Material Matters: Exploring Materiality in Digital Musical Instruments Design

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ABSTRACT

Research on the design of Digital Musical Instruments (DMIs) has highlighted the importance of musical gestures and embodied interaction in DMI design. However, this research often focuses on technical and sonic factors of design, with less attention on how materials influence the design process and DMI design idea generation. To address this gap, this paper explores materiality in DMIs design through a material probe approach with deformable materials. This paper reports on a study with fifteen DMI designers investigating the evoked meaning of material properties in a musical context beyond their digital interactivity. Results suggest that material properties inspired participants' design thinking, and there was a strong connection between tactility and imagined sound production. We also reported the patterns of gestural interaction of deformable materials in DMIs. We reflect on these results to report lessons learned that could inform interactive systems' material design within and beyond the musical domain.

CCS CONCEPTS

• **Human-centered computing → Activity centered design**; *Interaction design theory, concepts and paradigms*; HCI theory, concepts and models.

KEYWORDS

Materiality, Embodiment, Musical Instruments design, HCI

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1 INTRODUCTION

Digital Musical Instruments (DMIs) are musical instruments consisting of a physical interface (also called control surface or gestural controller) and computer-based sound and feedback synthesis system [2, 6, 47, 49, 52, 69]. Sensors from the control surface measure a person's gestures and interaction, and these values are mapped to sound synthesis algorithms [49]. As Human-Computer Interaction (HCI) and computational technology, in general, become more tangible, research on the materiality of DMI physical interface design has also gained more attention [37, 46, 55]. This raises physical interface design questions for DMI design, including how to seamlessly "combine physical and digital qualities in computational materials" and how to create new aesthetic qualities (i.e., affective, embodied, and meaningful) of DMIs [24, 37, 38]. Indeed, musicians' expectations of the gestural and sonic interaction of an instrument are fundamentally linked to its material properties [55]. However, the role of materiality in DMI design has been underexplored compared to technology-oriented research such as research on sensing technology, audio modulation techniques, and synthesis algorithms [44, 46, 49]. To contribute to this area, we explore the materiality of deformable materials (i.e. non-rigid materials) and interfaces which offer the potential for novel interaction design using gestures that are not possible with rigid interfaces, such as stretching, twisting, and squeezing [65].

DMI designers and researchers have explored the use of non-rigid materials in musical instruments, and interfaces [4, 12, 26, 34, 42, 48]. Previous research indicated musicians' affirmations and expectations on deformable DMI [5, 65], but the material properties of deformable DMIs are underexplored. Similarly, exploring the evoked meaning of those materials in DMI design apart from their digital interactivity has been under explored.

This paper presents a study investigating materiality in digital musical instruments design, focusing specifically on deformable materials as they offer underexplored opportunities for physical interface design and materiality research. We take a step back from pre-made objects to focus on the materials themselves and ask *How do DMI designers explore and question possible and preferable futures of deformable DMIs through material probe?* To explore this question, we firstly review how materiality and materials have been considered in HCI research and DMI design. Then we present the method and results of a study with three aims: 1) To understand how DMI designers perceive material qualities in general and in the DMI context, 2) to investigate how they interpret the properties of the materials and interact with deformable materials in the musical context, and 3) to analyse their understanding and expectation of materials in DMI design. Finally, we discuss our findings and conclude the paper.

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2 BACKGROUND

2.1 Materiality in HCI

Tangible interaction encompasses a wide range of systems and interfaces from a variety of disciplines [28]. Definitions of tangible interaction vary, but all share the following characteristics: tangibility and materiality, "physical embodiment of data", "embodied interaction and bodily movement", and "embeddedness in real space" [7, 10, 15, 66]. Moreover, understanding the relationship between the physical and digital is a fundamental concern for materials within the context of computing and interaction design [16, 41, 58, 67, 71]. The materials that a tangible interface is constructed from containing massive amounts of information [1, 17, 18, 27, 30, 59]. Fuchsberger et al. state "materiality as the theoretical discourse about materials", which includes all "illustrations and discussions of materials in HCI" [17]. For example, Wiberg systematically reviewed material-centered interaction design methods for materiality [71], and Gross et al. presented three views on materiality in HCI, which included the physical materials (TUIs), computation as material, and craft materials (as tradition communicating) [22]. The above perspectives have "shifted our focus among physical, metaphysical, and communicative dimensions of materiality" [22].

