GesFabri: Exploring Affordances and Experience of Textile Interfaces for Gesture-based Interaction

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Textile interfaces are of interest to ubiquitous computing as they are easy to carry and manipulate. However, interesting questions remain about what type of natural gestures people make when interacting with textile interfaces and their emotional response to this interaction. We introduce *GesFabri*, a set of five interactive textile interfaces with distinct textures created to investigate the intuitive interaction gestures and their accompanied emotional experience. This research sought to design textile interfaces with intuitive gesture affordance and explore the emotional effects of the developed gesture-based interfaces under four feedback modes (haptic, visual, audio, and combination of visual and audio). The experimental results verify our hypotheses that (1) textile texture could provide natural gesture affordances; (2) the *GesFabri* interfaces' feedback mode was the main factor in the differences in emotional valence, arousal, galvanic skin response; and (3) both gesture-based interaction on textiles and the feedback mode had an impact on user emotions. These results highlight the gesture affordances of the e-textile interfaces and contribute to a better understanding of the user experience when interacting with gesture-based textile interfaces.

CCS Concepts: • **Human-centered computing → Empirical studies in interaction design**.

Additional Key Words and Phrases: Interactive textiles, E-textiles, Texture, Emotion, Affordance, Gesture interface

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1 INTRODUCTION

Gesture-based interaction enables people to use gestures particularly enacted from their hands as the primary input [6][62]. A human-device system with a gesture-based interface enables two-way communication through touch [69]. Its naturalness has made gesture-based interaction one of the most dominant input modalities [52]. From birth, people are often exposed to different ways of touching and surfaces of objects they are touching [70]. Research has shown that touch triggers

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a range of chemical responses that change epinephrine levels, serotonin, and dopamine released by the brain based on the objects' surfaces [19]. In addition, different touch gestures can produce diverse affective experiences [34][70]. There is an apparent link between emotion and gestural interaction; for example, people's typing patterns are different when they are calm or angry [65]. In reverse, gestures have the potential to facilitate affections [65][27]. This connection has led researchers to explore how affective attributes could be implemented in everyday objects such as textiles [1][16].

Touch-based haptics interfaces have become ubiquitous as computing technology has advanced. Touch-screen devices have made gestures like tapping, flicking, and dragging very common. Unlike other objects we touch daily, the surface of these devices is often smooth and flat, making affective haptics communication difficult [16]. With the increasing understanding of the affective properties of touch on interactive devices, the relationship between emotions and surface properties has been found to be significant. For example, Essick et al. [18] revealed that fabric materials that are soft or smooth were reported more pleasant than those that were stiff, rough, or coarse. In this case, a textile-based interface, with its inherent flexibility and comfort [21], can be more advantageous in connecting touch gestures and emotions and be manifested as tangible objects and wearable artefacts.

The term *affordance* was coined by Gibson [22], later developed further in human-computer interaction domain [51]. *Affordance* is described as a design aspect that offers or provides visual cues to the user on using a physical artifact [23][51][68]. Typically, humans learn how to handle a physical object in the physical world through its visual depiction and form factor [33], including textiles. These learning experiences from everyday life are utilised in tangible interfaces. With the availability of a wide range of textile-sensing technologies, conductive materials have been sewn, woven, or knitted into smart textiles, clothing, or textile-based interfaces (e.g. [54]) to detect physical movements (e.g., [48] [24]). While smart textiles are not new, our understanding of how people interact with them is still growing. As addressed by Mlakar et al. [46], textile interfaces should inform or remind users regarding the supported gestures, which can be utilised as an input to trigger the desired output. However, there is a lack of information available for exploring perceptible *affordances* for smart textile interfaces. Two critical aspects that remain unknown are (1) can the gesture affordance of textile texture will lead to intuitive interactive gestures? (2) what will be the user's emotional experience when interacting with intuitive gesture-based textile interfaces [24].

This research attempts to fill these two gaps with the design of interactive textile, *GesFabri* interfaces. Texture affordances will improve the intuitiveness of gestural interaction, thus favours higher user acceptance [9]. User affections might be triggered automatically after being induced to perform certain gestures with textile interfaces and becoming familiar with the associated experiences [75]. However, no investigation has been conducted on users' emotional response to gesture-based interaction with textile textures.

In this paper, we introduce *GesFabri*, a textile texture-based interface, which can provide gestural-based interactions with additional different sensory feedback to provide emotional support in real-time. Our *GesFabri* utilises five different textile textures with two motivations, subsequently resulting in two hypotheses:

- To validate whether textile interfaces can provide gesture affordances by systematically investigating textile textures to elicit more natural and intuitive gestures to improve the usability of textile interfaces.
- To investigate the user's emotional responses after interacting with the textile interfaces by examining two important factors: intuitive gestural-based interactions and feedback modes.

Thus, we hypothesised that **H1: the textile texture could provide natural gesture affordances**, and **H2: intuitive gesture-based e-textile interfaces would result in various emotional effects**.

For the definition of *intuitive interaction*, Bastick [4] described *intuition* as a cognitive process that uses information previously perceived by the senses, which aids in finishing tasks quickly and improving usability [7]. *Intuitive interfaces* are associated with "feeling easy" or "natural" in their use, which can be used without the user having to go through a lengthy and effortful learning process [45]. While *intuitive gestures* are those which employ users' previous experiential knowledge and are perceived as "easy" by users [39], like buttons are for gentle pressing, and ropes are for pulling [59]. Therefore, *intuitive interaction* can be summarized as when a user can immediately and non-consciously use an interface [12], it utilizes stored subconscious knowledge, like physical affordance (sensorimotor) and even population stereotypes (culture) [6]. Blackler et al. [6] further summarized approaches for applying *intuitive interaction*: image schemata; applying feedback; assessing and applying affordances. We refer *intuitive gestures* as indicators for designing natural gestural e-textile interfaces.

The research presented in this paper involved four phases. First, we investigated the textile textures and their potential gesture affordances and produced textiles pieces with five different textures. Second, we elicited user-preferred intuitive gestures for the proposed textile textures and derived four distinctive gestures with higher consensus. Third, we implemented sensing and feedback mechanisms for the five textile textures, resulting in *GesFabri* interface. Finally, we evaluated the *GesFabri* interfaces for gesture-based emotional support with a dedicated user study. This study constituted quantitative data (from emotion Valence, Arousal, Stress-Relaxation level, Heart Rate Variability (HRV), Galvanic Skin Response (GSR)) and qualitative data (from semi-structured interviews) to assess user experience and feedback interacting with *GesFabri* interfaces.

The contributions of our study are as follows: (1) we present a systematic investigation to explore textile textures and their gesture affordances and understand users' preferences for intuitive gestures. Our practical results consist of inverted material-driven design method; (2) we introduce a layer-based fabrication technique which replaces the standard yarns and fabric with conductive yarns and fabrics to achieve four different sensing mechanisms; (3) we evaluate *GesFabri* interfaces in terms of how textile textures and their supported gesture affordances support self-emotion regulation; and (4) we derive design guidelines and provide two example applications of the *GesFabri* interfaces for emotion regulation and connection.

2 RELATED WORK

This section gives a review of gestural-based interactive textiles designed for emotional interaction. From which, we identified the research gaps in (1) intuitive gestures design for textile texture affordances, (2) exploring the emotional effect of intuitive gestural textile interfaces and (3) sensory feedback modes.

2.1 E-textile Interfaces for Gestural Interaction

Electronic textiles (e-textile) are produced by embedding electronic and digital components with regular everyday fabrics, textiles, and clothes [60]. These resulted in a range of fabric-based sensors, actuators and interfaces, which can detect physical movement through the way the fabrics stretch or react to touch when people hold, squeeze or press against fabric layers [24].

E-textile interfaces manifested as tangible objects or wearable items that enable computational sensing devices to be embedded seamlessly into our everyday clothes. These type of interfaces opens up opportunities for new forms of gestural input for busy hands; for instance, subtle and rapid micro gestures [58], which could potentially be used for affective communication [16]. For example, traditional textile materials like embroidery, beads, ribbon, and sequins were embedded with the sensors and electronics, resulting in a series of novel textile interfaces for gesture-based recognition, perception, and interaction [76][25][47].

RESi [54] is based on resistive yarn and could be used in textile manufacturing processes; shown to be usable for light control with tap or swipe gestures and for controlling music with swipe gestures. Besides, these resistive yarn woven into any textiles can distinguish actions such as corned bend, tap, open and slide grip with the help of machine learning techniques. *FabricKeyboard* [72] is a deformable keyboard interface based on a multimodal textile sensate surface. Its multilayer textile sensors could detect touch, proximity, electric field, pressure and stretch in a keyboard pattern. It enables unique tactile experiences through interaction gestures such as pressing, pulling, stretching and twisting the keys or the fabric. Other cases include the *Skweezee System* [66], designed for squeeze-based interactions, such as bend, push, punch and stretch. *zPatch* [63] uses a single sensor or a cluster of sensors that can detect hand hovers, touches, and pressure on the clothes. *zPatches* capable of recognizing variations of hand gestures, including gentle tap, firm tap, push, and swipe. *Pinstripe* [38] is produced using fields of parallel conductive lines sewn inside of a regular everyday T-shirt sleeve to detect continuous inputs using pinch and roll gestures. Whereas the *Grabrics* [29] allows manipulation by grabbing a fold and moving it between the users' fingers.

The above e-textile systems, while well-designed, followed a bottom-up approach, first taking functions and then finding matching gestures for interaction. They have mainly focused on the underlying technology and the robustness and accuracy of gesture recognition. However, the relationship between the types of gestures and the affordance of the surfaces of e-textile received limited attention. For example, the *Skweezee System*, despite the high gesture recognition rate, participants found it was hard to come up with meaningful gestures by themselves that can be easy to remember and reproduce [66]. Similarly, *Pinstripe*'s pre-set behaviour did not match up to the user expectations, particularly for the 'move forward' commands in a menu navigation application [38].

