# SoundMorphTPU: Exploring Gesture Mapping in Deformable Interfaces for Music Interaction

Zhen Wu
Hong Kong University of Science and Technology
Hong Kong SAR
zwuch@connect.ust.hk

Ze Gao
Hong Kong University of Science and Technology & Hong Kong Polytechnic University
Hong Kong SAR
zgaoap@connect.ust.hk

Hua Xu
Hong Kong University of Science and Technology
Hong Kong SAR
epxuhua@ust.hk

Xingxing Yang
Hong Kong University of Science and Technology
Hong Kong SAR
xyangbx@connect.ust.hk

Tristan Braud*
Hong Kong University of Science and Technology
Hong Kong SAR
braudt@ust.hk

## ABSTRACT

Deformable interface is an emerging field with significant potential for use in computing applications, particularly in the design of Digital Music Instruments (DMIs). While prior works have investigated the design of gestural input for deformable interfaces and developed novel musical interactions, there remains a gap in understanding the tangible gestures as input and their corresponding output from the user's perspectives. This study explores the relationship between gestural input and the output of a deformable interface for multi-gestural music interaction. Following a pilot study to explore materials and their corresponding intuitive gestures with participants, we develop a TPU fabric interface as a probe to investigate this question in the context of musical interaction. Through user engagement with the probe as a sound control, we discovered that the input-output relationship between gestures and the sound can have meaningful implications for users' embodied interaction with the system. Our research deepens the understanding of designing deformable interfaces and their capacity to enhance embodied experiences in music interaction scenarios.

## Author Keywords

Material-Driven-Design, smart textile, sensorial interaction, musical instruments, gestures, playability.

## CCS Concepts

**•Human-centered computing → Interface design prototyping; Sound-based input / output;**

*Corresponding author of this work.



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## 1. INTRODUCTION

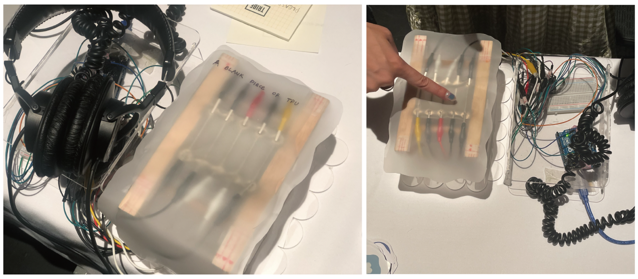

**Figure 1: SoundMorphTPU, the probe with which participants engaged during the study.**

Gestures are essential in musical interaction and expression [38, 59, 43]. Musicians utilize specific gestures to produce sound when playing traditional acoustic instruments, such as pressing a key on a piano or blowing air into a horn to convey musical intention beyond sound through their body language [12]. Digital Music Instruments (DMIs) free the artist from the acoustic relationship between gesture and sound, allowing the automation of music production through sequencers, triggers, and predefined effectors [59]. As a result, electronic music artists have developed new ways to leverage gestures during live performances, either relying on automation to detach themselves from the instrument or associating effectors with highly visual interactions [47, 48]. In the meantime, gestural interaction is essential in material-based interaction [56], with the I/O relation between user input and system output playing a vital role in shaping meaningful experiences [49, 15, 42, 54, 20].

Deformable interfaces stand at the intersection between materiality and gestural interaction, facilitating interactive experiences unattainable with rigid interface [8, 5, 3, 53]. Material-oriented thinking has inspired the design of musical interfaces, specifically deformable materials [67, 68, 53]. Fabric, as a deformable material, has been applied in designing DMIs and music performances by mapping different gestures such as stretching, pressing, touching, and grabbing to musical parameters [64, 63, 17, 39]. While existing studies show the potential of gestural inputs in providing rich interaction, how to design the output based on the input remains unclear.

To address this gap, this paper investigates the tri-modal relationship between the characteristics of deformable materials, sound generation, and gestural input for music interaction. We aim to reintroduce gesture (input)-sound (output) relationships while facilitating expressive interactions in the design of DMIs applying deformable interfaces. We formulate the following research questions to guide our investigation:

- **RQ1:** Can gestures mediated through the multi-gestural deformable interface be significantly associated with specific sound effects?
- **RQ2:** What constitutes the mapping between gestures and sound effects?
- **RQ3:** How do users perceive using a deformable interface with specific gestural (input) -sound effects (output) relationships?

We particularly explore the potential of fabric materials, which exhibit greater potential for multi-gestural sensing and application in ubiquitous computing scenarios [51, 19, 32]. We approach these research questions through a material-centric approach, relying on material probes [26]. We first conduct an exploratory workshop to establish how users intuitively associate several fabric materials with sound and gestures. We then selected one fabric material and developed a material probe using inkjet circuit printing that can sense four types of gestures elicited from the pilot study: sliding, tapping, poking, and patting. Using this probe, we conducted a user experiment with 12 participants interested in musical interaction to further explore the interactions.

This research yields the following findings:

- Although gesture-specific sound control matching could be personal, common patterns were discovered, such as sliding matched with continuous control and poking and tapping to instant control.
- Common patterns were found in how users match the material-mediated gesture with sound control. These patterns involve making analogies with real-life experience, thinking of the direction and continuity of the gesture, and imagining the sound deformation as the deformation of the material. These observations indicate the emergence of the concept of embodiment within the context of deformable interaction.
- Multi-gestural deformable interfaces offer advantages for musical interaction, including intuitiveness, learnability, and playability, and provide a richer sensory experience, with the potential for mapping richer sound parameters than rigid input methods.

These findings highlight the importance of considering the IO relation based on materiality when designing deformable interfaces for music interaction, and its relationship with the embodiment of the experience.