Related work shows that materiality significantly affects the way that digital artefacts are designed and experienced beyond their look and feel [37]. Meanwhile, it shows the potential of a material-driven design approach, focusing on the materiality of an interface rather than taking a functional requirements approach [53, 71]. In this context, we are particularly interested in how design approaches and practices develop in the material exploration and material-led design experience.

2.2 Materials and Tactile Interaction in DMI design

Digital Musical Instruments (DMIs) are musical instruments consisting of a physical interface (also called control surface or gestural controller) and computer-based sound and feedback synthesis system [47, 49, 52]. Sensors from the control surface measure user's gestures and interactions, and then the values are mapped to sound synthesis algorithms [49]. The synthesis system and physical interface are separate in such types of instruments, which offers possibilities for physical interface design. However, in a DMI, the sound comes from speakers, and detailed feedback like the vibration is lost. Thus, research on the design of physical interfaces for DMIs and how to create tactile feedback has been gaining attention [19, 32, 46].

Without the constraints of the physical design and fabrication in acoustic instruments, DMI allows more freedom for designers regarding the connection between gestural input and sound output [50, 60]. The mapping strategies are believed as the essence of DMI, and how to make mappings between tactile interactions and the sound is a critical aspect of DMI design [12, 29]. Previous research finds that the tactile interactions and the materiality of DMIs provide clues to the design and performance of their sound. Pigrem and McPherson find that when musicians play non-functional mock-up instruments, their gestures and imagined sound of the instrument will be different in response to its material properties [55]. Mice and McPherson also discuss that a DMI's sound and function are linked to musicians' understanding of materiality [51]. Leitman et al. mention that the materiality of an instrument provides users tactile feedback, which allows them to be more willing to play with it [44].

The above literature shows that it is clear that materiality is worth to be considered when designing DMIs. Whereas directing the DMI designers' attention to materials at early design stages to investigate the role of materiality in the design process is underexplored. Instead of focusing on new interactions enabled by technological advances, we intend to explore the tactile interactions in DMI by rethinking the materials. Existing research has explored one aspect of this question [55]. However, we wanted to free designers from 'pre-built DMIs' to think about the possibilities of materials in DMI design in a more open context.

2.3 Materiality in Deformable DMIs

Human-Computer Interaction (HCI) research has moved beyond concerns of rigid interaction devices to explore deformable materials (i.e. non-rigid materials) and interfaces, such as new interactive paradigms, materials study, and control possibilities [4, 13, 26, 48, 56, 57, 62]. Music is an ideal domain to explore deformable interface design as they offer a wide range of gestural interaction [65] which may be exploited in music-making and performance practice. One perspective of DMI design is concerned with designing gestures [11, 29, 35, 49, 69]. Troiano et al. [65] investigated deformable gestures in musical performance and found that musicians have some common understandings of deformable gestures in performing music. For example, it was suggested that musicians find squeeze and stretch related to volume and pitch, and twist could be regarded as distortion in music [65].

In the New Interfaces for Musical Expression (NIME) community, some designers and researchers try to make use of deformable materials in their design as these materials offer support for rich gestures and movements in interaction [13, 26, 48]. In this context, deformable interfaces need to be easily controlled while resisting extreme deformation, meaning that the materials used need to be robust and flexible [61, 72]. For example, foam is soft, rugged and offers deformations including push and squeeze [20, 34, 42, 48]. Fabric is softer and more elastic than foam and affords stretching, but long-time use of fabric may cause wear due to the weak abrasion resistance [12, 45, 70]. However, it should be noted that the use of these materials in DMI design has mainly been reported as design results, with little research on how DMI designers understand the deformable materials in a musical context.

In other words, whilst deformable interfaces have become a research area in HCI [57], it is unclear how DMI designers design with different deformable materials and how different material properties influence DMI design practice. This is partly because most previous research focused on technical strategies such as mapping strategies and sensing techniques, resulting in a lack of explorations of how people design physical interactions based on deformable interfaces' materiality [3].

2.4 Research through a Material Lens

Researchers have investigated how to conduct material explorations in HCI and design research [16, 18, 63, 64], with one direction focussing on how to bring material considerations into HCI design activities [23, 67, 71]. One particular method is the material-driven design (MDD) method [40] which includes, on the one hand, designers framing design concepts based on their understandings of the materials and, on the other hand materializing the conceptual ideas through material design. When designing with material from this perspective, a thorough understanding of the material is necessary to discover its unique qualities [21, 53].