Users need to learn where, when and how to apply a "gesture" to interact with gesture-based systems. Many studies investigated how to design intuitive and easy-to-remember gestures [75]. Well-designed *physical affordances* support high usability and engender greater satisfaction when interacting with products [31]. However, what is often ignored is that the e-textiles' inherent texture also has the potential to provide nature gesture affordance [29].

FabriClick [26] is a fabric-based push-button designed for wearable e-textiles. It utilizes the workflow of digital embroidery and 3D printing to achieve gestural input. *FabriClick* design isolated embroidered buttons to afford push-button gestures and used an extensive array of button structures to afford squeeze and rubbing gestures. Wrinkles on clothes are also embedded with sensing ability in an e-textile system, which is aimed at giving the affordance of being touched and pinched [64].

These gestures (i.e., push, pinch, squeeze, rub) informed our exploration concerning the likely gesture affordances from textures of e-textile interfaces. Prior works such as *RESi* [54] and *zPatch* [63] can be understood as technology-driven design as their potential interaction gestures have come from achieving the functionality of their e-textile interface. In this research, we focus on a material-driven design method for natural gesture-based interfaces. The intuitive interaction gestures of our proposed *GesFabri* prototypes achieved using textile texture affordance and materiality, followed by their implementation in the next stage. The primary question driving our research is to investigate what are the users' intuitive gestures facing different textile textures interfaces.

2.2 Users' Affective Response to Gesture-based Interaction

The emotional effects of touch have been addressed in the literature. The earliest work from the well-known Rhesus monkey experiment strived to understand the impact of "Mother's touch" [30].

Affective touch refers to psychological reactions to haptic stimuli [16]. Affective haptics studies developed into three subdomains: affective computing, haptic interfaces, and user experience [55][71]. Haptic interfaces provide bidirectional communication involving touch [16] and support users to interact with the devices with different types of touch-based gestures, e.g., pat, press, drag [32].

Touch-based therapies have been developed for emotional well-being. For instance, *Touch Me*, *Squeeze Me*, *Hurt Me*, *Cool Me Down* are four haptic textile interfaces that medical professionals created for clinical evaluation [67]. *TapTap*, also a textile device for haptic therapy, can record and replay certain kinds of touch (tap, press, stroke, contact) and is controlled by the wearer [8]. Besides, many therapeutic robots have been designed with various textile interfaces to create affective touch, like *Huggable*, *PARO*, *Aibo*, and *Probo* [20].

With gesture-based interaction applied in various domains, like education, gaming, retailing, and healthcare [10], it is believed that different gestures might lead to different types of cognitive and emotional responses [5]. Yang [75] concludes that our body actions can influence our mind via two mechanisms: eliciting mental imagery and activating abstract concepts associated with bodily feelings and actions.

Prior research has explored the difference in their affective reactions that can occur during gesture-based interaction. Research on violent video games indicates that users in the embodied gesture (striking) condition tended to show more anger than the standard interaction (clicking) condition [44]. Similarly, research from psychology [28] has revealed that inducing consumers to hug a product increased their emotional attachment compared to solely touching the product. Liu's research on physical interaction [75] shows that inducing people to press on a mobile device elicited a sense of determination and enhanced self-regulation compared to tapping.

Overall, these physical interaction gestures with interfaces or devices are thought to potentially trigger associated feelings, modulate human feelings, and even elicit positive behaviour change. Similarly, intuitive gestures that are elicited from the textures of textile interfaces could activate certain specific reactions. Our work also looked into if this is the case and what these emotions are when users engage with textile interfaces that allow for intuitive gestures.

2.3 Feedback Modes in E-textile Interfaces

Feedback can provide users with a sense of control and adjust their gestures more accurately [75]. Numerous types of feedback have widely been adopted in the design of e-textile interfaces. For instance, static patterns, dynamic patterns, and shape changes have been designed and used as visual clues in gesture guidance for adjusting the music volume in the textile interface [15]. Davis et al. investigated how emotions could be mapped to the environment through textiles. They designed *Textile Mirror*, a wall panel that aims to influence a person's affection through its shape-changing feedback interface [14]. They also compared users' feelings by interacting with static and dynamic textile interfaces, look and touch textile interfaces [13], and found participants' subjective feelings vary among textile interfaces and interaction modes.

The most recently introduced smart shirt, *E-motionWear*, regulates emotion by motivating users to perform body motions, like open and closed arms, shoulder flexion, or extension [37][36]. It integrated three different movement-based feedback modes: visual, audio, and vibrotactile. This study concluded that audio and vibrotactile feedback is more efficient in promoting joy expression and emotional engagement during body movement.

It should be noted that feedback modes, either uni- or multi-sensorial, can guide gestures performance, bias user perception, and activate affection [3]. As such, how feedback is delivered should be considered further to understand the gesture-based interaction of the textile interfaces. Therefore, after identifying intuitive gestures for textile interfaces, we enabled textiles with gesture sensing and multi-feedback abilities to probe if there is an interaction effect between gesture-based interface interaction and feedback mode on user experience.

2.4 Summary

Textile-based hand gestural input has a lot of potential for human-machine input systems (e.g., [54][63]), particularly for human emotion regulation (e.g., [35]). Prior works have focused almost solely on the sensing technology for accurate gesture recognition and neglected systematic investigation of how perceptible affordance of textile textures can be effectively used to design intuitive gestures for emotion regulation (e.g., [46]). Thus, a thorough investigation of gesture affordance of textile texture will unquestionably lead to understanding users' emotional experiences when interacting with intuitive gesture-based textile interfaces.

3 GESFABRI DESIGN

The key idea of developing *GesFabri* interfaces is to explore the gesture affordances that textiles' texture provides for gesture-based interactions. To this end, we developed five interactive textile prototypes, each with distinctive textures that could be perceived as unique affordances. These textiles could provide inherent shape change and augmented multi-sensory feedback in response to users' hand gestures and actions. Notably, we envision that our textile prototypes could bring diverse emotional responses to users through interacting with each textile interface. Our intent was twofold: (1) to observe the users' intuitive hand gestures when provided with each of the five textiles interfaces, and (2) to have the users express their emotions so that we can measure any changes when interacting with the interactive textiles using different gestures and under different feedback modes.

Before building these textile prototypes, we first had to: (1) select and prototype textile textures with potential gesture affordances, (2) determine what intuitive gestures these textile textures elicited with a preliminary experiment, (3) design the electronic circuitry that would be embedded in the textile interfaces for gesture sensing, and (4) build feedback mode(s) inside the e-textile interfaces.

3.1 Textile Texture Selection and Prototyping

The texture is an essential aspect of textiles, including the visual surface appearance and the tactile feeling of fabrics when touched or squeezed. The fibre determines the texture of a fabric, yarn, fabrication structure (i.e., weaved or knitted), and finishing [40]. The texture is predominantly used for aesthetics or structural integrity. In this work, we use it to investigate its perceivable affordances for gestures as part of e-textile interfaces. We follow Blackler et al.'s [6] assertion that intuitive interaction typically comes from image schemata. Thus, our study focuses on the texture design from the textile's structure as textile fibre and yarn do not generate distinctive textures.

To select a representative texture from vast textiles, we researched the well-known textbook *The Art of Manipulating Fabric* [73] which presents detailed descriptions of a diverse variety of three-dimensional textile surface design techniques inspired by visual clues. The textures are categorized based on their structure and the supported manipulation techniques, like shirring, gathering, ruffle, flounce, godet, pleating, smocking, tucking, cording, quilting, stuffing, and darts (see Figure 1). Among them, (1) the shirring and gathering textures are two kinds of controlled crushing textures, that achieve specific structural characteristics by shrinking fabric, (2) while the ruffle, flounce, godet are supplementary textures, function as decoration, (3) the smocking, tucking, and pleating are systemic folding textures, which manipulate fabrics with folding techniques, (4) the cording, stuffing, and quilting are filled relief texture, they enable the fabric with the effect of relief, (5) using darts is a widely-used structured surface technique in clothes-making.

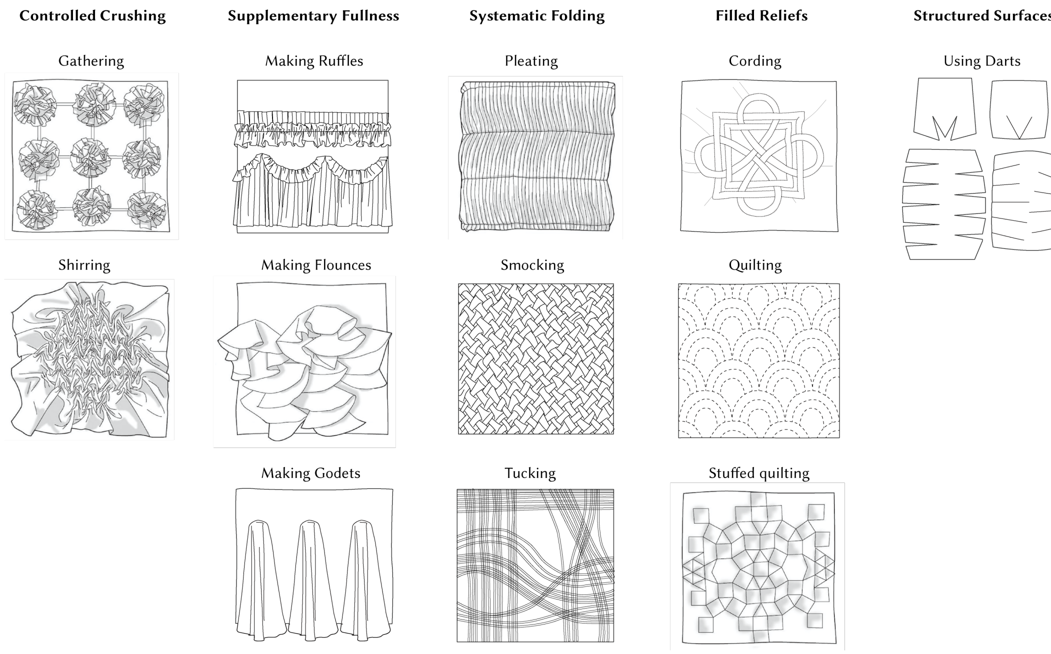

Fig. 1. The illustrative sketches summarize the five categories of textile textures and representative manipulation techniques.

