-3.44%	-0.90%
Volume Controller	-0.92%	-3.15%	-2.96%	-5.94%	-5.93%
Media Control Buttons	1.09%	-2.35%	-2.88%	-6.88%	-4.03%

gestures closely related to each-other, but also accidental touch events. From Figure 8, it can be seen that even gestures in the *random touch* class have the potential to be categorized together in future applications. For those gestures, as mentioned, participants were not specifically directed to trace a particular trajectory, but to emulate accidental touches on the sensor. These results hold promise for creating gesture recognizing applications built on the basis of this technology. However, since these sensors would need to operate in the real world, they should be able to resist different types of potential distortion. The section below starts to explore this aspect.

5 ROBUSTNESS TO EVERYDAY USE DISTORTIONS

In addition to creating models for high-accuracy touch location identification, exploring gesture recognition, and users' views regarding these sensors, it is also important to understand how robust they are when exposed to possibly disruptive everyday conditions. Sources of distortion in real-world environments can be many, however, in this section two are explored: sensor laundering and stretching. They were selected as intrinsically tied to the nature of fabric and its functionality. Other work has also performed stretching [66], and washing and drying tests on smart fabrics [37, 66], or highlighted their importance [52].

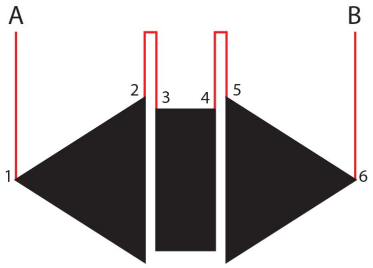


Figure 10: Sketch of the *Media Control Buttons* sensor, annotated with points along which the resistance was measured. The red lines show the unexposed carbon-coated yarn in the textile.

Table 4: The percent change in resistance ($\%\Delta R$) values between the *baseline (b)* and the *last washing and drying ($d5$)* test. These results are reported for measurements across and between visible sensor components.

	$[A, p1]$	$[A, p2]$	$[A, p3]$	$[A, p4]$	$[A, p5]$	$[A, p6]$	$[A, B]$
$\%\Delta R_{(b,d_5)}$	-5.81%	0.20%	-2.31%	-1.66%	-5.75%	-3.29%	-4.03%

5.1 Washing and Drying

Many applications for which these sensors were designed, and many of the ones discussed in the focus group above are wearable, which means that the fabric component of each sensor would need to be washed, for appropriate use in real-world settings. The integrity of the sensors after undergoing normal washing and drying was a concern that participants also mentioned. Below, we conduct several washing and drying tests to study any potential changes in resistance of the knitted sensor, which would affect their properties.

5.1.1 Methods. We tested the three sensors illustrated in 9(a): the *Volume Slider*, the *Single Button Controller*, and the *Media Control Buttons*. These sensors were selected to provide variety regarding their size and the structure of their interactive components. They were washed according to the American Association of Textile Chemists and Colorists (AATCC) Laboratory Procedure 1-2018 Home Laundering: Machine Washing protocol [1]. It specifies a 35–minute wash duration with 1.8 kg of laundry and 66 ± 1 g of detergent, and a standard tumble drying protocol, with a $68 \pm 6°C$ temperature. This protocol was considered appropriate for everyday laundering of clothing.

We completed five cycles of washing and drying using an industrial On-Premise Laundry (OPL) Wascomat WUD718cc washer, a Purex liquid detergent, and a Wascomat D735 dryer. It is worth noting that these sensors had been washed and dried before these experiments, in addition to being steamed, as part of their manufacturing process. Baseline resistance measurements (b) were recorded before the testing began. Following this, measurements were taken after each washing and drying cycle d_n (where $n = 1$ to 5 cycle number), resulting in 6 measurements in total per sensor. For the *Media Control Buttons* sensor, measurements were also taken between components of the sensor, in order to obtain a better understanding of the internal sensor structure integrity. For each test, the percent change in resistance between the baseline measurements and measurements after each washing and drying cycle was calculated as $\%\Delta R_{(b,d_n)} = (R_{d_n} - R_b)/R_b$. In this case, R_{d_n} stands for the resistance value between the endpoints of the sensor after the n^{-th} washing and drying cycle, and R_b for the baseline resistance value between those same endpoints, before any of the washing and drying cycles recorded. For each measurement, 100 samples were collected using a Keysight 34465A digital multi-meter, and their mean is reported as the measurement value.