# 2. RELATED WORK

## 2.1 Materiality and Tangible Embodiment

The recent development of computational materials has made designers and researchers rethink the relationship between physical and digital [45]. Wiberg emphasizes the importance of materiality in interaction design and later proposes materiality as a "turn away from metaphors toward directly with and via physical materials" [61, 62]. Karana et al. propose Material Driven Design (MDD), emphasizing that materials should elicit meaningful user experiences beyond their utilitarian assessment [28]. Studies have shown that different types of material afford different types of gestures corresponding to material properties, with textures and material sensations as the key influential factors [67, 25]. In the case of music interaction, several researchers have stressed the importance of materiality, highlighting the opportunities that arise from combining physical input through materials with virtual modalities [67, 53, 37, 36]. Tangible interaction bridges physical user interfaces with cyberspace, exploring the interplay between our bodies and the materiality of objects [14, 23, 22]. Within this context, Embodied Cognition (EC) emerges as a prominent framework [55, 30], stressing the role of the body in shaping perceptual and mental processes within the interaction loops [4, 31, 11, 35, 13].

## 2.2 Deformable Interfaces in DMIs

Deformable interfaces are made of soft and malleable materials, requiring physical input to be deformed for gestural interaction that is unlikely with rigid interfaces [5, 3, 53]. The tangibility of deformable interfaces enables a more organic way for HCI, opening up the potential for gestural interaction that becomes analogous to sculpting and expressive controls [8, 5]. Material property is important, as it links with how the interface deforms, what input parameter can be introduced by that deform, what gestures can act on it, and finally, what sensing technology to use [5, 53]. A Digital Music Instrument (DMI) is characterized by having a separate gestural interface, or gestural controller, from its sound generation unit, with the two units being independent yet connected through mapping strategies [59]. Deformable interfaces have been applied to DMI design and show the application of different materials to control different musical parameters, such as rubber [1], foam [29], and clay [60]. Fabric-like material presents interesting applications, especially in multi-gestural interactions. Examples include the *Knitted Keyboard*, which employs touch, proximity, finger pressure, and arm movements [64], *ZPatch*, a hybrid resistive/capacitive eTextile input that can sense multiple gestures [51], and *Grabbing at an Angle*, a fabric interface for menu selection [19]. Several sensing techniques have been put forward to support this type of material, including knitting and weaving using electronic yarn and printing [6, 24, 46, 50, 24, 7, 16]. Moreover, the Machine Learning method can be combined with the sensing surface for training and recognizing different gestures [18]. The multi-gestural interaction observed in fabric material has inspired us to utilize such materials as the focus of our research.

## 2.3 Gesture Mapping

Gestures are intertwined with the expressive aspect of electronic musical performance, the source of excitation moments [43]. DMIs allow for empty-handed, naked, or physical contact gestures [38], with the latter being typical for instruments with a material-oriented perspective. Gesturing with physical artifacts can be more meaningful from the perspective of embodiment [54, 14, 2, 56, 27]. In the meantime, the relationship between the input and output of an interactive system is called IO relation, and mapping is a term that denotes the steps between them [49, 15, 21]. Digital Music Instrument(DMI) is an area interacting with gestural control and placing an important focus on I/O mapping [54]. Compared with acoustic instruments, DMIs free the artist from the acoustic relationship, allowing assigning new sound mapping strategies to the gestural interaction.

Given the unique properties of deformable material, previous studies have contributed to examining how it is meaningful for gesture-based interaction. Lee et al. focused on user-defined gestures for flat deformable interfaces and found that higher flexibility enhanced consensus and intuitiveness of gestures [33]. Troiano et al. investigated deformable interfaces for music performance and found a stronger bond between gestures and effects compared to rigid controllers [53]. However, they did not explore the gesture mapping of deformable interfaces allowing multi-gestural interaction. Zheng et al. studied the meaning of material properties in a musical context but focused on designing gestures rather than the IO relation [67]. This lack of exploring the I/O relationship in the deformable interface was also mentioned in [5].

## 2.4 Methods for Material Exploration

User-elicitation studies are a specific type of participatory design methodology that involves end-users in the design of gesture-sets [65, 57, 66]. For DMI design, it is applied in the study from Zheng et al. [67] and Torani et al. [53]. This method can result in gestural inputs that are conceptually simpler [40]. The *Material Probe* method, proposed by Jung and Stolterman [26], uses physical materials to prompt participants to discuss, play with material samples, and compare the material qualities of physical-digital artifacts. The *Material Speculation* method, proposed by Wakkary et al. [58], involves crafting artifacts that support and question new possibilities that contradict the world around them, encouraging reflection on materiality instead of just functionality. These materials exploration methods can be applied in investigating the design opportunities of unfamiliar sensing materials [41]. They have also been applied in previous DMI studies [53, 67] to understand deformable sensing materials and use them as a resource for design.

# 3. EXPLORATORY STUDY

The exploratory study investigates the relationship between materiality and gesture in deformable interfaces for DMIs. Specifically, it seeks to identify the primary gestures associated with different types of fabric used as deformable materials and the users' sound imagination towards the different materials. We used gestural elicitation (see Section 2.4) as the primary method in this study to gather insights and uncover the unique gestures that emerge from each material. We were also inspired by the method of material probe [26] and the method of gathering user-defined gestures without considering the sensing ability by previous a study [33].

## 3.1 Materials

Durability is a significant concern when selecting materials for sensors in deformable interfaces [24, 5]. We thus chose fabric materials that are both durable and capable of supporting various deformations. We selected five high-density and hydrophobic fabric materials similar to those used in existing multi-gesture sensing sensors [52, 16]. These materials include elastic space cotton, PU(Polyurethane) fabric, Tyvek, TPU(Thermoplastic Polyurethane) fabric, and Silky down jacket fabric. Their surface appearance and material specification are listed in Figure 2. These fabric samples were purchased from the local market for garment material. For each material, we prepared three different sizes: small (10cm x 10cm), medium (A4 size), and large (A3 size).