We applied the following selection criteria from the above textures to identify the five representative textures: When touched, it changes shape instinctively to facilitate hand gesture engagement. First, we excluded smoking, tucking, cording, quilting and using darts textures, as their interfaces are relative static when touched. Then, we dropped the ruffle texture because its surface elements are too small to handle, and the godet texture is more widely used in clothes pattern-making than textile pieces. Last, five textures were chosen: (A) gathering texture, (B) stuffed quilting texture, (C) shirring texture, (D) flounce texture, and (E) pleating texture. All of these textures allow gesture sensing electronics to be deployed beneath their shape-changing portions.

For the material, we are looking for an elastic fabric that is easy to cut and manipulate. Furthermore, we wanted to remove the impact of fabric colour and material [18], so we used a creamy-white stretch scuba knitted fabric with a 1.3mm thickness as the main surface material. It has good elasticity and provides excellent support for hand gestural interaction. Also, its stable structure prevents the fabric from falling apart after cutting them into pieces. We believe these five textiles are suitable candidates for the design of the gestural textile interfaces.

3.2 Preliminary Study: Identifying Intuitive Gestures from Textile Textures

We conducted a user study to observe intuitive hand gestures afforded by the five different textile textures to verify our Hypothesis 1. We adopted and followed the bottom-up method recommended in the previous work [61], taking functions (commands), then finding matching gestures. We use the perceived affordance of each textile texture as commands/referents to elicit intuitive gestures, similar to buttons and ropes elicit pressing pulling gestures, respectively[59], then identify the gestures with higher consensus. We recruited 20 student volunteers (16 female, average age = 20.8, SD = 3.31) with different educational backgrounds, including Industrial Design, Computer

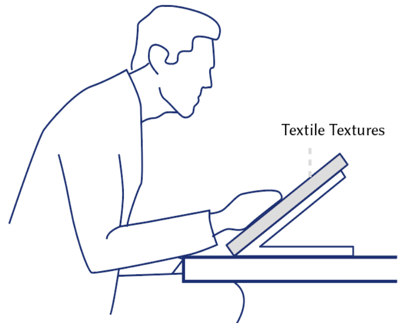

Fig. 2. Illustration of the preliminary experiment apparatus (side view).

Science, Business, and Biology, from the local university via the social media platform. Only four participants have had prior experience with interactive textiles. Participants were seated in front of a table facing the textile textures fixed on the wood board, tilted to a 40° angle on the table to interact comfortably (see Figure 2). We asked each participant to produce at least one but different interaction proposal for each textile design. To reduce the learning effects, we counterbalanced the order of texture designs using a Latin square design. They were encouraged to interact with each textile design using any hand gestures they thought appropriate, either single or dual hands. The whole process was video-recorded for further analysis. We labelled the gestures using the Code Gesture Entry method [61]; participants physically generated the gesture and then entered gesture configuration information to have accurate gesture labelling.

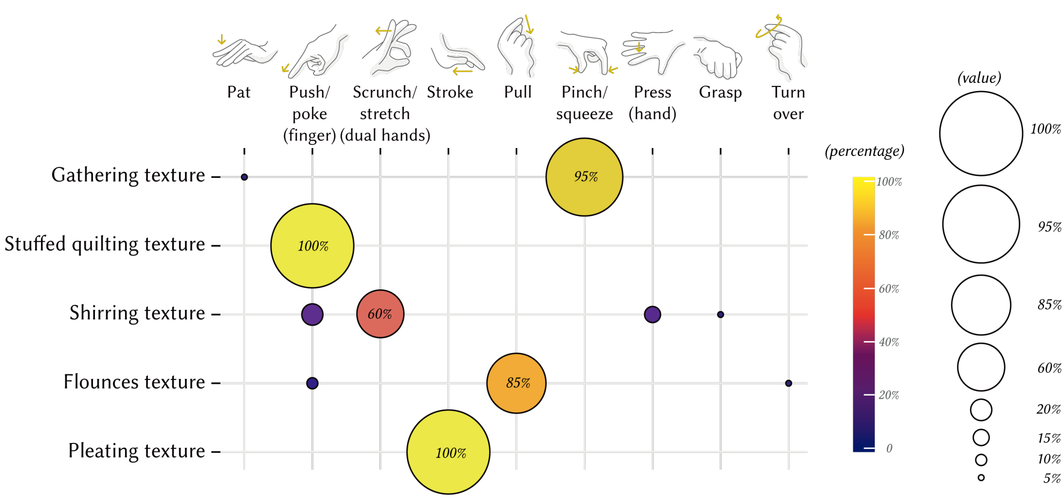

Fig. 3. Frequency distribution of user-preferred intuitive gestures (in percentages) for each of the five textile textures.

We collected a total of nine hand gestures from our 20 participants for the given five texture designs. Figure 3 presents the frequency of user-preferred gestures for each design. Of the nine gestures, stroke and push/poke gestures were unanimously preferred for pleating texture and stuffed quilting texture, respectively. For the push/poke gesture, our users preferred to use the index finger.

Pinch gesture (95%) was highly preferred for gathering texture. 85% of our participants felt the pull gesture is more suitable for the flounce texture than the push (10%) and turn over (5%) gestures. Participants preferred four different gestures for the shirring texture, including scrunch/stretch (60%), push, poke and grasp. They only used two hands to perform the scrunch/stretch gesture (see Figure 4c).

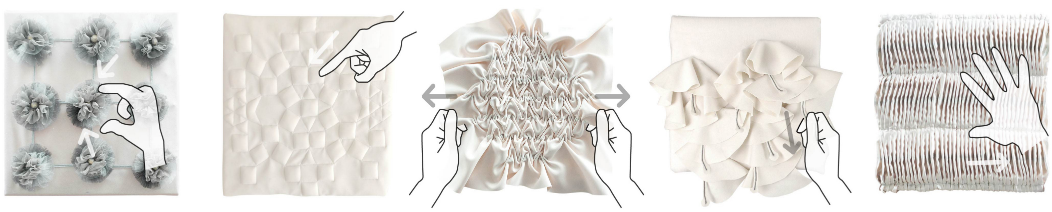

Fig. 4. The most frequent gestures that participants performed with the five textiles are: (a) Pinch/squeeze gesture with gathering texture; (b) Poke gesture with stuffed quilting texture; (c) Scrunch/stretch gesture with shirring texture; (d) Pull gesture with flounce texture and (e) Stroke gesture with pleating texture.

To improve the intuitiveness of the pull gesture for the flounce texture, we added the sting-shape textile for flounces textile to pull, as [59] said, ropes have physical affordance for pulling. Participants also reconfirmed the iterated flounce textile to show more intuitive pull gesture affordance (see Figure 4d).

Based on the user preferences, we identified and assigned the gesture which achieved the highest consensus for each textile interface to explore users' affection and emotional responses when enacting each gesture with these textiles, Figure 4 illustrates the assigned gestures for each textile design.

3.3 Gesture Sensing Mechanisms

As mentioned earlier, we use stretch scuba knitting fabric as the base layer to develop all our five e-textile interfaces. We achieved the sensing abilities on each design by replacing the standard yarns and fabric with conductive yarns and fabrics. Of course, these conductive textile materials did not change the natural characteristics of the textiles. Nevertheless, their structure made them sensitive to touch gestures. The change of the resistance values serves as potential touch input indicators. Figure 5 illustrates the detailed implementation of the interfaces in terms of their textile texture and structure.

- **A** - Pinch/squeeze gesture for gathering texture: The gathering textile interface is made by shrinking 5cm wide net fabric strips. We use a combination of conductive (silver fibre) net fabric and non-conductive net fabric in a sandwich structure to form a rheostat (see Figure 5a). Its resistance and subsequent current produce the corresponding changes when the user pinches or squeezes the gathering texture interface.
- **B** - Poke gesture for stuffed quilting texture: We adopted the quilting manipulation process to implement this textile interface. We stitch the straight lines using a sewing machine in a grid structure, leaving precise spaces for stuffing the cotton. We then embed a layer of Velostat[1] and a pressure-sensitive material under the base layer (made of scuba knitting fabric) for measuring the pressure values by the poking gesture (see Figure 5b).

[1]https://www.adafruit.com/product/1361

- **C** - Scrunch/stretch gesture for shirring texture: With elastic thread in the bobbin and the scuba knitting fabric stretched taut in a hoop, we stitch the fabric in a meandering pattern and produce stretchy shirring with a crinkly texture. In addition, we use a silver fiber conductive fabric[2] layer under the surface layer (see Figure 5c). When the user stretches this interface, its structure spreads apart, and the resistance changes.
- **D** - Pull gesture for flounce texture: We cut a piece of scuba knitting fabric into 5cm wide spiral-cut flounces and sew them into the swinging-shaped exterior (see Figure 5d). Then, we cut the scuba knitting fabric into strips (0.75*9cm) with a round end and machine-stitch 0.4cm wide zigzag and trace them with stainless conductive thread[3]. Since the scuba knitting fabric is stretchable, when the zigzag-stitched strips are pulled, the conductive thread's contact density decreases, leading to higher resistance.
- **E** - Stroke gesture for pleating texture: We vertically arrange pleats (folds), and the press stitching on the pleats change the pleats' undulated direction (see Figure 5e). We place a silver fibre conductive fabric layer under the pleated surface layer, like the shirring texture method. The structure of the interface deforms when the user strokes it. Thus, the contact area of conductive fabric increases, and its resistance decreases.