The *Material Probe* approach presented by Jung and Stolterman consists of three parts [37], where participants are asked 1) to tell stories about material qualities based on their memories, 2) to interact with material samples, and 3) to compare and contrast the material qualities to their experience with digital artefacts. *Material Probe* method aims to understand how people perceive material qualities and to discuss how designers could "intentionally and methodologically" include desires related to material qualities in the design of digital artefacts [37].

3 METHODOLOGY

To explore the role of materiality in DMIs design, we structured a study that combined Material Probe and Material Speculation approaches – exploring and questioning the possible and preferable futures of DMIs [37, 68]. This study takes deformable DMIs as a specific domain of material design with a high potential for novel design.

We loosely structured our study following *Material Probe* approach and questions to guide participants to focus on the wholeness of the material in the first part and then invited participants to generate speculative or hypothetical instruments based on the materials after playing with the materials. Participants were then encouraged to talk about their previous DMI design experience in relation to the materials and views on deformable DMIs in general.

3.1 Materials

We made five types of non-rigid materials for participants to use in this study (see Figure 1), which include fabric, foam in low density (softer), foam in high density (more rigid), rubber, and copper. The materials samples were made in two categories: raw material (i.e. on its own) and constructed material combinations. The selection of materials was informed by: (1) these are the most commonly used deformable materials in DMIs design [65]; (2) the materials can provide the most frequently used gestures from previous studies [4]; (3) all the material samples were conductive or constructed with conductive material, which could be used in functional sensor making.

3.2 Procedure

As the study took place during a period of lockdown in which in-person social interaction was heavily restricted, we structured our study to take place remotely, with participants taking part on their own and in their homes. Participants were connected to the facilitator using Zoom video-conferencing software. The study lasted between 30 and 50 minutes. Before the study, participants were sent

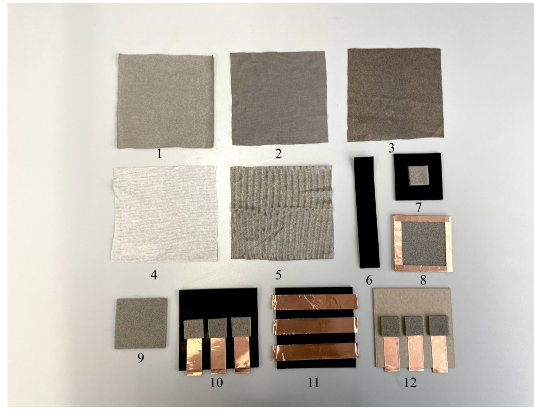


Figure 1: Material Samples (N1-5: fabric; N6: rubber; N7: rubber and foam; N8,N9: foam in different density; N10: rubber, foam, copper tape; N11: rubber, copper tape; N12: cardboard, foam, copper tape)

the materials detailed in Figure 1 by post. Participants signed a consent form and were informed that they could drop out at any time and that the institution's ethics policies were followed. They then completed a pre-study questionnaire to collect information about their musical ability, design experience, and technical experience.

At the start of the study, participants were asked to place all the material samples randomly on their desks. As outlined below, the facilitator led the study activity structured in three parts. A semi-structured interview followed this. As noted at the start of this section, the procedure and questions are based on Jung and Stolterman's Material probe approach (2010) and Wiberg's methodology for material interaction design research [71].

3.2.1 Part 1: Familiarisation. The first part of the study is loosely described as *Talk about the initial impression of the material samples.* For example, participants were asked to discuss their initial impression of the material samples by selecting their most liked and least liked ones without overthinking. Then, participants were asked to talk about their ideas about the material samples in a musical context.

3.2.2 Part 2: Interaction and Interpretation. The second part is loosely *Play with material samples* inspired by the material probe approach. The facilitator gave participants a brief introduction to all the material samples and invited them to interact with each material sample. Then, participants were invited to give more details of their ideas on using the materials in DMI design by generating speculative or hypothetical instruments based on the materials.

3.2.3 Part 3: Compare and Contrast. The third part is *Compare and contrast to other DMIs* which aimed to investigate how people interpret their previous DMI design experience in relation to the materials and how they compare and contrast deformable materials to rigid materials. At the end of the study, the facilitator invited participants to talk about their design expectations of deformable materials in general and the potential challenges of using them in DMI design in an open discussion.