## 3.2 Participants

Eight participants (4 females and 4 males, aged 23 to 25 years) were invited to this study. All participants had previous experience playing musical instruments at a level self-described as amateur. In terms of their playing habits, three participants played instruments regularly every week.

## 3.3 Procedure

This study used a within-subject design. Before the experiment, participants were asked to complete a consent form and a questionnaire that collected their demographic background and previous music experience. All participants underwent five sessions, each corresponding to a set of samples of one of the five types of material provided in the three sizes. Participants were asked to perform gestures on the material samples, imagining that the gestures would be sensed and used to control sounds. Participants were encouraged to imagine and report the sounds they thought of while performing the gesture. Participants' gestures while interacting with the material samples were recorded using a webcam from the computer.

## 3.4 Analysis and Results

Figure 2 summarizes the findings observed from this material exploration study. Fabric materials used in the pilot study are placed at the top, and gestures elicited by the participants during the study are placed in the middle, followed by the description of the imagined sounds that the material can generate if it is an instrument. For the gestures and descriptions of sounds, the words appear larger, meaning higher frequencies of occurrence during the study. Some common gestures were shared among different material samples. For instance, the gesture *drag*. This gesture takes advantage of the material's elasticity, as it involves pulling the material in the horizontal direction. Additionally, we noticed that single-handed gestures were more prevalent in small and medium-sized material samples. These gestures included sliding with the palm, patting, and sliding with the finger. Overall, the exploratory demonstrates that different fabric materials may evoke different types of gestures to interact, and the feeling towards the sound produced by the fabric is also unique to the materiality. This inspired us to explore further the relationship between the applied gestures and the type of sound control in our main study.

We chose TPU fabric as the proof-of-concept material. Although other fabric samples present interesting insights, compared with the other sample, the TPU fabric is effective in being manufactured into a sensing unit, as demonstrated in a previous study(see [9, 52]). Furthermore, the TPU fabric evoked diverse gestures and elicited intriguing imagined feelings toward sound. Our investigations revealed that participants tended to poke the fabric when imagining sounds associated with raindrops. Additionally, participants engaged in patting, tapping, and sliding gestures. Participants also associated the fabric with soft sounds and sounds produced by electronic instruments. Figure 3 shows some gestures with which participants interacted with the TPU fabric during the exploratory study.

# 4. SOUNDMORPHTPU

## 4.1 Probe design and fabrication process

Our exploratory study identified several interactive gestures that can be applied to our chosen fabric materials, TPU. Although flipping and flickering are interesting, the sens-

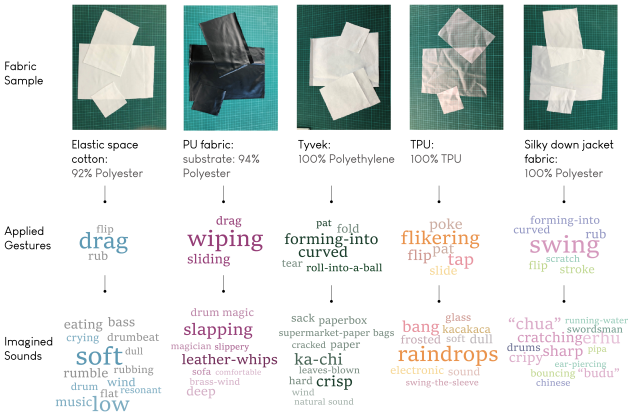


**Figure 2: Fabric material used in the exploratory study (on the top) with the corresponding name and specification, applied gestures (on the middle), and the imagined sounds observed based on the corresponding fabric (on the bottom). The words that appear larger represent a higher frequency of occurrence during the study.**


**Figure 3: Participants employed diverse gestures to interact with the TPU fabric samples, as captured in the video recordings. Beside the captures are demonstrations of the gestures.**

ing mechanism was not easy to implement and was hard for users to control. Gestures that are both easily sensed and show the deformation quality: sliding with one finger (index finger), patting, poking, and tapping were finally selected to implement. We thus developed SoundMorphTPU, a soft, thin and flat deformable interface for multi-gesture recognition, as the key material probe for our main study. To develop this material into a sensing surface, we aim to avoid compromising the original materiality of the TPU fabric by minimizing the impact of sensing unit attachment. We characterize the TPU material as flexible, transparent, lightweight, smooth, and nonporous. It is waterproof and hydrophobic, while its shape can be sustained as flat after deformation. Considering the sensing technology, applying embroidered conductive thread onto its nonporous and continuous surface is not appropriate, and attaching a conductive fabric as another layer would compromise the transparency and smoothness of this material. Islam [24] has identified wettability and surface roughness as necessary material requirements for conductive ink printing. Our TPU fabric's properties make it suitable for printing. Inspired by Gong et al.'s [16] array pattern for sensing multiple gestures, we designed a five-vertical line pattern array with two circles at the end of each line. The circle patterns facilitate the attachment of the conductor wire to the circuit. The size of our sensing pattern and the circuit diagram for its connection with the Arduino Uno board are shown in Figure 4. This pattern is similar to the pattern used in *Silver Tape* [7], further supporting the feasibility of using this pattern to sense deformation. With the five sensing units as input, we aim to apply a machine learning model to train gestures, as described in previous work [18].