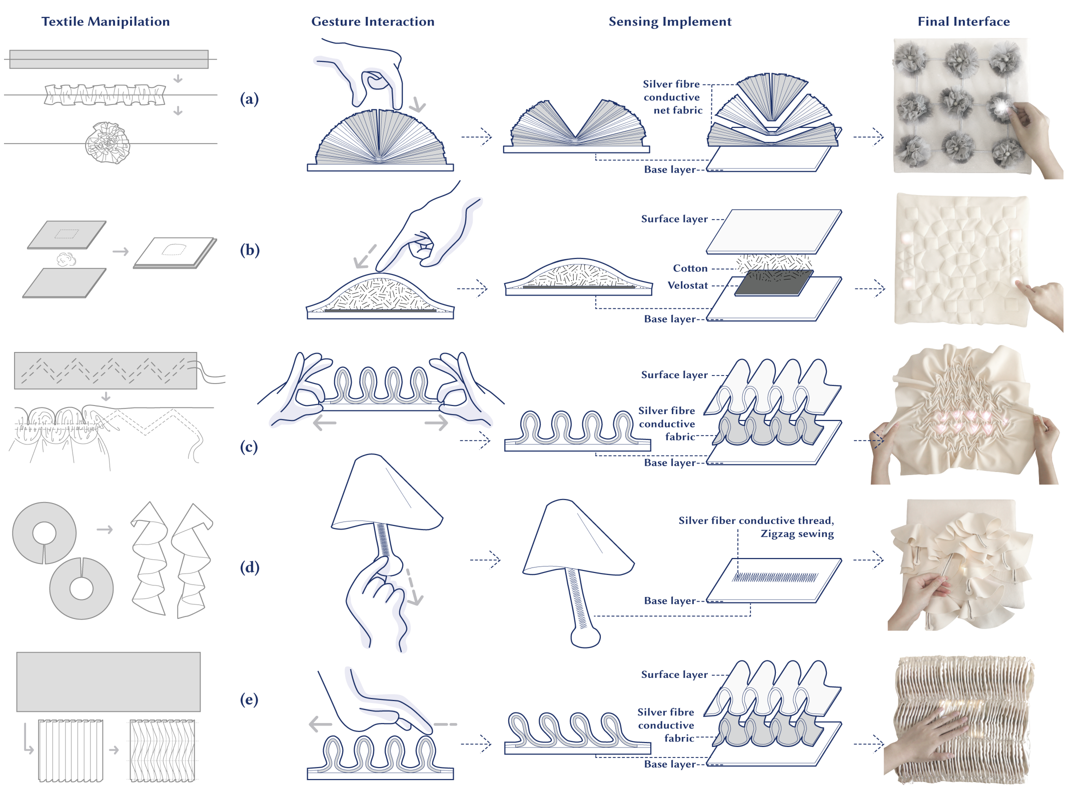

Fig. 5. Illustrations of the structure of the *GesFabri* interfaces: (a) Pinch/squeeze gesture with gathering texture; (b) Poke gesture with stuffed quilting texture; (c) Scrunch/stretch gesture with shirring texture; (d) Pull gesture with flounce texture and (e) Stroke gesture with pleating texture.

[2]https://www.adafruit.com/product/1167
[3]https://www.adafruit.com/product/640

3.4 Feedback Modes

We implemented the following four types of easily perceived, naturally available and augmented feedback modes for *GesFabri* interfaces: (1) haptic, (2) visual, (3) audio, and (4) multi-sensory (combination of visual and audio). In which the haptic mode is the only non-augmented, naturally available feedback through touch senses on the surface of each texture. We embedded white LEDs in our designs to provide visual feedback to the users. The brightness of the LEDs is mapped with the force or pressure applied to the textile interfaces. White LEDs are used to avoid any potential emotional bias (see Figure 5). On the other hand, a tiny MP3 module with neutral-emotion audition clips and a speaker is used to provide audio feedback. The speaker is fixed on the backside of each textile interface. The volume would either increase or decrease based on the force of the gesture [53]. Both audio and visual feedback is provided simultaneously when a user interacts with the textile interfaces in the multi-sensory feedback mode.

Each textile interface is fixed on a wooden frame (30*30 cm) and controlled with Arduino Mega. A dip switch is connected to the Mega board to allow the researcher to switch the interaction mode. The data relating to gestures from resistance-sensitive textile interfaces is stored in a TF card attached to the CH376S module. All five *GesFabri* interfaces use similar electronic components.

4 USER EVALUATION

The main objective of the user evaluation experiment was to explore the gesture affordance supported by the *GesFabri* design, as illustrated above. In this section, we summarize the rationale behind the user evaluation and illustrate the key elements of the experiment to verify Hypothesis 2.

4.1 Design

We employed a two-factorial experimental design using gestural-based interface interactions and feedback modes (haptic, visual, audio, and multi-sensory) as independent variables. Five gestural-based interface interactions are: (a) Pinch/squeeze gesture interaction on the gathering texture; (b) Poke gesture interaction on the stuffed quilting texture; (c) Scrunch/stretch gesture with shirring texture; (d) Pull gesture with flounce texture and (e) Stroke gesture with pleating texture. The order of gestural-based interface interaction and feedback modes were counter-balanced using a Latin-square design. Thus, in total, we conducted 20 testing sessions (5 gesture-based interface interactions × 4 feedback modes).

Emotional states are associated with various factors, such as thoughts, feelings, and behavioural responses, and they dynamically change with different events [17]. We adopted emotion-related subjective data (self-assessed emotion questionnaires) and objective data (physiological data) as dependent measures to measure their emotional states before and after their interactions with the textile textures. We used these data to verify whether two independent factors produce emotional effects on participants. The primary dependent measures were emotion Valence, Arousal, Stress-relaxation level, and HRV, GSR. We recorded participants' initial emotional state as the benchmark before performing interactions with the *GesFabri* interfaces. Additionally, we collected user perception and feedback during the experiment.

4.2 Participants

Twenty student volunteers participated in our user evaluation study. Though they were all recruited using the social media platform, all of them participated in the preliminary experiment that took place six weeks earlier. All our participants were right-handed.

4.3 Apparatus

The user evaluation was conducted in a dedicated laboratory space, where participants had seated in front of a table facing the tilted wooden board. *GesFabri* designs were attached to the tilted board using firm clips (see Figure 6). We used a Grove GSR sensor[4], which consists of two electrodes to measure the electrical conductance of the user's skin and a POLAR H102 sensor[5] to collect heart rate, respectively. An Android phone installed with POLAR Sensor APP was used to collect the heart-rate data wirelessly.

4.4 Procedure

The procedure for the user evaluation followed three key stages. First, all participants were introduced to the five *GesFabri* interfaces before the testing stages. This involved an introduction to the functionality of each *GesFabri* design and the predefined gestures. Additionally, the participants were asked to perform interactions with each interface to ensure that the functionality was understood correctly. Furthermore, a breath test was performed for each participant to calibrate the GSR and HRV sensors prior to the formal evaluation.

Second, a researcher helped all participants to wear GSR and HRV devices before each session. Since all our participants were right-handed, they wore the two sensing devices on their left hand and arm to avoid any potential motion artifact brought by abrupt movements. While the HRV sensor band was placed on the middle of the upper arm, the two electrodes of the GSR sensor were placed on the pulps of the index and middle fingers of each user. All participants were asked to interact with each *GesFabri* interface using the predefined gesture and feedback mode 15 times. During this practice, a researcher would introduce the four feedback modes, demonstrate the right way of performing each gesture, explain the procedure, and give general instructions. For each *GesFabri* interface, all participants were asked to interact with the predefined gesture with four feedback modes, resulting in 20 sessions (5 interfaces × 4 feedback modes) for each participant. Their emotional states before the session and after each feedback mode were recorded using a questionnaire. Thus, we collected 25 questionnaires from each participant (5 interfaces × (1 initial state + 4 feedback modes)). Participants were given an approximately two-minute break in between each *GesFabri* interface.

At the end of the experiment, all participants were asked to inform us of their favourite textile interface and feedback mode. They were also encouraged to share their experience interacting with *GesFabri* interfaces. All verbal communications between the researcher and participant during the experiment process were audio-recorded. The whole process took approximately 60 minutes for each participant.

4.5 Data Analysis

We chose to integrate several parameters for the assessment of personal emotional experiences. From the literature on psychophysiology, we identified the use of subjective measures of valence and arousal levels to indicate users' emotions [11]. Equally, physiological variables, such as electrodermal activity (EDA) and heart rate variability, also have been widely used for emotion-related measurements [2]. The included measures in our experiment were: (1) subjective emotion measurement, Emotion Valence, Arousal, and Stress-Relaxation levels, and (2) physiological measures EDA and HRV.

We measured the Emotion Valence-Arousal and Stress-Relaxation emotion measurement on a nine-point Likert scale [41] and physiological data using HRV and GSR sensors. For the HRV data

[4]https://wiki.seeedstudio.com/Grove-GSR_Sensor/

[5]https://www.polar.com/us-en/products/accessories/polar-verity-sense

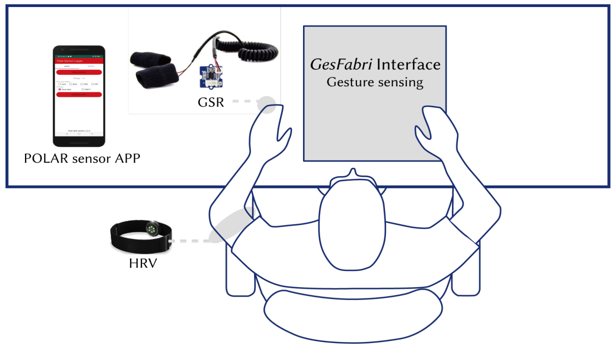

Fig. 6. An illustration of the electronic components of *GesFabri* interfaces and the experiment apparatus (top view).

(R-R interval), the typical values range from 0.6-1 second. We discarded values out of this range and only considered the standard deviation of the normal-to-normal R-R intervals (SDNN) data from heart rate's R-R interval. This data is believed to be closely associated with the user's emotional state [74]. We removed its motion artefacts for the GSR signal by applying a median filter with a time window of 500ms, and the average GSR peak amplitude was taken for statistical analysis.