Participant	Age	Gender	Country	Years of Experience	DMIs Built
P1	29	M	China	3-5 years	more than 20
P2	31	F	China	1 year	2
P3	23	M	China	2 years	3
P4	27	M	China	2 years	5
P5	29	F	China	2 years	3
P6	36	F	China	1 year	1
P7	23	M	China	0.5 year	1
P8	33	F	UK	3-5 years	3
P9	28	F	Turkey	1 year	3
P10	32	M	Ireland	2 years	1
P11	30	M	Italy	2 years	3
P12	31	M	Germany	3-5 years	5
P13	33	M	Chile	3-5 years	4
P14	39	F	Australia	3-5 years	6
P15	45	M	UK	6-9 years	more than 10

Table 1: Participants' demographic background (Years of experience: how many years of experience they have on DMI design; DMIs built: how many DMIs they have been built.)

3.3 Participants

Participants were recruited using academic mailing lists and the researcher's social networks. Participants were recruited in two groups, the first group (N=7) was recruited from China, and the second group (N=8) was recruited in the UK. Both groups followed the same study methodology as described above. All participants from the first group come from China, and the demographic information of participants from the second group can be found in Table 1. The interviews were conducted in Chinese for group 1 and in English for group 2, which allowed participants to express themselves fluently. Table 1 summarises participants' background in DMI design as collected in the pre-study questionnaire. All participants had an experience of making music with DMIs. Fifteen participants had built 1 to more than 20 DMIs (mean 4.86).

3.4 Data Analysis

The study sessions were audio and video recorded and transcribed to facilitate thematic analysis. Data analysis included the analysis of video observations (i.e. what gestures people used to interact with each material sample) and the interview feedback. We followed the guidance of thematic analysis and conducted an inductive (bottom-up) thematic analysis approach to extract participants' ideas about the interpretation of deformable material in DMI [8]. A data-driven approach avoids any preliminary assumptions about the participants' design process. Following the step-by-step guide with six phases of analysis, the analysis process started with getting familiar with the feedback data, followed by generating initial codes, then searching and reviewing themes, and finally defining and naming themes [8]. This process was carried out using MAXQDA software.

A similar thematic analysis approach was then performed on the transcripts of the video recordings, allowing the researcher to reinforce the codes from the interviews and identify the thematisation of participants' gesture interaction with the material samples. This process was done because when taken in isolation, the interview feedback does not necessarily give the whole picture of the ideas and gestures participants employed when they played with the materials.

4 FINDINGS

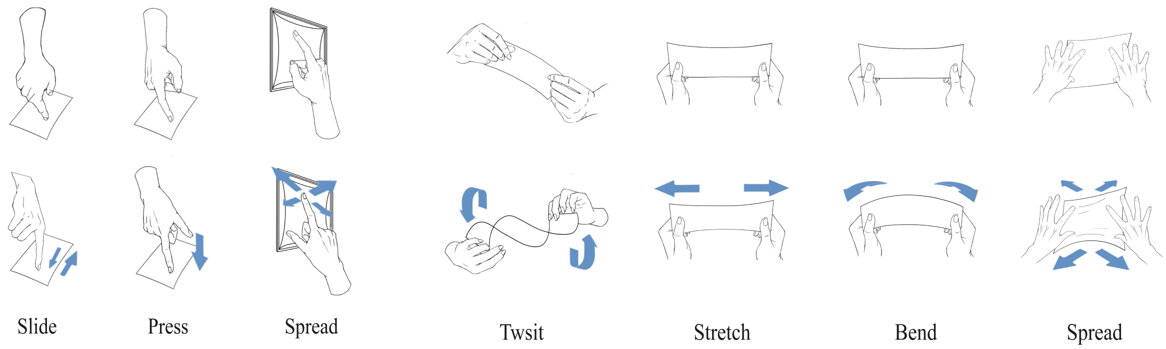
Five themes were identified in the thematic analysis of the interview data and the video observations. A list of themes and codes is provided in Table 2 for the reference of coding process. These were common to both participant groups: 1) the design ideas that participants came up with from materials; 2) the gestures of how participants engaged with the material samples; 3) interaction and functionality; 4) affordances and constraints; and 5) controllability. The themes reported below are illustrated with representative quotes from participants (Participant ID is included in brackets).

4.1 From Materials to Sonic Response

When participants were asked to generate speculative or hypothetical instruments based on the material, the most frequently mentioned design thinking approach was based on the material properties. Nine participants (P1, 4, 5, 6, 7, 8, 9, 14, 15) commented that the texture and haptic feedback of the material gave them ideas of its control mechanism in music. For example, P4 and P5 mentioned that material sample N8 had a rough texture which "encouraged people to use for white noise or background sounds". Also, P7 mentioned that "when you are touching the rubber, the feeling was similar to a keyboard" because "it was very controllable and solid".