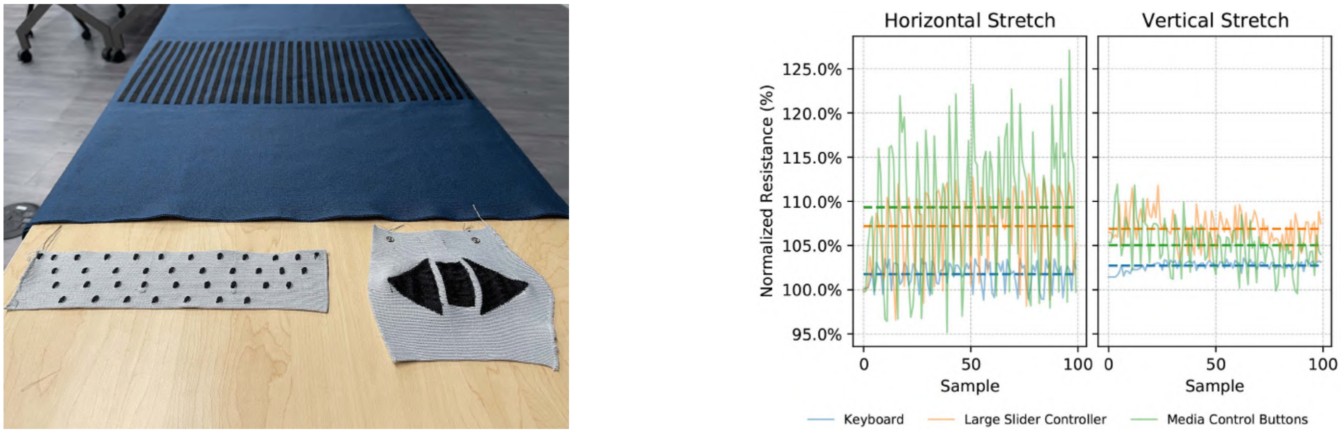
5.1.2 Results. Results from the washing and drying trials of all three sensors are included in 9(b) and Table 3. 9(b) shows how the resistance changes from the baseline after each washing and drying cycle for the three sensors in this test. There is a slight downward trend of the resistance between the first and last trials. Table 3 calculates the percent change in resistance between each trial and the baseline, with changes ranging from approximately 0% to 7%. More extensive tests should be run with such sensors to quantify the amount of change in resistance due to laundering, and subsequently those changes need to be incorporated into the models which enable their fundamental working for later use in interactive systems.

In addition, Figure 10 and Table 4 show the change in resistance between different points in the sensor, calculated between the *baseline, b* test and the last *washing and drying test, $d5$*. The visible interactive components in the *Media Control Buttons* are designed with the conductive yarn knitted closely together, and between the components, there are connections running within the fabric substrate, which are also part of the circuit. Measurements were taken from point A, an endpoint of the carbon-coated yarn, to every point where the conductive yarn enters ($p1, p3, p5$) or exits ($p2, p4, p6$) an interactive component, until reaching the other yarn endpoint B. The reported results show a cumulative effect of the resistance of the hidden and visible conductive components from A to B. The resistance measures indicate more change in the unexposed conductive yarn connections compared to the rest of the components, possibly due to them being more resistive than the rest of the components, since the current path is not as widely spread as the bigger interactive components. Knitting a bigger area with conductive material decreases its resistance, allowing more current to flow through it. Further studies need to investigate these relationships to predict the sensor's and its components' behaviour after several cycles of washing and drying. Nevertheless, the most prominent changes reported here are still within 6% compared to the baseline, which is in line with the results from Table 3.

Together, these results demonstrate that there are slight changes in the resistance values of the sensors, due to washing and drying, but these changes are bounded and predictable, indicating sensor robustness. They should be taken into consideration however, when creating location identification or gesture recognition models, such that interactive applications can be reliably built upon them.

5.2 Sensor Stretching

Stretchability is another inherent property of knitted fabric that affects the electrical connections within a conductive mesh. Continuous capacitive touch localization depends on knowing or measuring the cumulative cross-circuit resistance and knowing or estimating the resistance distribution between discretized touch locations, which may change due to flexing or folding. The purpose of subjecting the fabrics to this stretch test is to record a minimum and maximum value of cross-circuit resistance due to deformation. In this experiment, the fabrics are manually stretched in the vertical V and horizontal H directions while the cumulative pad resistance is measured. The relationship between force and resistance is not quantified as the sensor is not intended to transduce force due to stretch. Rather, the minimum and maximum readings of resistance



(a)

(b)

Figure 11: In *(a)*, we can see the samples that were used for the horizontal and vertical stretch tests. In *(b)*, the change in resistance values of those sensors over the 100 consecutive collected samples is shown. The solid lines show the resistance values over time, while the dotted lines, the average for that sensor's samples. The y-axis values are calculated as the rate between the sample and baseline resistance values.

indicate an expected range for the resistance value at any given time. Additionally, we measure an initial baseline state b while the sensor is not being stretched.