5 RESULTS

We aggregated the results of the 20 sessions. We ran a series of two-way repeated measured ANOVA using the factors - *GesFabri* interfaces (gathering, stuffed quilting, shirring, flounce, and pleating textures) and Feedback modes (haptic, visual, audio, and multi-sensory) on the users' emotion levels with subjective and physiological measures. We also used the initial state as a benchmark. All our statistical tests revealed normal data distribution. The Greenhouse–Geisser correction was applied if the assumption of sphericity was violated. All post-hoc tests were corrected for multiple comparisons using Bonferroni corrections where necessary.

5.1 Emotion Valence and Arousal

To analyse the subjective source of emotion changes, we performed a series of two-way RM-ANOVA of the emotion valance and arousal with the type of *GesFabri* interface and Feedback mode as factors. The analysis showed a significant main effect of Feedback factor for emotion valance ($F_{(2.619,49.755)}$=18.252, p<0.001) and emotion arousal ($F_{(2.349,44.630)}$=29.758, p<0.001). However, there was no significance for the interaction effect for emotional valance and arousal. The post-hoc pairwise comparisons were different for each feedback mode. Compared with the initial state, except for audio, the emotion valance increased significantly for haptic (p=0.038), visual (p<0.001), multi-sensory feedback (p<0.001) (see Figure 7a and Table 1). In addition, the differences between haptic and visual feedback (p<0.001), multi-sensory feedback mode (p=0.03), are statistically significant. The difference was also significant from visual feedback to audio feedback (p=0.004), audio feedback to multi-sensory feedback (p=0.001). Compared with the initial state and haptic feedback, the emotion arousal value of visual feedback (p<0.001), audio feedback (p<0.001), multi-sensory feedback (p<0.001) all increased significantly (see Figure 7b and Table 1). Besides, the multi-sensory feedback was significantly higher than the visual (p=0.028) and audio (p<0.001) feedback.

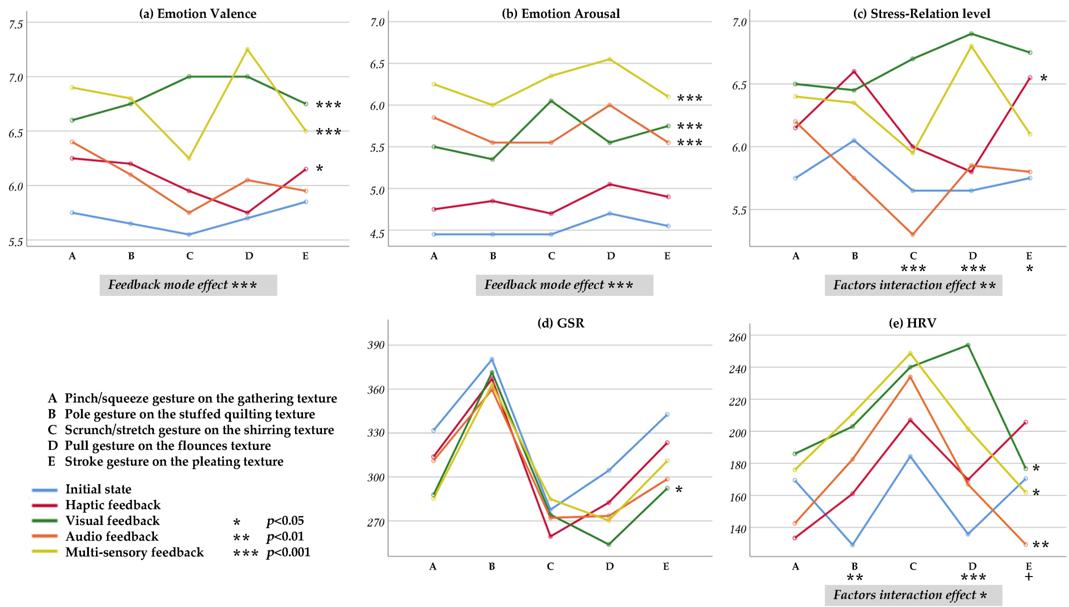

Fig. 7. Summary of results according to interaction gestures and feedback modes. After the gesture performance: (a) Valence—the means of emotion Valence level; (b) Arousal—the means of emotion Arousal level; and (c) Stress-Relaxation level—the means of Stress-Relaxation level. During the gesture performance: (d) GSR—the means of GSR and (e) HRV—the SDNN of HRV (R-R interval).

Table 1. Results of the two-way repeated measures ANOVAs for the self-assessment scales and physiological parameters on two variables - *GesFabri* interface and Feedback mode.

Items	**Variables**	**SS (TypeIII)**	**DF**	**MF**	**F**	***p*-value**
Emotion Valence	Feedback	94.072	2.619	35.924	18.252	<0.001***
	Interface	4.912	2.280	2.155	0.520	0.616
	Feedback × Interface	18.228	6.831	2.668	1.755	0.104
Emotion Arousal	Feedback	194.668	2.349	82.874	29.758	<0.001***
	Interface	5.708	4.000	1.427	0.708	0.589
	Feedback × Interface	9.892	6.886	1.436	0.829	0.563
Stress-Relaxation	Feedback	57.520	1.945	29.570	5.578	0.008**
	Interface	6.760	4.000	1.690	0.569	0.686
	Feedback × Interface	24.520	16.000	1.532	2.102	0.008**
GSR	Feedback	31492.895	2.065	15250.985	3.202	0.060
	Interface	319739.076	1.831	174638.322	0.992	0.383
	Feedback × Interface	24785.869	3.129	7922.119	0.781	0.518
HRV	Feedback	185536.556	4.000	46384.139	5.869	<0.001***
	Interface	217285.082	4.000	54321.271	3.378	0.014*
	Feedback × Interface	199242.371	6.578	30290.768	2.297	0.034*

5.2 Stress-Relaxation level

We performed a two-way RM-ANOVA to understand the subjective feelings of stress and relaxation level with the type of *GesFabri* interface and Feedback mode as factors. We found significant interaction effect ($F_{(16,304)}$=2.102, p=0.008). See Figure 7c and Table 1.

In haptic mode, the *GesFabri* factor ($F_{(4,76)}$=2.624, p=0.041) was significant to the stress-relaxation level. When the user interacted with the stuffed quilting texture, they felt more relaxed than touching the shirring texture (p=0.03), flounce texture significantly (p=0.003). Moreover, pleating texture made people feel relaxed than flounce texture (p=0.044).

In scrunch/stretch gesture with shirring texture condition, the Feedback factor ($F_{(4,76)}$=5.088, p=0.001) was showed significance. Of which, the visual feedback was reported to make participants more relaxed significantly, compared with the initial state (p=0.003), haptic feedback (p=0.027), audio feedback (p<0.001), and multi-sensory feedback (p=0.032). In pull gesture interaction with flounce texture condition, the Feedback factor ($F_{(2.515,47.790)}$=7.563, p=0.001) was found to be significant, where visual feedback was higher than the initial state (p<0.001), haptic feedback (p<0.001), and audio feedback (p=0.011). In addition, multi-sensory feedback was scored higher than the Initial state (p=0.001), haptic feedback (p=0.008), and audio feedback (p=0.02). For the stroke gesture interaction with pleating texture, the Feedback factor ($F_{(2.792,50.051)}$=2.899, p=0.047) was also found to be significant, where haptic feedback (p=0.009) and visual feedback (p=0.029) made participants feel more relaxed compared to the initial state. Furthermore, the audio feedback made them more stressed than the visual feedback (p=0.04).

5.3 Physiological Measures

The two-way RM-ANOVA of physiological measures showed a significant interaction effect $F_{(6.578,118.398)}$=2.297, p=0.034) for HRV (see Figure 7e and Table 1). In haptic feedback, the HRV is significantly higher for the stuffed quilting texture (p=0.007) as well as pleating texture (p=0.006) than the gathering texture. In visual feedback, the gestural-based interface factor ($F_{(4,72)}$=2.73, p=0.036) was found to be significant. Of these, the flounce texture condition showed higher HRV than gathering texture (p=0.032), stuffed quilting texture (p=0.077), and pleating texture (p=0.017). In audio feedback, the gestural-based interface factor ($F_{(2.667,48.009)}$=4.777, p=0.007) had significance. Stuffed quilting texture was higher than gathering texture (p=0.071) and pleating texture (p=0.036). And shirring texture was higher than gathering texture (p=0.014), flounce texture (p=0.029) and pleating texture (p=0.005).

The *GesFabri* interface factor ($F_{(4,72)}$=2.729, p=0.036) was also significant in multi-sensory feedback. Shirring texture was higher than gathering texture (p=0.019) and pleating texture (p=0.013). In poke gesture interaction with stuffed quilting texture condition, the Feedback factor ($F_{(4,72)}$=4.02, p=0.005) showed significance. The visual feedback was significantly higher compared with the initial state (p=0.028). Moreover, the multi-sensory feedback mode was higher than the initial state (p=0.007) and the haptic feedback (p=0.039). In pull gesture interaction with flounce texture condition, the Feedback factor ($F_{(4,72)}$=9.797, p<0.001) was found to be significant. In which the visual feedback was significantly higher than the initial state (p<0.001), haptic feedback (p<0.001), audio feedback (p<0.001), and multi-sensory feedback (p=0.017). Moreover, the multi-sensory feedback was higher than the initial state (p=0.012).

There was no evidence that the *GesFabri* interface and Feedback factors affected GSR data. However, the Feedback factor's main effect ($F_{(2.065,20.605)}$=3.202, p=0.06) on participants' GSR data was marginally significant. The difference between the initial state and the visual feedback was significant (p=0.027). Furthermore, the haptic feedback was significantly higher than the visual feedback (p=0.019) (see Figure 7d and Table 1).