> *"It reminds me of technological objects with some good control. Like a good quality, soft-touch feeling, and at the same time, rigid but deformable. I really like N6 (the rubber)." (P9)*

The quote above exemplifies the tactile of the material as a medium in music perception for musicians as the sense of touch always suggests perceptual information for a tangible interface [25, 31]. Seven participants (P1, 4, 5, 6, 7, 8, 15) mentioned that the "feeling of the material" delivered a music-related message. "Because



(a) Finger-based Gesture Input

(b) Hand-Based Gesture Input

Figure 2: Finger-based and Hand-Based Gesture Interaction

the texture of the material was firmer when touching it by hand (N8), which should be mapped to a crisp and hard sound effect" (P1).

> *"They just seemed to be lots of different combinations of sliding and pressing and squeezing (N10). They seem to continue one to the other because they were touching." (P15)*

Eight participants (P1, 3, 4, 7, 8, 13, 14, 15) suggested that the visual properties of the materials gave them ideas for DMIs design. For example, one fabric material looks shiny, reminiscent of light music (P4). The texture and colour look pretty technical, which should be linked to some electronic music (P1). A very grainy sound could be mapped to the more rigid material such as rubber because "it will match how the material looks like" (P7). P13 mentioned that the "visual thing of the material caught my attention", and the texture of the material "looks more synthetic in a way", which reminds people of synthetic music. Also, P1 said "I do not like these two materials for their colour and appearance, so I would use it as a padding material in DMIs instead of directly manipulating or interacting with the material".

Six participants (P4, 6, 7, 8, 9, 13) mentioned the unexpected properties of the material beyond their speculation. The tactile of the material surprised people as the material feels different to the touch than it looks. For example, one of the material samples looks like foam (N8), but it is more rigid and could be shape-retaining than expected (P6).

4.2 The Patterns of Gestural Interaction

As expected, different types of material afforded different types of gestures that corresponded with the material properties. The three most common patterns of interaction with different materials appeared: finger-based gestures, hand-based gestures, and body gestures. Here, we discuss the different gestures people used with the same material sample (i.e. the single-handed and bi-manual gestures with the same stretchable fabric) and what mapping strategies they expected to have in DMIs.

4.2.1 Finger-Based Gesture Input: Press, Slide, Spread. One type of gesture input that participants used with the materials was based finger-based gesture input, which included press, slide, and spread (see Figure 2a). Press was the most frequently occurring gesture and was primarily performed on spongy materials, leading to continuous control (i.e. pitch, amplitude, or speed) or discrete control (i.e. on/off, trigger). For example, 14/15 of the participants pressed the foam in the centre of N7.

The sliding gesture occurred when participants interacted with flat shaped materials or surfaces (N8, 10, 11, 12) and looked for continuous sound control (e.g. amplitude). This material has a flatter and more rigid surface than foam and fabric. The spread gesture emerged when participants interacted with the fabric. Participants tried to use their fingers to stretch the fabric, which gave them opportunities to have more control over multiple dimensions.

4.2.2 Hand-Based Gesture Input: Twist, Stretch, Bend, Spread. The hand-based gestures included four kinds of input: twist, stretch, bend and spread. Twist emerged when participants interacted with foam and rubber (N6, N7, N9). P9 mentioned that even though it was not known whether the foam could sense such a gesture, it was nice to twist it as a novel interaction in DMI. All the participants tried to stretch the fabric, but they noted they did not know much the material could be stretched. P13 tried to stretch the rubber strip (N6 in Figure 1) as P13 expected laborious stretching for musical performance. Bend input appeared with rubber material only.

4.2.3 Body-Based Gesture Input. Body-based input was widely used in e-textile computing in wearable sensors, and the movement was dependent on "the location of the sensor material" (P3). For example, attaching the material along the arms or wrist would provide a gesture of bending the arm (P2, 3, 7, 13). P13 also mentioned that using fabric as a wearable instrument was a great idea as it is soft to the skin and the form is flexible. When the sensor material has a bigger size, "complex body movement also might be possible" (P7).

4.2.4 Multi-dimension Gesture Control. In addition to the above classification of gestural interaction, several multi-dimensional gestures were used when participants interacted with the material samples, including bend + press, twist + press, and stretch + press. The feature of these gestures is that they all include a finger-based gesture: press. This is because the multi-dimensional gesture inputs are mainly based on the hand-based gesture (see Figure 2b).

