When Materials Meet Sound: Discovering the Meaning of Deformable Materials in Musical Interaction

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ABSTRACT

Research on Digital Musical Instruments (DMIs) design highlights that materiality plays an important role in DMI design and musical interaction. However, DMI design research often focuses on technology-oriented factors, with less exploration of the meaning of materials in design practice. In this paper, we explore how DMI designers understand deformable sensor materials and how they use these as a resource for creative aesthetic design. Eleven DMI designers were invited to use a selection of deformable sensor materials to create prototype DMIs with them in a design activity. Three design approaches emerged, determined by how designers perceived and explored sensor materials. We discuss the potential of the methodology for exploring strongly entangled elements, such as material, gesture, and sound, in DMI design. The results contribute to the design practice for DMI designers and to further exploration of material-based design research in Human-Computer Interaction.

CCS CONCEPTS

• **Human-centered computing → Interaction design theory, concepts and paradigms**; *Activity centered design*; • **Applied computing →** *Sound and music computing*.

KEYWORDS

Materiality, Research through Design, Musical Instruments design, Design Methods

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1 INTRODUCTION

Digital Musical Instruments (DMIs) are musical instruments that combine a physical interface and a computer-based sound synthesis system [44, 48, 51]. The physical interface of a DMI may consist of the sensors used to measure the gestural interaction of the performer and the actuators that provide feedback to the performer, these values are then mapped to sound synthesis algorithms [48]. The influence of engineering on Human-Computer Interaction (HCI) often manifests itself in the focus on digital or interactive elements at the expense of the physical construction of an interactive object and the materials that comprise it [15, 16, 34, 72]. As a creative and expressive form of HCI, DMI design research explores how to create new aesthetic qualities (that is, affective, embodied, and meaningful) through combinations of physical and virtual interfaces, computation, and sound feedback [7, 25, 33, 35, 43, 74]. This raises design questions for DMIs, including (i) how musicians gain knowledge through an exploration of the specific properties of materials in musical interaction, and (ii) how musicians seamlessly create digital (sound algorithms) and physical (material) interaction in DMI design [18, 60].

Waters argues that a musical instrument cannot be regarded as an object but as a process: "a dynamic system in constant state of change, seasoning, adjustment, and decay" [75]. People have always engaged "materially" in making musical instruments, and so too in interactive control, recording, and performance with electronic or computationally mediated music [51, 58]. Mudd's material-oriented approach highlights tools "as instigators and collaborators in the formation of creative outputs" and acknowledges that "creative ideas, directions, goals and outcomes are developed through an exploration of the specific properties of tools" [55]. However, not every DMI seeks to create a material-orientated interaction; even for many that do, the design process often focuses on digital and sonic factors (e.g., particular coding environments, platforms), with less attention to the meaning of materials (e.g., physical materials and components) in the creative process [38, 43, 46, 48].

To explore the meaning of materials in DMI design, we invited eleven DMI designers with different levels of experience to design functional prototypes with a set of deformable sensor materials. We deliberately chose to use deformable interfaces as probes because they offer nuanced and responsive physical interaction with digital technologies and allowed unique gestures – such as squeezing, stretching, and bending – that are unlikely to be achieved with rigid interfaces [10, 14, 26, 32, 37, 42]. Our research probes how designers develop the practice knowledge of deformable sensor materials that lets them, in Ingold's words, "follow the materials" [30], in DMI design. To focus on the role of materials in DMI design, we constrained the sound synthesis process and invited participants to focus on the physical interaction with materials.

This paper presents two main contributions: (i) an examination of how designers perceive and explore sensor materials in design practice with the aim of benefiting the HCI research and practice

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communities, and (ii) a reflective summary of the methodology's potential in exploring strongly entangled elements in DMI design. Based on the design practice and comments of the designers, we reflect on the value of exploring materiality in DMI design and how to encourage more consideration of materiality in both DMI design and HCI. For a musical instrument, the sound – or at least the relationship between sound and interaction – cannot exist entirely independently of materials. Although material, gesture, and sound are strongly entangled, we discuss the potential of our method in analysing them separately to understand the connections between them and their different weights in DMI design. The results contribute to design practice for DMI designers and the further exploration of material-based design research in HCI.