5.4 Users' Feedback

At the end of the experiment, participants informed us of their favourite textile interface and preferred feedback mode. Participants perceived performing interactions with *GesFabri* interfaces are aesthetically pleasant, comfortable, enjoyable, and relaxed. Pleating texture with stroke gesture was the favourite *GesFabri* interface among our participants (9 out of 20). While three of them highlighted that stroke gestures gave them a soft, relaxed, and comfortable feeling, five participants mentioned that they liked the surface of this texture as it appeared very similar to a rhythmic stringed instrument or keyboard. Thus, they treated this texture as a musical instrument in the audio feedback mode to compose a piece of music. Six users stated that performing the pull gesture with flounce texture was exciting and interesting. Some of them alluded to the impression of turning on the light in the visual feedback mode, while it reminded them of tinkling a bell in the audio feedback mode. Three participants mentioned that the shirring texture looked like a fish in the visual feedback mode. Others mentioned that poke gestures on stuffed quilting texture in visual and multi-sensory feedback modes were like poking soap bubbles or playing a pixel game. One compared stuffed quilting texture to biscuits. Some participants compared the textures with music instruments, particularly in multi-sensory feedback mode. While a male participant commented that the scrunch/stretch gesture with shirring texture made him feel like a music conductor of concert bands, a female user felt like playing the drum kit with the pinch gesture of the gathering texture.

6 DISCUSSION

Our investigation with e-textile texture interfaces provided insight into how participants performed various gestures and their emotional responses. We investigated five different textile textures in their appropriateness and affordances to support intuitive hand gestural interaction. Multiple analyses (both subjective and physiological) revealed that the interaction between *GesFabri* interfaces and feedback mode positively influenced the user's emotions while interacting with *GesFabri* interfaces. In particular, the feedback mode had a more significant impact on their emotional experience than textile textures. The results showed that the subjective emotional valence, arousal, and electrodermal activity positively affected the users in haptic, visual, and multi-sensory feedback. These three modes quickly raised the participants' emotional arousal levels. The GSR data revealed that only visual feedback significantly affected their physiological emotions. The results of the subjective stress-relaxation level indicated that the haptic mode helped the users release their pressure. The HRV data also confirm this result.

On the other hand, the audio and multi-sensory feedback modes of the *GesFabri* interfaces made our participants feel excited or stressed. Our users reported feeling more relaxed while performing poke and stroke gestures on stuffed quilting and pleating textures, respectively, in haptic mode. While the stretch, pull, and stroke gestures on shirring, flounce and stuffed quilting textures resulted in a higher HRV for multi-sensory mode, the HRV was higher for stretch and pull gestures in audio and visual feedback modes as well. Prior research reported that gross upper body movement-based interactions using smart textiles affected users' emotions [37]. Our findings align with their results as *GesFabri* interfaces supported by hand gestural interactions brought diverse emotional experiences for the users.

6.1 Design Guidelines for Gestural Interaction on e-Textile Interfaces

In the following, we derived several guidelines for the design of textile interfaces for emotional interaction combining the results from the two studies as well as the results of the semi-structured interviews conducted with the users at the end of each study.

6.1.1 Consider Material-Inspired Tangible Design Method for e-Textile Interfaces. The tangible interactions literature has stated that designers and engineers commonly follow the "form follows function" rule to support interaction with a purpose-built interface [57]. In human-computer interaction, material-induced interaction is novel means of designing future tangible interfaces [57]. Our study follows the material-inspired tangible design method, thus enhancing the expressiveness of materials' attributes and forms. By following the methodology [57], we identified and validated five suitable textures with gesture affordances for our further investigation. We believe that our inverted material driven design method might help e-textile researchers develop interactive textile interfaces by drawing their attention to the importance of materiality for textile interfaces.

6.1.2 Textile Texture Design that Nurtures Gesture Affordances. The meaningful ecosystem fosters affordance, which forms the basis for intuitive interfaces [51]. Our user-preferred gestures confirm that intuitive gesture interaction can be achieved through texture affordances. We recommend an investigation of textile textures, which might elicit gestures with high consensus from the users due to the benefit of the natural affordances of these textures.

6.1.3 Consider Gesture Designs that Exploit the Surface of the Textile Texture Factor. Prior work asserted the benefits of image schemata in eliciting intuitive interactions [6]. Textile textures can easily change the image schemata of textiles compared to fibre/yarn. Our participants not only utilised the image schema supported by each texture design to elicit gestures but went further to associate existing metaphors with interacting with *GesFabri* interfaces. These observations align with prior studies on eliciting gestures using textiles [49][50]. We suggest that gesture designers must consider the surface of each texture design, the existing metaphors and their suitability for the intended design and whether the expected users of these interfaces commonly use these metaphors.

6.1.4 Users Prefer Single-handed Gestures to Interact with E-Textiles. During our user studies, we found that single-handed gestures were more prevalent in textile texture affordances. In particular, the single-handed push and stroke gestures were unanimously preferred for stuffed quilting and pleating textures, respectively. In contrast, our participants proposed different gestures for the shirring texture with higher consensus for the dual-handed scrunch/stretch gesture. Nevertheless, our participants preferred variations of single-hand gestures (4 out of 5 gestures). Therefore, we recommend associating single-hand gestures with e-textile texture interfaces to achieve high intuitiveness.

6.1.5 Favor Haptic and Visual Feedback Modes in Designing Interactive Textiles for Emotional Support. We found that the feedback played a significant role in influencing the participants' emotions. Especially the haptic and visual modes enhanced positive feelings. Research from psychology found that spatially congruent visual clues could affect textiles' perception [43]. Another research proposed a framework in which a cross-modal interaction was built between vision and touch [77]. The authors reported that visual clues improved haptic spatial perception speed and enhanced tactile accuracy. Our results further confirm their findings that haptic can influence and be influenced by other somatosensory stimuli leading to emotional fluctuations.

6.1.6 Design that Fosters Synergy with Feedback Mechanisms. Prior research on gesture-based interaction on user behaviour indicated that intuitive gestures elicited from natural and meaningful feedback mechanisms are essential factors for pleasant user experience and usability [75]. It should be noted that touch behaviour and physical sensations, such as tactile, visual, and audio, considerably change the affective experience. The same conclusion can also be applied to embodied interactive textile interfaces. Our results show that gestural interactions on textile interfaces with sensory feedback mechanisms can create new visual schemata and metaphors for the users. We recommend designing sensory feedback mechanisms associated with the aim, format, and usage scenario of interactive textiles, which might benefit from intuitive gestures due to the positive affective experience.

6.1.7 Explicate Emotional Aims in Designing E-Textiles for Gestural Interaction. We found that the five textile textures led to various emotional experiences. Our participants felt relaxed while performing poke and stroke gestures with *GesFabri* interfaces. They mentioned their excitement and interest in the pull gesture. The literature has documented the benefits of stroke-based input systems, particularly efficiently transmitting longing, and empathy, providing comfort, offering positive emotional sensations, and motivating healthier habits [56]. Our findings further strengthen the idea that intuitive gesture-based interaction would evoke complex and multidimensional emotions. As the review of affective haptics suggests, the cross dependencies between gesture-based interaction and emotions are a challenge. They should be accurately modelled to understand further their internal relationship [42]. When designing an intuitive gestural textile for emotional interaction, we recommend clarifying the emotional aim first, such as stress relief, enhancing positive emotions, emotional bonding, or social relationships.

6.2 Limitations

The performed study used a wooden frame to attach the *GesFabri* prototypes. They were placed on a table in a tilted position in a dedicated laboratory space to enable participants to perform interactions with them. Allowing the participants to use the textile prototypes in real-life outdoor scenarios as they normally use textiles and perform socially acceptable, subtle hand gestural interactions could have increased the validity of the study. We believe that the usage of a more controlled indoor setup is appropriate for initial evaluation. However, our *iPillowPal* prototype was tested with couples in a long-distance relationship, where they performed our elicited gestures in various indoor environments (such as home and office). Though the same pool of 20 participants volunteered for both studies, there was a six-week gap (approximately 44 days for each participant) between the two studies. In the preliminary study, users proposed their preferred gestures for each textile texture, whereas later, they performed the defined gestures on each prototype with four feedback modes. Nevertheless, the order of texture designs was counterbalanced for both studies to minimize any learning effect. In addition, we did not investigate how environmental conditions, such as rain or snow, influence user emotions when interacting with textile interfaces. Our two studies were conducted in a normal room temperature setup. Thus, our design guidelines are more suitable for using textile interfaces to regulate emotions in various indoor environments.

7 APPLICATION SCENARIOS/DEMOS

Design guidelines in the previous section show the potential of the *GesFabri* interfaces. Here we present two demos of *GesFabri* interfaces in use. These two prototypes use creamy-white stretch scuba knitted fabrics.

7.1 Gesture-based Interaction for Emotion Regulation

To demonstrate how the poke gestural interactions and visual and vibrotactile feedback modalities can be used to regulate emotions in daily life, we present an interactive Shawl interface [35]. The prototype features modified fashionable 14 separate shirring textures as fabric bubbles (see Figure 8a). Participants all used poking gestures to interact with the smart shawl intuitively, which was afforded by its bubble-like textile texture. Each texture integrates a piezoresistive pressure sensor made of pressure-sensitive Velostat foil, a LED light, and a vibration motor. When the wearer's arousal level (indicated by the GSR sensor worn separately on the user's fingers) changes, each

(a) (b)

Fig. 8. (a) the smart shawl prototype for self-emotion regulation in daily life; (b) the *iPillowPal* prototype for remote emotional communication and interaction using affective gestures.

fabric bubble module will react by changes in intensity. The users can choose their preferred feedback mode (visual or vibrotactile) according to their usage scenarios. Our results showed that the interactions with the smart Shawl prototype using poke gestures helped the users to visualize their emotions and minimize their stress levels.