We printed the conductive pattern with a programmable dispenser PC-400H with a piezoelectric nozzle PDV-8000. We programmed the pattern using the dispenser's software. We used Sicrys™ I60PM-116, a conductive ink based on single-crystal silver nanoparticles, to print the pattern and fill it in the dispenser. We stabilized the TPU fabric with an embroidery hoop and tape during the printing process (see Figure 5). We repeated the printing process twice to ensure conductivity and then cured the printed ink in a chamber at 85 degrees Celsius for 30 minutes. After confirming the conductivity of the printed patterns, we connected the ends of each pattern link with crocodile clips. We constructed it into a circuit linked with an Arduino Uno board. The deformation of each sensing pattern results in continuous changes in the input pin's analogue values. When the printed pattern is deformed, its resistance and the analogue value output in Arduino IDE change. We first tested the analogue signal changes of each pattern using visualizers, as shown in Figure 6; the deformation of each unit is distinguishable. After that, we link the signal input to Wekinator [1], an open-source software for using machine learning to train different gestures. Figure 7 shows the four gestures we aimed to sense through the SoundMorphTPU. The researcher who developed the prototype trained these gestures in Wekinator until they could be successfully differentiated from each other. To protect our printing pattern when interacting with it, we placed another TPU fabric above the sensing unit. Figure 8 shows the final printed pattern on TPU fabric and the constructed SoundMorphTPU.

## 4.2 Software and Sound Design

We connected SoundMorphTPU with Wekinator for gesture recognition. We pre-trained the four tested gestures and a

[1] http://www.wekinator.org/

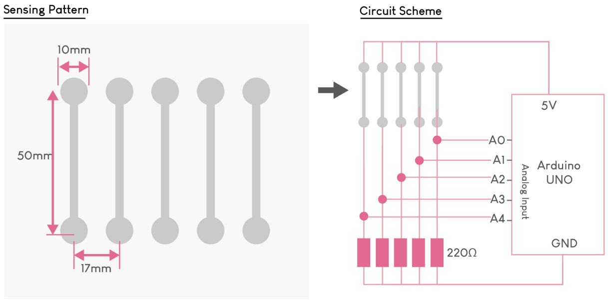


**Figure 4: The Sensing Pattern and Circuit Scheme of SoundMorphTPU consists of units with two circles placed at the beginning and end of a line, each having a diameter of 10mm. The distance between each unit is 17mm.**

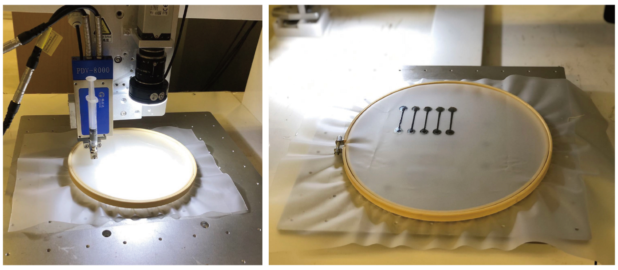

**Figure 5: A programmable dispenser was used to perform the conductive pattern printing process. To maintain a flat surface during the printing, we placed the TPU material on an embroidery hoop.**

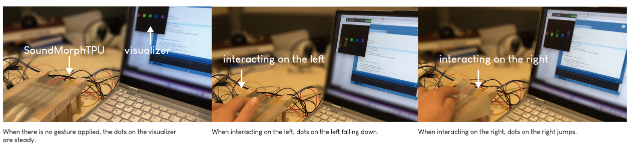


**Figure 6: The usability of SoundMorphTPU in sensing actions applied to different conductive units was tested, and the force exerted during the interactions was visualized using the Processing programming language.**

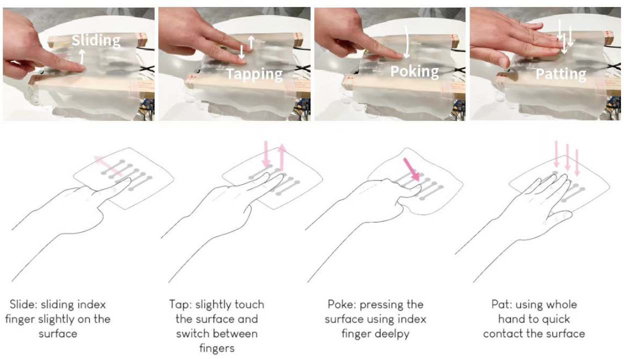


**Figure 7: The Four Gestural Inputs of SoundMorphTPU, including sliding with the index finger, tapping with two fingers, poking with the index finger, and patting.**

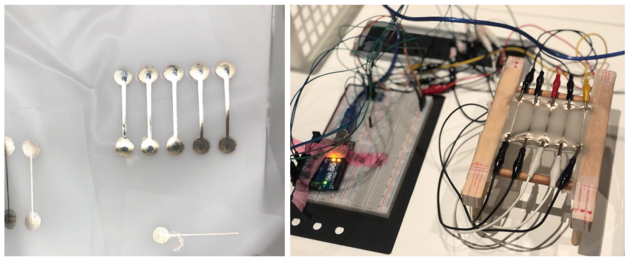

**Figure 8: Final printed pattern on TPU fabric, which was constructed and linked with an Arduino Uno board to create the SoundMorphTPU system.**

no-gesture status before the study. We linked Wekinator with MaxMsp [2] via Processing [3] as a signal transmitter to trigger different sound effectors. We select six effectors, *pitchshifting* (in our example, shifting the sound sample in a higher tone), *reverb*, *flanger*, *chorus*, *EQ filter* (in our example a high pass filter) and *delay* and programmed them in MaxMsp.