5.2.1 Methods. Similarly to the experiment above, for each measurement, 100 samples are recorded using a Keysight 34465A digital multi-meter and their mean is reported as the measurement value. For this experiment, three sensors were used, shown in 11(a): the *Keyboard*, the *Media Control Buttons*, and the *Slider Controller*. For each test case, one researcher manually stretched the sensor in one direction and allowed it to revert to its natural position. This happened continuously over the 40 seconds during which the 100 samples were being recorded. 11(b) shows the resistance values during the horizontal and vertical stretch test for the three samples, and Table 5 summarizes it, by reporting the maximum and average change in resistance during stretching as compared to the baseline, calculated over the 100 sample points per test.

5.2.2 Results. The changes observed depend on the shape of the sensors and the carbon-coated yarn pattern. From these results, we can see that the changes in the *Slider Controller* were the most consistently low, possibly due to the fabric's large size and thicker, sturdier construction. The two smaller, thinner samples showed more variability, with the maximum change in resistance being the *Keyboard* sensor stretched horizontally, at 27%. While these samples get stretched, the structure of the circuit changes as air gets in between the yarn loops, affecting current flow across the conductive areas, which could explain these results.

The sensing method used to localize touch along the conductive pathway is robust to variations in resistance from between 100 kΩ to 2MΩ, given the sensing hardware signal generation and sampling parameters. The changes in resistance recorded during manual stretching were within the acceptable range supported by the sensing hardware. Changes in the knitted circuit resistance due to stretching affect how touch location is discretized when operating the sensor. Obtaining consistent touch location measurements and improving Signal-to-Noise Ratio (SNR) requires a static resistance when capturing data. In practice, the effects of stretch can be mitigated through increasing the resistance separation between touch points and designing the sensor such that the touch location input range varies greatly for a given action. For instance, a sensor such as the *Slider Controller* measures continuous changes in touch location along the entirety of the circuit and would be more robust to changes in resistance during use. The *Keyboard*, however, may suffer from touch location inaccuracies when stretched due to the relatively small change in resistance between buttons and the requirement of precise touch localization.

Changes in resistance during operation can be mitigated through continuous calibration by measuring the cross-circuit resistance as a part of the calibration and touch localization process. Given an approximate resistance distribution of a sensor, changes in resistance would proportionally scale the resistance distribution by the percentage change. Practically, the effects of stretch on the knitted electrical network may not produce uniform and predictable resistance changes due to the effects of *Poisson's Ratio*: a material property which induces a decrease in horizontal cross-section length due to an increase in length from vertical stretch and vice-versa. The effects within the circuit would not be uniform nor easily predictable and may require more intensive characterization to mitigate. Solutions to this issue may be to create a fabric that resists horizontal and vertical stretch, thus mitigating the effects of resistance change, or creating fabrics with proportionally large changes in resistance between discrete contact points, as in the case of the *Media Control Buttons*.

Future work should explore these aspects more, including more rigorous stretch testing, such as incrementally increasing the amount of force applied and measuring the change in resistance to better understand and characterize this phenomenon. Moreover, for each

Table 5: The percent change in resistance $\%\Delta R$ between the baseline and each of the two stretch tests (*horizontal, H* and *vertical, V*) is reported. 11(a) shows the three sensors used for this experiment. The resistance is measured between the two yarn endpoints of each sensor. The maximum and average changes in resistance are reported.

	$\%\Delta R_{max}(V)$	$\%\Delta R_{avg}(V)$	$\%\Delta R_{max}(H)$	$\%\Delta R_{avg}(H)$
Slider Controller	3.61%	2.73%	3.54%	1.77%
Media Control Buttons	11.81%	6.90%	13.12%	7.21%
Keyboard	11.92%	5.04%	27.09%	9.34%

application designed using any of these sensors, testing related to resistance changes of that particular design due to stretching needs to be performed to determine the resistance range for its different interactive components. Such dynamism needs to be included in the computational models designed to interpret the sensor behavior.

6 LIMITATIONS AND FUTURE WORK

6.1 Formative Study

The qualitative study conducted in this work provides user perspectives regarding the many ways touch–sensitive fabrics in general, and the minimalistic scalable knitted fabrics that rely on one conductive yarn and two external connections in particular, can be integrated into everyday environments. However, this was a formative study which focused on general ideas instead of a usability study of any particular use case, which could provide a more comprehensive view of its feasibility or adoptability.