7.2 Affective Gesture-based Interaction for Emotion Connection

To demonstrate how multiple textile textures, gestural inputs, and feedback modalities can be combined in a single interface for remote emotional connection or communication, we present *iPillowPal*, a throw-pillow-based interface. To build our pillow prototype, we identified four user-preferred affective gestures (Poke, Stroke, Pull and Hug) for textile textures associated with various emotions for couples in long-distance relationships. We use two independent sensing and feedback layers (front and back sides) to provide visual feedback for Poke, Stroke and Pull gestures. The two larger sensing areas at the backside support the Hug gesture with visual and haptic feedback. Our *iPillowPal* prototype is powered by an Arduino Nano 33 BLE with a multiplexer that streams data in real-time to a cloud server via a mobile APP over a Bluetooth connection. Two *iPillowPal* systems are paired or connected via the mobile APP to the cloud server. The pressure applied to the sensing areas to perform a particular affective gesture is used to determine the saturation of the lights and also the vibration intensity. For instance, any applied gentle pressure on the sensing areas will respond in the mellow chromatic colours, while the more powerful pressure will result in the bright colours. The colour phase of the sensing areas is diverse and changes gradually with time (see Figure 8b). Thus, users can observe the visual effect or sense the vibration caused by their partner's mediated affective gesture interaction on the corresponding area of the pillow, and their affective gesture reactions can be transferred to their partner's pillow. We conducted a preliminary real-life study with three heterogeneous couples using our prototype for seven consecutive days at different places, including workplaces and homes, to assess the performance of our system. Our results show that using our *iPillowPal* prototype (1) increased LDR couples' positive emotions and decreased negative emotions, and (2) improved their remote emotional connections.

8 CONCLUSION

This research sought to extend the textile interface boundary for gesture interaction by examining (1) how *GesFabri* interfaces afforded intuitive interaction gestures and (2) user experience when interacting with five textile interfaces via multi feedback modes. We built five e-textile interfaces with different gesture affordances: pinch/squeeze with gathering texture, poke with stuffed quilting texture, scrunch/stretch with shirring texture, pull with flounce texture, and stroke with pleating texture. We also demonstrated the fabrication process of *GesFabri* interfaces. We then compared various subjective and physiological emotion measurements in four feedback conditions: haptic, visual, audio, and multi-sensory (combination of visual and audio) modes. Our experiment results show that the feedback modes led to differences in emotional valence, arousal, and GSR. When considering Stress-Relaxation level and HRV, both the textile-afforded gesture and the feedback mode influenced participants' affective perception. We also derived design guidelines for textile-based interfaces for emotion regulation. Finally, to demonstrate the versatility of textile texture-based interfaces, we presented two example prototypes.

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REFERENCES

[1] Miguel Bruns Alonso, David V Keyson, and Caroline CM Hummels. 2008. Squeeze, rock, and roll; can tangible interaction with affective products support stress reduction?. In *Proceedings of the 2nd international conference on Tangible and embedded interaction*. 105–108. https://doi.org/10.1145/1347390.1347413
[2] Bradley M Appelhans and Linda J Luecken. 2006. Heart rate variability as an index of regulated emotional responding. *Review of general psychology* 10, 3 (2006), 229–240. https://doi.org/10.1037/1089-2680.10.3.229
[3] Lawrence W Barsalou. 2008. Grounded cognition. *Annu. Rev. Psychol.* 59 (2008), 617–645. https://doi.org/10.1146/annurev.psych.59.103006.093639
[4] Tony Bastick. 1982. *Intuition: How we think and act.* John Wiley & Sons Incorporated.
[5] Sian L Beilock and Susan Goldin-Meadow. 2010. Gesture changes thought by grounding it in action. *Psychological science* 21, 11 (2010), 1605–1610. https://doi.org/10.1177/0956797610385353
[6] Alethea Blackler and Vesna Popovic. 2015. Towards intuitive interaction theory. , 203–209 pages. https://doi.org/10.1093/iwc/iwv011
[7] Alethea Blackler, Vesna Popovic, and Douglas Mahar. 2003. The nature of intuitive use of products: an experimental approach. *Design Studies* 24, 6 (2003), 491–506. https://doi.org/10.1016/S0142-694X(03)00038-3
[8] Leonardo Bonanni, Cati Vaucelle, Jeff Lieberman, and Orit Zuckerman. 2006. Taptap: a haptic wearable for asynchronous distributed touch therapy. In *CHI'06 extended abstracts on Human factors in computing systems*. 580–585. https://doi.org/10.1145/1125451.1125573
[9] Hans-Jörg Bullinger, Jürgen Ziegler, and Wilhelm Bauer. 2002. Intuitive human-computer interaction-toward a user-friendly information society. *International Journal of Human-Computer Interaction* 14, 1 (2002), 1–23. https://doi.org/10.1207/S15327590IJHC1401_1
[10] Bill Buxton and Mark Billinghurst. 2011. Gesture based interaction. *Human Input to Computer Systems: Theories, Techniques and Technology* (2011).
[11] Rafael A Calvo and Sidney D'Mello. 2010. Affect detection: An interdisciplinary review of models, methods, and their applications. *IEEE Transactions on affective computing* 1, 1 (2010), 18–37. https://doi.org/10.1109/T-AFFC.2010.1
[12] Li-Hao Chen and Yi-Chien Liu. 2017. Affordance and intuitive interface design for elder users with dementia. *Procedia CIRP* 60 (2017), 470–475. https://doi.org/10.1016/j.procir.2017.02.015
[13] Felecia Davis. 2015. The textility of emotion: A study relating computational textile textural expression to emotion. In *Proceedings of the 2015 ACM SIGCHI Conference on Creativity and Cognition*. 23–32. https://doi.org/10.1145/2757226.2757231
[14] Felecia Davis, Asta Roseway, Erin Carroll, and Mary Czerwinski. 2013. Actuating mood: design of the textile mirror. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*. 99–106. https://doi.org/10.1145/2460625.2460640
[15] Haoyu Dong. 2019. Disappearing textile interface with inherent feedforwards. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications: Adjunct Proceedings*. 489–493. https://doi.org/10.1145/3349263.3349598
[16] Mohamad A Eid and Hussein Al Osman. 2015. Affective haptics: Current research and future directions. *IEEE Access* 4 (2015), 26–40. https://doi.org/10.1109/ACCESS.2015.2497316

[17] Paul Ekman. 1999. Basic emotions. *Handbook of cognition and emotion* 98, 45-60 (1999), 16.
[18] Greg K Essick, Anuj James, and Francis P McGlone. 1999. Psychophysical assessment of the affective components of non-painful touch. *Neuroreport* 10, 10 (1999), 2083–2087.
[19] Tiffany Field. 2014. *Touch.* MIT press.
[20] Anna Flagg and Karon MacLean. 2013. Affective touch gesture recognition for a furry zoomorphic machine. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*. 25–32. https://doi.org/10.1145/2460625.2460629
[21] Mozhdeh Ghahremani Honarvar and Masoud Latifi. 2017. Overview of wearable electronics and smart textiles. *The Journal of The Textile Institute* 108, 4 (2017), 631–652. https://doi.org/10.1080/00405000.2016.1177870
[22] James J Gibson. 1977. The concept of affordances. *Perceiving, acting, and knowing* 1 (1977).
[23] James J Gibson. 2014. *The ecological approach to visual perception: classic edition.* Psychology Press.
[24] Emilie Giles and Janet van der Linden. 2014. Using eTextile objects for touch based interaction for visual impairment. In *Proceedings of the 2014 ACM International Symposium on Wearable Computers: Adjunct Program*. 177–183. https://doi.org/10.1145/2641248.2641351
[25] Scott Gilliland, Nicholas Komor, Thad Starner, and Clint Zeagler. 2010. The textile interface swatchbook: Creating graphical user interface-like widgets with conductive embroidery. In *International Symposium on Wearable Computers (ISWC) 2010*. IEEE, 1–8. https://doi.org/10.1109/ISWC.2012.29
[26] Maas Goudswaard, Abel Abraham, Bruna Goveia da Rocha, Kristina Andersen, and Rong-Hao Liang. 2020. FabriClick: Interweaving Pushbuttons into Fabrics Using 3D Printing and Digital Embroidery. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference*. 379–393. https://doi.org/10.1145/3357236.3395569
[27] Rhonda Hadi and Lauren Block. 2014. I take therefore I choose? The impact of active vs. passive acquisition on food consumption. *Appetite* 80 (2014), 168–173. https://doi.org/10.1016/j.appet.2014.05.003
[28] Rhonda Hadi and Ana Valenzuela. 2014. A meaningful embrace: Contingent effects of embodied cues of affection. *Journal of Consumer Psychology* 24, 4 (2014), 520–532. https://doi.org/10.1016/j.jcps.2014.02.001
[29] Nur Al-huda Hamdan, Florian Heller, Chat Wacharamanotham, Jan Thar, and Jan Borchers. 2016. Grabrics: A foldable two-dimensional textile input controller. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. 2497–2503. https://doi.org/10.1145/2851581.2892529
[30] Harry F Harlow. 1958. The nature of love. *American psychologist* 13, 12 (1958), 673.
[31] Rex Hartson. 2003. Cognitive, physical, sensory, and functional affordances in interaction design. *Behaviour & information technology* 22, 5 (2003), 315–338. https://doi.org/10.1080/01449290310001592587
[32] Seongkook Heo and Geehyuk Lee. 2011. Force gestures: augmenting touch screen gestures with normal and tangential forces. In *Proceedings of the 24th annual ACM symposium on User interface software and technology*. 621–626. https://doi.org/10.1145/2047196.2047278
[33] Eva Hornecker. 2012. Beyond affordance: tangibles' hybrid nature. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction*. 175–182. https://doi.org/10.1145/2148131.2148168
[34] Gijs Huisman. 2012. A touch of affect: Mediated social touch and affect. In *Proceedings of the 14th ACM international conference on Multimodal interaction*. 317–320. https://doi.org/10.1145/2388676.2388746
[35] Mengqi Jiang, Martijn ten Bhömer, and Hai-Ning Liang. 2020. Exploring the design of interactive smart textiles for emotion regulation. In *International Conference on Human-Computer Interaction*. Springer, 298–315. https://doi.org/10.1007/978-3-030-59987-4_22
[36] Mengqi Jiang, Vijayakumar Nanjappan, Hai-Ning Liang, and Martijn ten Bhömer. 2021. In-Situ exploration of emotion regulation via smart clothing: an empirical study of healthcare workers in their work environment. *Behaviour & Information Technology* (2021), 1–14. https://doi.org/10.1007/978-3-030-59987-4_22
[37] Mengqi Jiang, Vijayakumar Nanjappan, Martijn Ten Bhömer, and Hai-Ning Liang. 2021. On the use of movement-based interaction with smart textiles for emotion regulation. *Sensors* 21, 3 (2021), 990. https://doi.org/10.3390/s21030990
[38] Thorsten Karrer, Moritz Wittenhagen, Leonhard Lichtschlag, Florian Heller, and Jan Borchers. 2011. Pinstripe: eyes-free continuous input on interactive clothing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 1313–1322. https://doi.org/10.1145/1978942.1979137
[39] Sumbul Khan and Bige Tunçer. 2017. Intuitive and Effective Gestures for Conceptual Architectural Design: An Analysis Of User Elicited Hand Gestures For 3D CAD Modeling. (2017).
[40] Ardis W Koester et al. 1993. Analyzing the color, design, and texture of fabric. (1993).
[41] Rensis Likert. 1932. A technique for the measurement of attitudes. *Archives of psychology* (1932).
[42] Laís Lopes and Pedro Campos. 2019. SCAARF: a subtle conditioning approach for anxiety relief facilitation. In *Proceedings of the 18th International Conference on Mobile and Ubiquitous Multimedia*. 1–5. https://doi.org/10.1145/3365610.3368417
[43] Emiliano Macaluso and Angelo Maravita. 2010. The representation of space near the body through touch and vision. *Neuropsychologia* 48, 3 (2010), 782–795. https://doi.org/10.1016/j.neuropsychologia.2009.10.010