2 RELATED WORK

2.1 Material-Oriented Perspectives and Ambiguity in HCI

The materiality of an artifact is recognized as a crucial aspect of HCI due to its tactile or embodied presence, which is shaped by the diverse forms and functions of digital artifacts [27, 31, 35, 65]. With embodiment becoming central to third-wave HCI [17] and the rise of tangible user interfaces, our intimate entanglement with digital technologies is challenging the foundations of current HCI research and practice [19, 28]. Researchers challenged the prevailing convention that digital interaction solely involved pushing buttons and emphasized that a digital artifact not only "elicits emotionally expressive actions but that the feedback is intricately connected to these actions" [29, 41, 76]. Frens et al. further emphasized that tangible interfaces enriched the meaning of artifacts by evoking cognitive skills, as well as emotional and perceptual-motor skills [20]. The idea that humans, tools, materials, and technologies are "ontologically inseparable" forms the basis of entanglement theories of HCI [19, 50]. In a musical context, entanglement in HCI proposes that "the instrument (DMI) does not become an instrument until it is played by a performer" which asks design researchers to focus on "processes of emergence and re-configuration, and to focus on what humans and designs become as they are entangled together" [23, 45, 50]. An open question remains about what role materials play in this entanglement.

The design or materiality of the objects dictate what we can ultimately do with them [46]. In context of DMI design, Worth defines a material-oriented approach to be one that views the tool as "something to be engaged with and experimented with, and as a source of ideas" [78]. Bailey proposes a view that has particular significance for HCI design, which is that an "instrument (DMI) is not just a tool but an ally; It is not only a means to an end, it is a source of material" [4]. A material-oriented approach focuses on exploration and often means that the sound output of the instrument "are not necessarily fully anticipated by the musician" [55]. In addition, finding something unexpected in the design process is regarded as a significant factor in material-oriented DMI design [54]. The lack of familiarity with material-oriented design approaches and the ambiguous perception and reception of materials offer opportunities for design exploration [8, 54, 55]. Indeed, a lack of familiarity and an ambiguity of design have been found to offer a novel and rich creative practice for designers [21, 67, 73]. Gaver argues that ambiguity has the advantage of "enabling designers to go beyond the limits of their technologies" and encourages users to "supplement them (for example, inaccurate sensors, inaccurate mappings) with their own interpretations and beliefs" [21].

2.2 Deformable DMIs: Materials and Affordances

Previous research on DMI design shows that the materiality of an instrument plays an essential role in embodied interaction, design practice, and performance [49, 61, 81]. Designers and researchers have used deformable materials in musical instruments and interfaces, as they provide rich possibilities for deformation and interaction [14, 22, 32, 37, 68]. The definition of deformable interfaces is provided by Boem and Troiano as interfaces made of soft and malleable materials that require physical input to be deformed and allow users to provide input in unique ways [9]. Deformable musical interfaces have been shown to offer intuitive and easy ways of control [10]. Troiano et al. investigated deformable gestures in musical performance and found that musicians have some common understanding of deformable gestures in performing music. For example, musicians found that squeeze and stretch are related to volume and pitch, and twisting could be considered control of distortion in music [70].

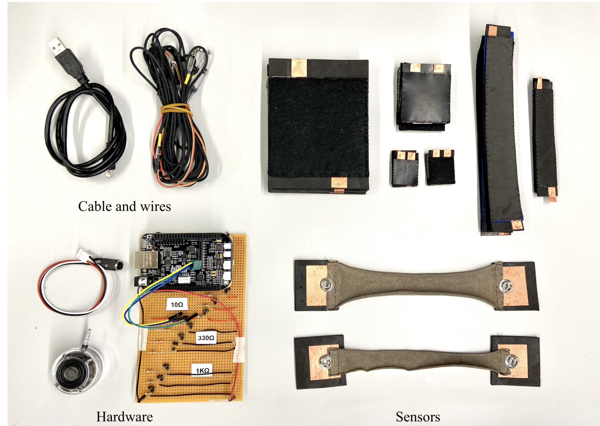
Deformable interfaces need to be easily controlled while resisting extreme deformation, so the choice of materials for them needs to be robust and flexible [70]. Foam is soft and rugged and affords deformations like push and squeeze. It has been used within deformable music interfaces in cubic and spherical shapes [22, 32, 37]. However, foam cannot be stretched as this can damage the material. Fabric is softer, more elastic than foam and can be stretched; however, long-time use of fabric can cause tear or wear due to weak abrasion resistance [14, 70]. Rubber and silicone are used as deformable interfaces that allow bending or twisting [68, 77]. They are more durable than fabric but relatively hard to stretch compared to elastic fabric. The elasticity of these different materials is also different. For example, without external force, some fabrics only partially return to their original shape, while others such as rubber could quickly return to its original form. Deformable interfaces also pose concrete design challenges as the gestures used are inexorably intertwined with the sensor material's physical properties, its affordances, and constraints [9, 70]. However, whilst the materials listed above have been explored in DMI design and usage, in this paper we focus has typically been on sound production, music making, or performing music.