The formative study was structured as focus groups, which has many benefits in terms of exploring ideas from several different perspectives, with opinions and perceptions building on those of other participants. However, in such a setting, the speaking time of each participant is relatively low, compared to one–on–one interviews, and in many cases time allocation among participants is disproportionate, since it largely depends on participants taking the initiative to share their ideas. Additionally, individual participant's ideas are typically not explored as in depth or detail as in interviews, due to the faster pace of the process. The setting is also more public, which might have prevented users from expressing and developing use cases that are more personal.

Another limitation of this study is the fact that the 32 participants were graduate or undergraduate students recruited from one university, a relatively narrow segment of the population. For a more complete investigation, participants of different ages, cultures, and backgrounds should be included in such studies. Our participants also mentioned use cases and applications related to accessibility, however, in order to properly study each of those use cases, participants and researchers that are part of those specific communities should be involved in the process.

6.2 Building Interactive Systems

Our gesture representation study showed promising results regarding the sensor's ability to differentiate between different gestures and accidental touch events using a similarity metric. However, for interactive applications to rely on these sensors, they need to have gesture recognition functionalities. Future studies should include more users, to increase variability, and more gesture types, including more complex ones. In addition, experiments should be run while the sensor is being worn, and accidental touch events should be recorded as they happen in a less controlled environment than the lab.

Another area of interest could be exploring the recognition of gestures in 3D space, taking full advantage of the fabric form, capable of stretching, flexing, and folding. Additionally, as mentioned in the user study as well, multi–touch capabilities are necessary for this technology to reach its full potential. Pressure sensitivity is another area that needs to be properly investigated, as it can be useful in several applications, also mentioned in our formative study.

6.3 Experiments for Everyday Use

Our sensor laundering and stretching tests start to address some practical questions regarding the sensors' resistance to potential daily use distortions. However, there are many more factors that need to be explored, such as the sensor exposure to heat sources, or different weather conditions. In addition, the sensors' resistance should be measured while they are wet, while controlling for the level of moisture in the knitted component. We expect the resistance to change according to the amount of water in the sensor, and future work should investigate this aspect more rigorously. Along those lines, the sensors' resistance should be investigated while wet with electrolyte solutions. Their conductive properties are expected to interfere with the current flow within the fabric circuit, causing the output signal to be different from expected. This use case is especially important for wearable applications since sweat contains electrolytes. Future work should investigate these aspects further and consider their results when creating models and systems based on this technology.

7 CONCLUSION

This work focused on exploring user perceptions of touch–sensitive knitted fabrics in general, and digitally knitted capacitive touch sensors constructed using one conductive yarn and two external connections in particular. By conducting a formative study and performing thematic analysis on the collected data, we summarized users' sentiments, discussed potential applications and their feasibility, investigated the relationship between choices in design patterns, system construction, and expected sensor functionality, and explored user concerns and suggestions. Many of these insights, although elicited as a results of users interacting with sensors produced using this technology, can be extended to fabric touch sensors in general, and several others, to the broader category of smart fabrics. Our results indicate that there is considerable potential for this sensing strategy to enable interactive applications and be seamlessly integrated into users' lives. To those ends, we offer guidelines to future interaction designers who aim to use knitted sensors as an input modality for a variety of applications. Furthermore, we start addressing some salient user concerns related to the sensors' performance in the real world by conducting another user study and two experiments.

First, we investigated the ability of the *Volume Controller* sensor to represent simple swipe gestures with high fidelity. This experiment's results demonstrate that it is possible to differentiate between different gestures, as well as emulated accidental touch events, which are common in daily life, indicating potential in building gesture recognition systems on these sensors. We also conducted two more experiments measuring the sensors' resistance values: a washing and drying test, and a stretching test. The sensor resistance value is related to its circuit design and affects the data that can be output from the sensor. A stable resistance value is an important factor for building a reliable sensing system. Results from both experiments indicate relative robustness in the resistance measurements, however there are differences that emerge as a result of the design pattern and sensor construction. These differences need to be considered and included when creating computational models for accurate touch location and gesture identification, such that these sensors can reliably function in the real world.

Several aspects of this technology need to be explored and developed, including accurate multi–touch and gesture recognition on any sensor design pattern, which is a considerable undertaking. More experiments need to be conducted while these sensors are being used as intended by different applications in the real world. Further qualitative user studies need to address more focused aspects of the design, integration, and their usability potential. Nevertheless, through our user studies and experiments, we have moved closer to having knitted smart sensors ubiquitously integrated into everyday environments, similarly to regular fabric.

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