Theme	Relevant Codes	CO
From Materials to Sonic Response	From material properties	36
	Link the timbre to material properties	12
	Tactile as a medium	76
	Feel of the material	45
	Link hardness to percussion	9
	Multi-dimension control	22
	From the visual properties	22
	The texture and colour	14
	From the unexpected properties	11
	Total	145
The Patterns of Gestural Interaction	Finger-based gesture input	91
	Continuous control	65
	Discreet control	26
	Hand-based gesture input	45
	Body-based gesture input	16
	Wearable instruments	6
	Interact with arm	4
	Interact with the whole body	6
	Total	152
Interaction and Functionality	Intuitive interaction	39
	Texture, shape, colour	24
	From existing DMIs/acoustic instruments	16
	Augmented existing DMIs	4
	From materials' properties	22
	The extra layer of interaction	7
	Expectations of the object/material	27
	Intimate interaction	5
	Total	109
Affordances and Constraints	Unexpected affordances	16
	Material metaphor	14
	The level of flexibility	22
	Rich control dimensions	17
	Total	52
Controllability	Precise control	15
	Deal with signal input	8
	Categorize the data/signal	6
	High learning curve	5
	Stability	11
	Total	39
Performance	Audience engagement	9
	Sound exploration	4
	Controllability during performance	8
	Meaningful music	9
	Total	30
Art Concept	Sound installation	3
	Aesthetics	8
	Total	11
All		538

Table 2: Main themes and relevant codes, and code occurrence (CO)

4.3 Interaction and Functionality

This theme emerged in the second part of the study, playing with the material samples. During that part, participants talked about materiality regarding the interaction techniques, meaning, and practical applications of specific samples. As discussed in Section 2.2, one of the characteristics of deformable interfaces is their intuitiveness which suggests what kind of gestures to use to interact with the interface. For example, participants commented that the fabric makes people "actively want to touch and stretch", "the foam makes people want to press and squeeze", and the rubber makes people feel like they press and bend (P6). Similarly, the copper elements invited sliding interaction (N10):

> *"The copper strips kind of suggests some sort of functionality already, and it actually feels pretty nice to just slide up and down on it." (P12)*

Eight participants (P3, 4, 5, 6, 12, 13, 14, 15) suggested that the interaction implication of the object was mainly based on their previous experience with existing interfaces. P13 mentioned that "every digital instrument has sliders and buttons" to trigger some events. The experience-based implication gives participants insights into using the material samples in DMI design. All participants performed the same gesture with N10, 11, and 12 material samples, sliding on the copper tape, pressing the squared foam button, and holding the surface in their hands. However, participants had different attitudes toward this type of interaction. Six participants (P3, 5, 7, 9, 12, 13) like these three objects as "they already look like a well-designed interface" which "could be played in a way". Some other participants (P1, 2, 4, 6) explained they do not like these three combinations as they are "too general" and "no surprising", which are easy to imagine what people can do with them. For example:

> *"Obviously, this is like a button (N10), so you can (turn it) on and off, playing a note like a keyboard note or turning on and off parameters, like a pad. " (P14)*

The above evidence suggests the materials implied their interaction techniques and functionalities from two aspects: i) the properties of the material, such as foam and fabric, are soft to be squeezed and stretched, ii) the prior expectations of layout/ construction/ structure of the object (N10, 11, 12), such as the smaller sized square foam suggested a button (N7).

4.4 Affordances and Constraints

Participants talked about the flexibility of using the material samples in specific musical contexts and their concerns with its use. As each deformable material could allow multiple gestures, participants discussed that designing intuitive and efficient musical gestures with such materials might be problematic as they need to consider the difficulty of playing the instrument in performance when designing it (P1, 4, 5, 6, 7, 8, 9, 13, 15).

> *"However, because these seem to offer a rich set of possible gestures or interaction gestures, I think it is very important that sound design offers rich exploration. Because without that, there is no point in having the material." (P8)*

Five participants (P1, 3, 7, 12, 13) mentioned that the nature of soft material allowed them to cover almost anything's surface as a DMI. For example, the foam, fabric, and rubber could cover cylindrical or spherical objects. The fabric could also be wearable to adapt to some body-based gestures of the musician, which could not be achieved by rigid materials (P13).