2.3 Research through Design: Approaches and Tools

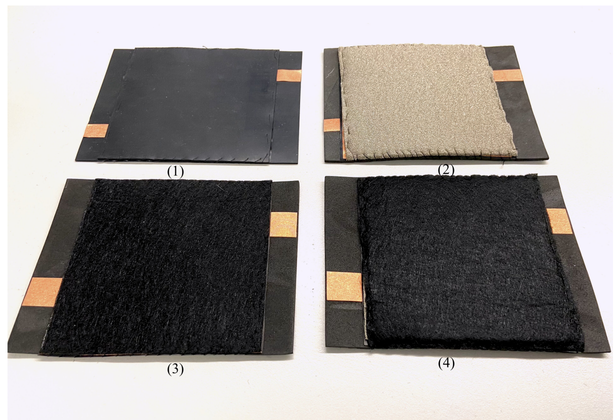
Although the above literature shows the application of deformable interfaces in a music context – such as musical performance, exploratory music experiences, and music therapy – there are substantial technical challenges for the implementation of deformable interfaces which often constrain the design space and process (such as finding robust sensors and materials [22, 24, 32, 37, 77]). The HCI community has a challenge in integrating design in research and practice and is experiencing a growing interest in Research through

Design. Research through design is a research approach that adopts methods and process from design practice to generate knowledge or theory [82, 83]. In particular, approaches such as design fiction, Material Speculation, Material Probe, and material improvisation are used to explore and understand the nature and meaning of materials in design research [1, 5, 64, 71, 73]. These approaches have been applied in material exploration and research on musical instrument design. Lepri and McPherson [39] present value discovery through a hands-on design activity with open-ended design contexts in the communities of musical practice. Andersen uses a Magic Machine approach to explore how materials shape the interaction [2]. Pigrem et al. [60] and Zheng et al. [81] explore the meaning of materiality in DMI design through Material Probe approaches. Moussette uses a workshop approach to explore how designers survey and embrace haptic design from different perspectives [52, 53]. Their exploration indicates that the approach of material improvisation in open-ended design contexts inspired designers to use craft as a way of thinking through material [2, 3, 33, 57].

In the implementation stage, Perner-Wilson et al. present A Kit-of-No-Parts approach to "build electronics from a diverse palette of craft materials", which are perhaps "more personal, understandable, and accessible than the construction of technology from a kit of pre-determined components" [59, 79]. Calegario et al. propose a method and toolkit that includes functional components for DMI design to generate ideas and prototypes [12]. Stewart et al. propose an e-textile audio workshop that creates wearable audio interfaces using handmade fabric sensors [69]. The literature above indicates that the tools provided to designers need to have enough openness, flexibility, and ease of access, and should address the technical barriers to making functional DMIs. We tried to avoid a toolkit for designers because it tends to strongly influence the ways they think about design, pushing them toward relatively simple combinations of available parts rather than more open-ended design thinking. Instead, we prefer a "No-Parts" kit [59] in which materials will be presented in a "raw" way that lets participants feel they are interacted with materials instead of sensors.



(a) All the tools and materials needed in the study



(b) Pressure sensors

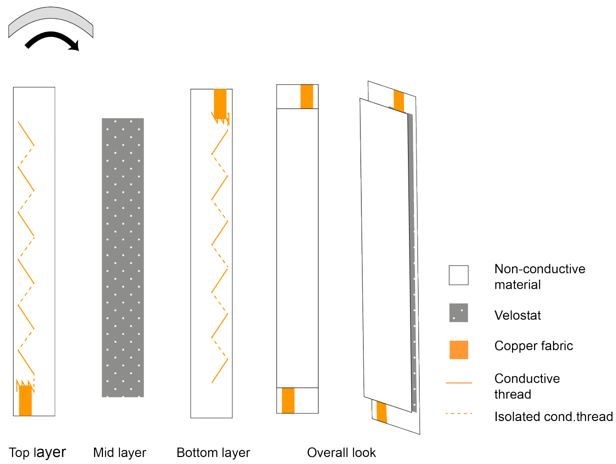
Figure 1: a) All the tools and materials needed in the study. Clockwise from top left: USB cable for power, audio cables for speaker, pressure and bend sensors, stretch sensors, and Bela embedded computer and breakout board with speaker; and b) Pressure sensors: (1) rubber (2) foam (3) fabric (4) foam filled fabric.