To evaluate the sound control, we included five samples based on the sound feeling towards the material in the previous exploratory study (Section 3), including a sine wave, a drum playing sample, a jazz music piece, a piano loop, and an electronic sound loop, which we produced using Garageband [4]. A counter was set to ensure the effect remains active for four seconds after the effector is successfully triggered. For reverb, we set a fade in and fade out lasting eight seconds to avoid sudden trigger effects. Figure 9 shows the Max Patch in the programming view and the presentation interface. In the presentation interface, the participants could interact with different samples from the list to try the corresponding effects triggered by gestures.

## 5. MAIN STUDY

The main study investigated the relationship between interactive gestures of deformable interface and music control using SoundMorphTPU as the material probe. Specifically, we aimed to explore (1) Whether certain gestures mediated through the material can be significantly associated with sound control. (2) What constitutes the mapping between gestures and sound effects? and (3) How do users perceive using a deformable interface with specific gestural (input) -sound effects (output) relationships? We focused on typical sound effects that are essential elements for electronic music, building upon previous studies that have indicated that deformations are commonly employed to modulate or apply effects to sounds [53].

### *5.0.1 Study Setup*

Figure 10 shows the setup of the study. The studies were conducted in a quiet environment, and we provided headsets for participants to listen to the samples. SoundMorphTPU was connected to a laptop, and the necessary software was installed. Participants sat on a chair beside SoundMorphTPU and used various gestures to control the sound. We also placed a traditional music controller, Launchpad [5], near the participants to facilitate discussion after the gesture-matching activities.

[2]https://cycling74.com/products/max
[3]https://processing.org/
[4]https://www.apple.com/mac/garageband/
[5]https://novationmusic.com/launch


**Figure 9: Interface in MaxMsp for the Six Effects. Left: the patches constituting the effects. Right: the presentation interface for the participants to select sound control and samples.**

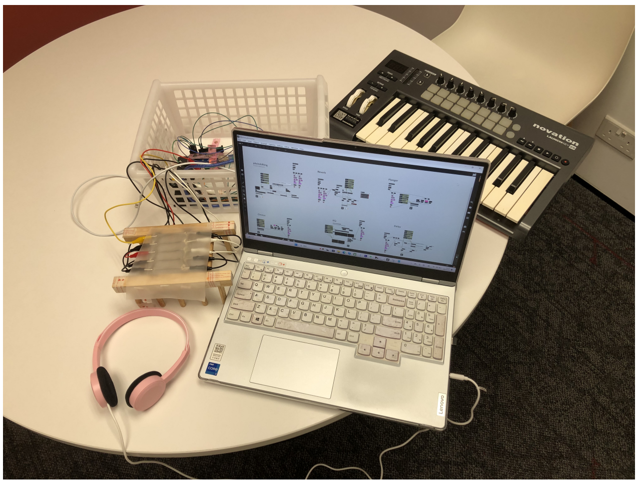


**Figure 10: Demonstration of the study setup, including experimental hardware and equipment.**

## 5.1 Study Design and Procedure

The study design is a combination of quantitative measurement and interviews. We used a within-subject experimental design where all participants tried four conditions: sliding, tapping, poking, and patting, which are the independent variables for gestural inputs. The presence of these conditions was counterbalanced among participants. The matched sound effects, including six variables (pitch shifting, reverb, flanger, chorus, EQ filter, and delay), were the dependent variables investigated. After completing the gestural input-sound effects matching tasks, we interviewed the participants to gather qualitative data on their experiences.

Initially, participants were asked to complete a consent form and a demographic questionnaire, which included age, gender, country, and profession. They also answered questions about their previous music experience and favourite music styles. Next, we introduced the study objectives and digital music controller for electronic music. To facilitate understanding, we presented the Novation Launchpad [6] as an example. Participants were introduced to the six effects and asked to wear the headset to try the different sound effects using the MaxMsp interface. Once familiar with the sound effects, participants proceeded to the first condition. The researcher first demonstrated the first gesture on SoundMorphTPU, after which participants used this gesture on SoundMorphTPU to trigger the effects. Participants could freely choose sound samples within each effect group and apply the studied gesture to the fabric surface to produce a corresponding sound effect. After trying all the effects, participants were asked to select an effect they thought fit the gestural input the most (**Q1**) and indicate their confidence level on a 5-point scale (**Q2**). Next, the researcher conducted a short open-ended interview to explore the reasons behind participants' choices and detailed thoughts on the gesture. Participants then moved on to the following condition to explore another gesture. After completing all conditions, the researcher conducted a further open-ended interview to gather participants' perceptions of using this deformable interface as input for music control and the differences between this method and existing music controllers. The study took approximately 30 minutes per participant.

## 5.2 Participants

We invited twelve participants, mainly students and researchers in human-computer interaction who had an interest in musical interaction, to participate in our study. Different from previous studies [67, 68, 53], we did not limit the participants to musicians or DMI designers. Participants were recruited from institutional recruitment and exhibition venues. There are nine females and three males ($25 \pm 1.25$ years, ranging from 21 to 38 years). All participants had to fill in the ethics and consent forms before participating in the study.

## 5.3 Data Collection and Analysis

We used Qualtrics [7] to record and manage participants' answers. We calculate the frequency of each choice from **Q1** and the rating data distribution of **Q2**. For the results obtained from the interview, the researchers transcribed the recorded audio into notes. Then, several Affinity Diagrams [34, 44] were built using an online whiteboard tool,

[6]https://novationmusic.com/launch
[7]https://www.qualtrics.com/

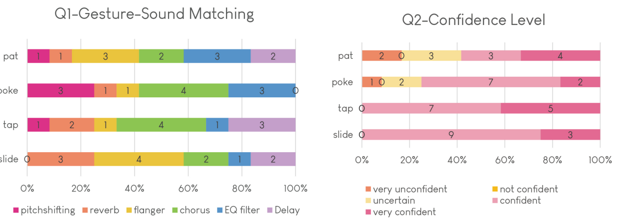


**Figure 11: Matching Level and Confidence Level Diagram**

Miro [8] to conduct basic coding of the answers and summarize topics originating from them.