> *"Because I think deformable material has the advantage that it can be adapted to different scenarios. For example, it can be portable, and then, for example, it fits better on some wearable instruments or some complex surfaces." (P7)*

4.5 Controllability

> *"The biggest challenge, I think, is first discovering the material and what you can get from it. Sometimes it can be complicated. Like, does the material respond differently to a different type of gesture?" (P9)*

Four participants (P5, 7, 9, 13) raised concerns about dealing with the signal input of deformable interfaces, including the signal quality, recognition and categorisation of the gestures, and the mapping to sound output. P9 mentioned that the data configuration in deformable DMIs would directly affect how they would be played. For example, if the system could not categorise different gestures as expected, the variety of gestures offered by the deformable interface would be pointless.

> *"For me, musical performance requires something to be regular. My instrument needs to be regular and repeatable. This is the problem. I do not see how a deformable object can give me regular service." (P15)*

Performance is one of the main ways to present and communicate new types of DMI ideas, pieces, and practices. Nine participants (P1, 4, 5, 6, 7, 8, 9, 13, 15) mentioned that the precise control of deformable DMIs was challenging for performing on the stage. To generate a good quality of music with DMIs, musicians need to prepare, rehearse and practice before the performance. However, some deformable materials were not very stable and robust. For example, the stretchy fabric sometimes needs to return to its original shape and position after it has been stretched after several times, and the conductivity of some conductive materials can change as they wear out over time [45]. These disadvantages of deformable DMIs would limit the performance style as it is difficult for musicians/ performers to show what they expected (P2, 5, 9, 14, 15).

Seven participants (P1, 3, 4, 6, 7, 13, 15) suggested that it was debatable whether deformable interfaces were deployable in design. P4 believed that the learning curve of deformable DMIs is too high, which does not fit with our fast-moving society as people look for something that might be easy to learn and produce good pieces of music with. They also had concerns about the difficulty of control with deformable DMIs.

5 DISCUSSION

Overall, this study presents an approach to investigating materiality in DMI design through the material lens. This section reflects on our findings and discusses what the evidence reveals about the design of deformable DMIs and broader areas of DMI design and HCI.

5.1 Subjective Experience of Materiality

Participants' intuitive attention to material properties in their first encounter with materials could be described as *sensorial level* in Giaccardi and Karana's materials experience framework, where the role of sensorial experience is "omnipresent and inevitable" [18]. The interpretation of materials occurs after the sensory encounter, in which people interpret and evaluat the materials and situat the meaning of the materials [18, 39]. Participants' subjective perceptions of the inherent properties of materials were also different. For example, participants showed opposite opinions about the material properties of one specific material (N8) – 8/15 of participants selected this material as their "favourite" for its "special" qualities, whereas 4/15 pointed out the rough texture of it makes them less likely to interact with it. Participants' initial perceptions of the materials influence their interpretation of the meaning of materials, thus influencing their design ideas developed by the materials.

In the second part of our study, participants were invited to discuss their understandings of the material samples in a musical context. In our study, we found that the interpretive level and sensorial levels mixed. When people talked about their interpretation of the materials, the most interpreted meaning came from the first sensorial level. One reason for that might be that music and sound are also regarded as sensory components. For example, musicians get feedback from an instrument while playing (i.e. sound and haptic feedback) [33, 69], so that musicians connect the sensory of the materials to the sense of sound. These results reinforce Mice et al.'s and Pigrem et al.'s findings that the performer's gestures and their imagined sound of a DMI are linked to their subjective experience and knowledge of materiality [51, 55]. As we described in Section 4.1, participants linked their perceptions of the materials to sound design.

5.2 Technology-centered Thinking

As mentioned in the results section, participants matched the same gestural interaction with the same type of material. One reason for this may be what we refer to here as technology-oriented thinking. All participants had experience designing DMIs, which means they can be assumed to have a basic understanding of sensor materials. We suggest that their gesture interaction with the material samples was influenced by what they believed to be possible with current (primarily digital) technology. Despite being told to focus on the material itself, participants still raised concerns such as "what type of data we can read", "whether it is conductive", and "how stable the data is". These findings echo embodied cognition theories, which suggest that tools reshape people's perceptions and alter people's actions, therefore changing how people think about things [43].

Participants in this study were not experts in deformable materials, and most were not familiar with the materials – and only three participants have built DMIs with such materials. So participants' speculations on materials are mainly based on other DMIs made from rigid materials. It is not clear if there would be any different results with experienced deformable interfaces designers. Nevertheless, this unfamiliarity and ambiguity with the materials stimulated the participants' thinking and catalyzed the creation of more divergent design ideas. For example, participants mentioned that the unexpected affordances of the materials inspired them to think more about materials and the possibilities in interaction design. This finding echoes Nordmoen et al.'s finding that is the indefinite and ambiguity as a source of richness in design artefacts [53].