[44] André Melzer, Ingmar Derks, Jens Heydekorn, and Georges Steffgen. 2010. Click or strike: Realistic versus standard game controls in violent video games and their effects on aggression. In *International Conference on Entertainment Computing*. Springer, 171–182. https://doi.org/10.1007/978-3-642-15399-0_16

[45] Laurent Mignonneau and Christa Sommerer. 2005. Designing emotional, metaphoric, natural and intuitive interfaces for interactive art, edutainment and mobile communications. *Computers & Graphics* 29, 6 (2005), 837–851. https://doi.org/10.1016/j.cag.2005.09.001

[46] Sara Mlakar, Mira Alida Haberfellner, Hans-Christian Jetter, and Michael Haller. 2021. Exploring Affordances of Surface Gestures on Textile User Interfaces. In *Designing Interactive Systems Conference 2021*. 1159–1170. https://doi.org/10.1145/3461778.3462139

[47] Sara Mlakar and Michael Haller. 2020. Design investigation of embroidered interactive elements on non-wearable textile interfaces. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–10. https://doi.org/10.1145/3461778.3462139

[48] Vijayakumar Nanjappan, Hai-Ning Liang, Kim Lau, Jaemin Choi, and Kyung Ki Kim. 2017. Clothing-based Wearable Sensors for Unobtrusive Interactions with Mobile Devices. In *2017 International SoC Design Conference (ISOCC)*. 139–140. https://doi.org/10.1109/ISOCC.2017.8368837

[49] Vijayakumar Nanjappan, Rongkai Shi, Hai-Ning Liang, Kim King-Tong Lau, Yong Yue, and Katie Atkinson. 2019. Towards a taxonomy for in-vehicle interactions using wearable smart textiles: insights from a user-elicitation study. *Multimodal Technologies and Interaction* 3, 2 (2019), 33. https://doi.org/10.3390/mti3020033

[50] Vijayakumar Nanjappan, Rongkai Shi, Hai-Ning Liang, Haoru Xiao, Kim King-Tong Lau, and Khalad Hasan. 2019. Design of interactions for handheld augmented reality devices using wearable smart textiles: findings from a user elicitation study. *Applied Sciences* 9, 15 (2019), 3177. https://doi.org/10.3390/app9153177

[51] Donald A Norman. 1988. *The psychology of everyday things.* Basic books.

[52] Nur Zuraifah Syazrah Othman, Mohd Shafry Mohd Rahim, Masitah Ghazali, and Sule Anjomshoae. 2019. Perspectives of Gestures for Gestural-Based Interaction Systems: Towards Natural Interaction. *Human IT: Journal for Information Technology Studies as a Human Science* 14, 3 (2019), 1–25.

[53] Sébastien Paquette, Isabelle Peretz, and Pascal Belin. 2013. The "Musical Emotional Bursts": a validated set of musical affect bursts to investigate auditory affective processing. *Frontiers in psychology* 4 (2013), 509. https://doi.org/10.3389/fpsyg.2013.00509

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

[55] Rosalind W Picard. 2000. *Affective computing.* MIT press.

[56] Jussi Rantala, Roope Raisamo, Jani Lylykangas, Teemu Ahmaniemi, Jukka Raisamo, Jyri Rantala, Kalle Makela, Katri Salminen, and Veikko Surakka. 2011. The role of gesture types and spatial feedback in haptic communication. *IEEE Transactions on Haptics* 4, 4 (2011), 295–306. https://doi.org/10.1109/TOH.2011.4

[57] Magdalena Schmid, Sonja Rümelin, and Hendrik Richter. 2013. Empowering materiality: inspiring the design of tangible interactions. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*. 91–98. https://doi.org/10.1145/2460625.2460639

[58] Adwait Sharma, Joan Sol Roo, and Jürgen Steimle. 2019. Grasping microgestures: Eliciting single-hand microgestures for handheld objects. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–13. https://doi.org/10.1145/3290605.3300632

[59] Marc Silver. 2013. *Exploring interface design.* Cengage Learning.

[60] T Stegmaier. 2012. Recent advances in textile manufacturing technology. *The Global Textile and Clothing Industry* (2012), 113–130. https://doi.org/10.1533/9780857095626.113

[61] Helman I Stern, Juan P Wachs, and Yael Edan. 2008. Optimal consensus intuitive hand gesture vocabulary design. In *2008 IEEE International Conference on Semantic Computing*. IEEE, 96–103. https://doi.org/10.1109/ICSC.2008.29

[62] Christian Stößel and Lucienne Blessing. 2009. Is gesture-based interaction a way to make interfaces more intuitive and accessible. *HCI 2009 Electronic proceedings: WS4–Prior Experience. British Computer Society, Cambridge* (2009).

[63] Paul Strohmeier, Jarrod Knibbe, Sebastian Boring, and Kasper Hornbæk. 2018. zPatch: Hybrid resistive/capacitive etextile input. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*. 188–198. https://doi.org/10.1145/3173225.3173242

[64] Kentaro Ueda, Tsutomu Terada, and Masahiko Tsukamoto. 2018. Evaluation of Input using Wrinkles on Clothes. In *Proceedings of the 16th International Conference on Advances in Mobile Computing and Multimedia*. 66–75. https://doi.org/10.1145/3282353.3282365

[65] Maurice HPH van Beurden, Wijnand A Ijsselsteijn, and Yvonne AW de Kort. 2011. User experience of gesture based interfaces: a comparison with traditional interaction methods on pragmatic and hedonic qualities. In *International*

Gesture Workshop. Springer, 36–47. https://doi.org/10.1007/978-3-642-34182-3_4

[66] Karen Vanderloock, Vero Vanden Abeele, Johan AK Suykens, and Luc Geurts. 2013. The skweezee system: enabling the design and the programming of squeeze interactions. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*. 521–530. https://doi.org/10.1145/2501988.2502033

[67] Cati Vaucelle, Leonardo Bonanni, and Hiroshi Ishii. 2009. Design of haptic interfaces for therapy. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 467–470. https://doi.org/10.1145/1518701.1518776

[68] Jo Vermeulen, Kris Luyten, Elise van den Hoven, and Karin Coninx. 2013. Crossing the bridge over Norman's Gulf of Execution: revealing feedforward's true identity. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 1931–1940. https://doi.org/10.1145/2470654.2466255

[69] Hayward Vincent, R Astley Oliver, Cruz-Hernandez Manuel, Grant Danny, and Robles-De-La-Torre Gabriel. 2004. Haptic interfaces and devices. *Sensor Review* 24, 1 (2004), 16–29. https://doi.org/10.1108/02602280410515770

[70] Rongrong Wang, Francis Quek, Deborah Tatar, Keng Soon Teh, and Adrian Cheok. 2012. Keep in touch: channel, expectation and experience. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 139–148. https://doi.org/10.1145/2207676.2207697

[71] Stephan AG Wensveen, Johan Partomo Djajadiningrat, and CJ Overbeeke. 2004. Interaction frogger: a design framework to couple action and function through feedback and feedforward. In *Proceedings of the 5th conference on Designing interactive systems: processes, practices, methods, and techniques*. 177–184. https://doi.org/10.1145/1013115.1013140

[72] Irmandy Wicaksono and Joseph A Paradiso. 2017. Fabrickeyboard: multimodal textile sensate media as an expressive and deformable musical interface. In *NIME*, Vol. 17. 348–353.

[73] Colette Wolff. 1996. *The art of manipulating fabric.* Krause publications Iola, WI.

[74] Wanqing Wu and Jungtae Lee. 2009. Improvement of HRV methodology for positive/negative emotion assessment. In *2009 5th International Conference on Collaborative Computing: Networking, Applications and Worksharing*. IEEE, 1–6. https://doi.org/10.1108/02602280410515770

[75] Liu Yang. 2017. *The effects of gesture-based interaction on user behavior: An embodied view.* Ph. D. Dissertation. National University of Singapore (Singapore).

[76] Clint Zeagler, Scott Gilliland, Halley Profita, and Thad Starner. 2012. Textile interfaces: Embroidered jog-wheel, beaded tilt sensor, twisted pair ribbon, and sound sequins. In *2012 16th International Symposium on Wearable Computers*. IEEE, 60–63. https://doi.org/10.1109/ISWC.2012.29

[77] Zhuoming Zhang, Robin Heron, Eric Lecolinet, Françoise Détienne, and Stéphane Safin. 2019. VisualTouch: Enhancing Affective Touch Communication with Multi-modality Stimulation. In *2019 International Conference on Multimodal Interaction*. 114–123. https://doi.org/10.1145/3340555.3353733