# 6. FINDINGS

## 6.1 Gesture-sound Effects Matching

As for the gesture-sound matching (**Q1**), for patting, the most selected sound effectors (3 times) are the flanger and EQ filter (3 times). For poking, the chorus was selected the most (4 times), as the same case for tapping (4 times). For sliding, flangers were selected the most(4 times). For the confidence level, tapping reaches the highest confidence level in matching with sound effectors ($M = 4.417, SD = 0.493$), and sliding is the second ($M = 4.250, SD = 0.433$). As shown in Figure 11, most participants were confident or very confident about the matching in these two conditions.

## 6.2 Perception of Gesture

The affinity diagram analysis identified several topics and common grounds from participants' thoughts about the gestures. We present the findings for different gestures. Figure 12 provides a simplified version of the affinity diagrams.

### 6.2.1 *Sliding*

When trying to control sound effects by sliding, some participants made analogies with real-life scenarios or nature. Four participants thought of water (P1, P2, P7, P8). P7 chose "chorus" and commented that interacting with the material is like "running your hand through the ripples". P2 chose "reverb" and also thought of water ripple. P12 chose "reverb" and described the gesture as "pushing the airflow". P11 described the match with 'delay' as "sliding appears similarly to trying to remove dust from the surface of an object, equivalent to the delay sound effect of bouncing the last few notes back". Five participants emphasized sliding as a directional gesture and would think of directional sound effects (P1, P2, P6, P8, P9). P9 said: "I chose 'reverb' because the sound is like moving from the side close to me to the side away from me, corresponding to the directional gestures I make". Some participants associated sliding with continuous sound effects like "reverb" because of the perceived similarity between the "continuous nature of the sliding gestures and the continuous quality of the sound effect" (P10).

### 6.2.2 *Tapping*

The most common thinking about this gesture is its instant nature, and four participants (P1, P2, P3, P10) thought that it should be matched with instant changes of the sound as "dots like (P10)" effectors. P2 chose the *EQ filter* as "it provides me a feeling of start and stop, instant, 'on' effect". In addition, three participants mentioned that the tapping gesture gave them a strong sense of how the sound changed through the movement of their fingers (P6, P7, P9). P7 described his feeling as "adding new tracks through the finger, and is like cell sorting". Two participants mentioned the gesture as "rush and messing up" and chose the effector based on this. P11 chose *flanger* since it "produces a messy feeling". When attempting to trigger sound effectors through tapping, some participants envisioned how the gesture would physically and tangibly transform the sound. For instance, P2 provided an example: "The 'delay' effect is like repeating the sounds, and tapping on the sound frequently may produce this effect."

### 6.2.3 *Poking*

Like sliding, poking on the fabric-like surface also shows a connection with other scenarios. Analogies with switch buttons were most common in the associations, and participants chose sound effects associated with switches (P1, P4, P10). P1 commented, "This gesture gives me a feeling of pushing a button, and it is temporal, one time, fitting the changes of sound by the *EQ filter*". Three participants reported that the feeling of sound effects corresponding to this gesture should be instant, which will disappear after release. P2 said, "Keep poking means turning the effector on", and P4 said, "This gesture does not have the feeling of slow changes". Another interesting finding is that three participants mentioned they think of poking people (P6, P9, P11) and that people produce funny sounds, which is the effect of *pitch-shifting* and *flanger*. P6 chose *pitch-shifting* and said, "It is like a person singing, and I poke him, then he changes the tone". Thinking of movement exert on sound inspired three participants (P8, P2, P5). P8 commented, "like the sound was jumping when I used poking. The sound seemed to mimic my hand gesture". P2 chose *pitch-shifting* as "a feeling of pressing on the sound and making it deform, very intuitive with poking".

### 6.2.4 *Patting*

The most apparent finding for the sound effects matching with patting was the analogy between interacting with the fabric surface and other things. This includes patting on a ball and making some bouncing sounds(P4, P6), covering the sound with something to filter out some noise (P1, P11) and analogizing it with existing musical tools like patting on cowbells or triangle irons (P5). The idea of sound deformation also came up. P7 chose *pitch-shifting* and felt like "patting on the sound and the notes shows distortion". P12 chose *EQ filter* since it felt like "pressing on sound and some part of the sound is filtered out".

## 6.3 Perceptions of multi-gestural deformable interface for Sound Control

Four main common topics were identified through the interview questions about using a multi-gesture deformable interface as input for music control.

### 6.3.1 *Perceived Advantages*

Two participants (P1, P2) considered the TPU material deformable and can be changed into different shapes, such as clothing or carpet. P2 proposed a carpet that can use feet to control music. They also mentioned that the TPU material can be placed above other stuff or as "another layer