Participants in both groups shared the same patterns of gestural interaction regardless of their country. This suggests that their understanding of the technical aspects of DMI is similar. NIME has been a rapidly growing international community since 2001, in which new DMIs emerge every year. Therefore, it is likely that the technology available to DMI designers around the world is similar [54, 73]. We have therefore found that 'unusual materials' stimulate DMI designers' creativity and thinking because they do not fall into previous experiences and technical constraints and help them focus their thinking on the materials themselves.

5.3 Art vs. Engineering Thinking

We found that the speculation of materiality was very subjective and determined by participants' backgrounds. Designers from engineering and technical backgrounds were less concerned with how a material would look like the final piece and more concerned with the technical implementation. For example, they would make a rapid functional prototype regardless of the material and its appearance; and the material itself would be one of the last considerations when producing the DMI (P4). This type of thinking mode is similar to the concept of making prototypes in HCI [9].

In contrast, those DMI designers who had a background in design and art were more focused on materiality during design thinking. For example, as reported in Sections 4.1 and 4.3, they would have positive expectations for materials whose colour looks appealing, participants mentioned "the texture would be great to touch when people engage with it", or there might be "some unique or artistic way to interact with the material".

5.4 Musical-oriented Thinking

We found that participants' negative perceptions of deformable materials in DMIs were mainly from their consideration of musical activities. When DMI designers consider the actual musical activity when interpreting the materials, there is a potential change in their thinking. They appeared to pay more attention to whether the material is strong, durable, and maintainable than its visual and tactile properties. Whether a material offers deformations such as squeeze and twist is of secondary importance in DMI design – whether the material could support repeatable gestures. This finding might be related to the musical challenge of DMIs design in which expressivity might be the most crucial artistic property of a musical instrument – to enable complex and subtle control of input gestures with their corresponding sound output is a significant challenge in musical instrument design [36]. It is not enough for a DMI to only play notes; it should also be able to play notes with a particular timbre, intonation or intensity [50]. This requirement makes the design of mappings and sensors harder because the sensors have to deal with subtle gestures and be reliable and robust.

Another aspect of musical-oriented thinking that emerged in our study was the interpretation of materials in DMI design in terms of existing DMIs. For example, in our results, participants showed interest in rubber for its robustness but also because it feels like some existing DMIs, such as the Roli Seaboard [14].

5.5 Breaking Design Barriers

The barriers that inhibited DMI designers' interpretations of materiality in deformable DMI included: limited previous experience with materials, lack of knowledge of deformable interfaces, and lack of clear motivation to design. We suggest some insights that could inform future research to break down these barriers.

Firstly, **training** DMI designers about deformable interfaces. For example, demonstrate how deformable interfaces work in general (beyond DMI design) and what kind of control configuration could be developed. Then, set clear **design tasks** to motivate designers, i.e. design for a performance in front of the audience - the social pressure from the audience as catalysts in the design activity, which motivates designers to explore more possibilities.

5.6 Limitation and Future Work

There are limitations to our work that might affect the results. One limitation of the study design is that in part 1, participants were invited to talk about their initial ideas of how they imagined the material samples could be used in a musical context - which would put people back into a technical mindset. Although the facilitator emphasized that the focus of the material samples should be the material themselves and the combination of different materials, participants still expressed their preference for other sizes.

Based on the results of the study, we found that the gestural interaction and the materiality as inspiration sources for DMIs design. Due to the technical challenges of designing with deformable materials, discarding technology constraints help DMI designers focus on the possibilities of deformable materials in music. Future research needs to explore how DMI designers might take such design decisions and approaches to the implementation phase. For example, one direction is examining how DMI designers would design sensor materials themselves and how DMI designers explore the potential of materials when designing functional prototypes.

6 CONCLUDING REMARKS

This paper presents a study undertaken to explore the materiality in DMI design through the material probe. The results from the study of fifteen participants highlighted some uniformity and differences in the expectation of deformable materials in DMI design. The uniformity mainly comes from the knowledge of existing DMIs (made in rigid materials), whereas differences come from an educational background and personal experience. The cultural background was less critical as participants from two countries shared common themes and results. The sensory encounter inspires design ideas with the materials and interpretation in a particular context (in our case, music). We believe there is great potential for further refining and applying the material exploration approach in digital musical instrument design.

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