[8] https://miro.com/

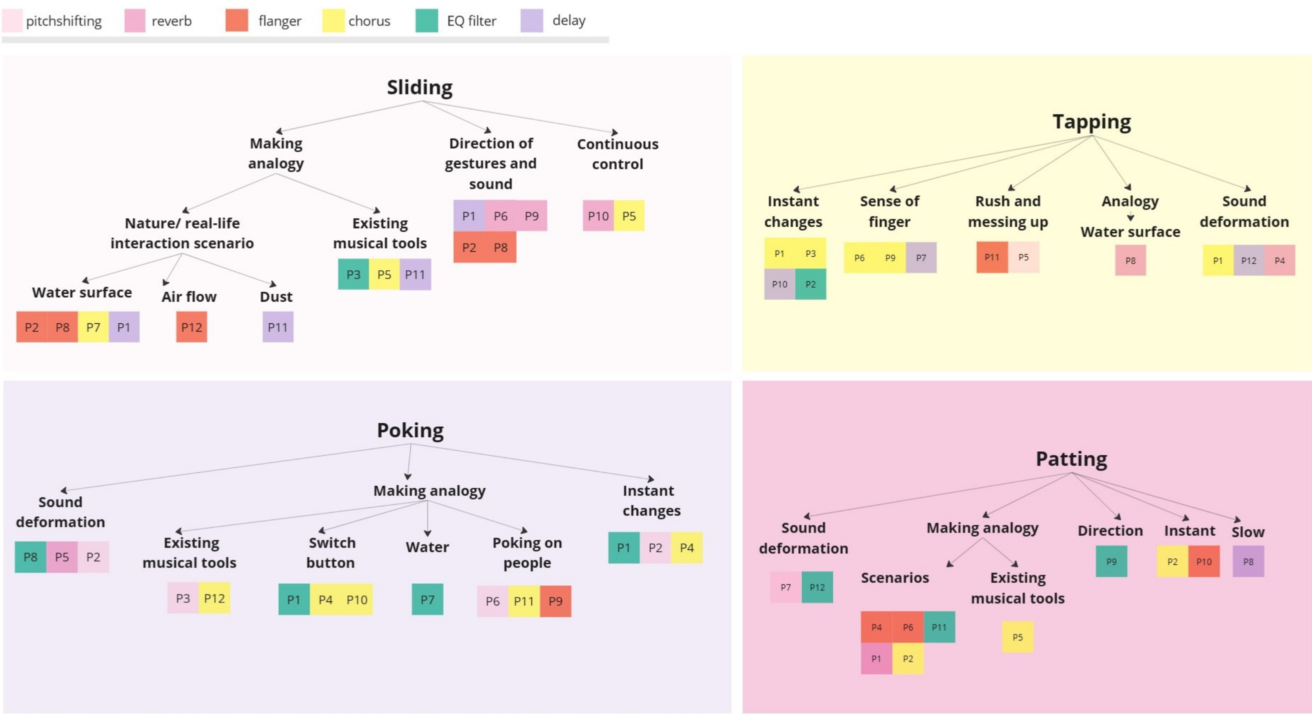


**Figure 12: Gesture-related data collection**

of an existing instrument" (P1). Compared with a rigid music controller, it is portable and flexible (P2) and can be placed at different room corners (P1).

#### 6.3.2 Intuitiveness and Playability

Four participants mentioned that deformable-based input is simple and easy to use. Beginners interested in electronic music wanted to use this probe to explore and experiment with sounds (P4, P6, P8. P9). P8 mentioned that deformable-based input is "more exploratory, more experimental, more creative for beginner, and I would prefer this deformable-based method". P8 also complained about the complexity of the existing music controller and synthesizer, as "they are limited in small interface and tiny buttons". Participant 4 discussed LaunchPad as "very complex compared with deformable input" and preferred to "control different sound effects using a simple interface". They also saw the deformable-based input as "free-minded and flexible for playing". When grasping the gesture, participants anticipate they can "play it without looking it—like the Touch Typing when using the computer" (P5). P4 also mentioned playability as "the deformable-based input method makes me more willing to play it and trigger my feeling of exploration".

#### 6.3.3 Richer Sensory Experience

Participants thought the deformable-based input method triggered their desire to pay close attention to the sound. P6 said, "I will guess and think about whether sound effects are being triggered, which requires me to listen closely". P11 mentioned that "the deformable-based input provides a stronger sense of connection and creates heavier emphasis on the senses of hearing and interaction". Participants also described the deformable-based input as exploratory, sensory, triggering exploration, and "more natural to human skin" (P11).

#### 6.3.4 Controlling Richer Sound Parameters

The last type of finding is the potential for richer gestural control away from the current gestures of SoundMorphTPU. P7 suggested that the TPU fabric surface can provide non-mechanical deformation and potentially use a 3-dimensional variable (x,y,z) to change sound. Strength, direction, distance, and speed can influence the sound. P11 thought that a deformable interface controller could be more interesting than a traditional music controller. It can utilize more subtle gestures, such as soft touch, caressing, or sliding. However, P11 was doubtful at sensing technology to differentiate between soft and hard gestures, but it would be "amazing" if it did. P11 and P1 proposed the same further gestures as drawing soft gestures (e.g., simple shapes such as circles) on the deformable surface as an interesting input. Moreover, P11 expressed his wish for more continuous input beyond the *on/off* effects, such as the finger's location, which can be sensed to control detailed intensity.

## 7. DISCUSSION

This section discusses the emerging themes from the study and summarizes their design implications and future research directions.

### 7.1 Gestures-Sound Mapping

While the choice of effects for each gesture varied among individuals in our study, further interviews revealed common themes. We identified several patterns across the perceptions of different gesture-sound effects matchings that supported the reasons for participants' choices and provided insights into their further thoughts about the gestures.

#### 7.1.1 Sound Association Based on Analogy

In this study, all four gestures have answers based on an analogy with other things. These include: (1) Considering the deformable surface with other substances such as water and airflow and interacting with them through gestures. (2) Think of the same gestures utilized in existing musical tools that they have experienced and choose a sound effector based on that. (3) Thinking of real-life scenarios, such as poking a person or putting off dust. Our findings are consistent with Troiano et al.'s study [53], which found that deformable interfaces embody the parameters of the musician's control. The thinking observed in our study, based on established experience, is also similar to the study by Zheng et al. [67], which investigated the materiality of different deformable materials. In their study, eight participants suggested that the interaction implication of the material for music context mainly came from their previous experience with existing interfaces. Similarly, in Troiano et al.'s study, six participants twisted an object to control sound effects and reported their inspiration from previous experience with knobs embedded in synthesizers and MIDI controllers [53]. The analogy of the material surface and the speculation of real-life scenarios based on performing the gestures corresponds to the material-oriented thinking in interaction design introduced in Section 2.1. Participants felt the gestural interaction with the deformable interface, generating imaginations away from the musical concept, and then linked it with the sound feeling. Relating music interaction to scenarios outside of the musical field has rarely been mentioned in previous studies. Introducing specific gestures in the material exploration may lead to more divergent speculations. In an interactive tactile-sonic artwork [39], the author also utilizes the imaginative stories and emotional aspects of the gestural interaction with textiles as inspiration. Our findings can provide some empirical support to this art-making approach.

#### 7.1.2 Thinking of Sound Deformation

Many participants in our study imagine that sound has a physical form and use gestures to transform it, a pattern similar to the "thinking from material to sonic response" found in Zheng et al.'s study [67]. In their study, the participants' thinking of sonic response was linked with material properties such as texture and rigidity. Troiano et al.'s study [53] also revealed mappings of physical properties of the material related to music, such as shape-retaining material to dynamic changes of sound parameters. In contrast, our study presents the idea of thinking from the gestural influence of sound, where sound is considered a material morphed by the gesture.

#### 7.1.3 Instant or Continuous

Comparing answers from different gestures, the descriptions of "instant" and "continuous" appear frequently and point to specific gestures. For sliding, the sound change was thought to be continuous, and tapping and poking were mentioned as instant control. Troiano et al. [53] discovered that participants tended to use simple surface contact to generate sounds and object deformation to modulate or apply effects to sounds. Zhang et al. [67] also mentioned the apparent deformation-continuous control matching. These can further support our findings on instant and continuous control. These previous findings may indicate that the difference between instant and continuous may have a close relationship with whether the gesture will cause obvious deformation on the TPU surface.

### 7.2 Perceived Benefits

Another important aspect of this study is finding the perceived benefits of fabric-like deformable interfaces for multi-gestural music control and its potential. Our study's deformable input method is an intuitive design for electronic music beginners. Rigid input systems such as MIDI control offer diverse gestural interaction but are regarded as hard to learn and remember by our participants. In contrast, deformation-based input is viewed as attractive, easy, and intuitive by participants who were beginners in electronic music, and they showed high interest in using it in the future. Participants also pointed out that gesture-sound control can be remembered more easily. The intuitiveness and embodiment are also mentioned in previous studies in deformable interface [67, 53]. However, since this last study was conducted among DMI designers and musicians, the value of establishing interest in electronic music for beginners was not discussed. Moreover, Cibrian et al. [10] have applied fabric-based interactive surfaces, playing piano sounds to support early classroom development. This further proposes the potential of using deformation-based music control for users who are not music experts. Another benefit is that deformation-based input can provide a richer sensory experience. This echoes the materiality aspect and its application in expressive performance.

Deformable interface-based input shows great potential. Firstly, it has the potential to be developed into other formats, such as garments and carpets, or placed over other stuff to have an add-on function. Secondly, the flexibility of fabric-like deformable interfaces in their ability to be deformed dynamically can be used to map richer and more complex musical parameters. However, concerns about affordance and whether the technology is feasible were also raised.

### 7.3 Limitations and Future Directions

The first limitation is our proposed study probe. The technology of printed sensors lacks maturity. As the worries raised by one of our participants, although continuous and precise control is interesting, the sensing technologies may be a problem. Our current prototype is limited in recognizing certain types of gestures, and whether the direction and intensity of gestures can be sensed needs to be explored.

Future research could explore several avenues in deformable fabric-like interfaces as sensorial interfaces for controlling musical instruments through gesture-based input. Firstly, using material-driven design to inspire new musical interfaces could be investigated, along with how specific gestures mediated by a particular material, such as silicone or rubber, can vary in sound control. Additionally, the potential for combining multiple materials in the design of digital music instruments to create more complex and nuanced gestural interactions could be explored. Secondly, the potential of a deformable flat interface for controlling richer sound parameters could be studied, as well as the use of machine learning and other sensing technologies to enable a deformable flat interface to sense different gestures. This could lead to the creation of more sophisticated musical instruments that provide a greater degree of control over sound. Furthermore, deformable flat interfaces in other domains beyond music, such as gaming or healthcare, could be explored to determine the potential of material-driven design in these areas. This could lead to developing new types of interfaces for various applications that prioritize playability and rich gestural interaction.

## 8. CONCLUSION

This research explores the relationship between input and output in deformable interfaces, focusing on gestural input and sound output in the design of digital music instruments. This study examines common patterns that emerge from user-centred studies by utilizing a deformable material, TPU, and transforming it into a deformable interface capable of sensing multiple gestures. These patterns involve drawing analogies from real-life experiences, considering gesture direction and continuity, and imagining sound deformation as a reflection of material deformation. These observations highlight the concept of embodiment within the context of deformable interaction. Additionally, the study reveals the advantages of multi-gestural deformable interfaces in musical interaction, including intuitiveness, learnability, playability, and a richer sensory experience. Such interfaces also enable the mapping of diverse sound parameters compared to rigid input methods. These findings emphasize the importance of considering the input-output relationship when designing deformable interfaces to facilitate meaningful and immersive gestural interactions.

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## 10. ETHICAL STATEMENT

All individuals who participated in our evaluation voluntarily did so. Prior to participating in the study, we informed the participants of the purpose of the study and obtained their informed consent, ensuring their understanding of the procedures involved. No individuals under the age of 18 were included in the study.

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