3 METHOD

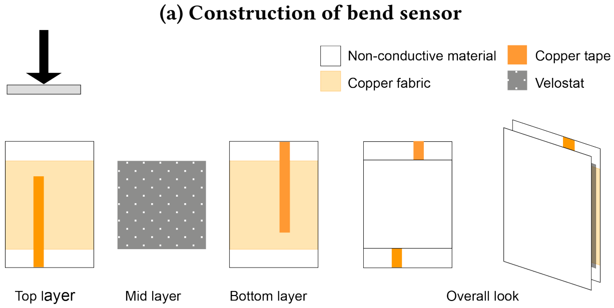
Instead of focusing on new interactions enabled by technological advances, we explore the possible interaction in DMI design by rethinking the materials used in the prototyping phase. To explore the values that emerge through the influence of materials in DMI design, we proposed a design activity where music technology practitioners were provided with a set of materials and tools and asked to design a prototype DMI. Participants were given a set of sensors made in different materials (fabric, foam, rubber) and electronics. The sensors could sense different gestures such as pressing, stretching and bending (which are introduced in Section 3.1.1). Participants could connect / disconnect the sensors to a breakout board, which was prewired to a Bela board using (16-bit) analog inputs [47]. As the activity focused on the evoked meaning of materials, participants were instructed to design a physical DMI with the same sound synthesis. They were informed that they would demo their final design after the design activity to show how the instrument could be played and what kind of musical interaction was designed. The following sections introduce the materials and tools in detail, including the selection of materials, the study setup, and procedure.

3.1 Study Design

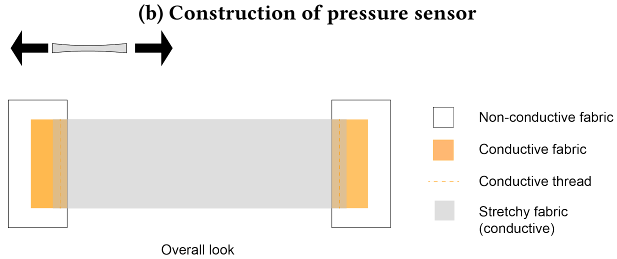
In our study, participants were provided with three types of sensor materials which afforded the following gestures: press, bend, and stretch. These gestures were identified as the most commonly used or expected gestures by musicians in musical interaction [10, 70, 80, 81]. Pressure and bend sensors were made of four types of materials that provide different tactile properties: (1) rubber, (2) foam, (3) fabric, and (4) foam-filled fabric. The texture, resilience, and softness of each sensor were different. The stretch sensors were made in one type of stretchy fabric, which will be clarified in more detail in the following sections. The study materials were selected according to findings from previous research: (1) the materials selected provide the most commonly used gesture by musicians



(a) Construction of bend sensor



(b) Construction of pressure sensor



(c) Construction of stretch sensor

Figure 2: Construction of three types of sensors

with deformable interfaces to perform music [70, 80], and (2) they are the most commonly used deformable materials in DMI design [10, 70]. The tool includes four core components:

(1) Material under investigation: the deformable sensor materials.
(2) Supporting materials: stick, rubber bands, craft polystyrene cube, and different sizes of polystyrene balls. These are chosen because the sensors are easily attached to wooden sticks or polystyrene by pins, which offers flexibility of construction, destruction, and reconstruction ideal for rapid prototyping and testing ideas.
(3) Computing hardware: a Bela embedded computer [47] - see Section 3.1.2,
(4) Software: a sound design patch in PureData (PD) [62] - see Section 3.1.3.

3.1.1 Sensor Materials: Form and Making. The construction of the sensors followed the documentation of projects and material experiments developed by Hannah Perner- Wilson and Mika Satomi on their website *How to Get What You Want* [66]. The approach is summarised here to allow readers to construct their own sensors for rapid prototyping.

For the pressure sensor, sandwich the Velostat between two squares of copper fabric connected to the copper tape. One copper tape goes to 3.3V, and the other side goes to the ground – the direction does not matter (see Figure 2b). This type of pressure sensor can only detect the pressure but cannot detect the location (i.e. the results of pressing the left top corner and the centre might be the same). The pressure sensors were made in three sizes: fingertip-sized (small 2.5 * 2.5 cm), finger-sized (medium 5 * 5 cm) and hand-sized (large 10*10cm). The design intention was to allow participants to play and interact with the sensor materials with different parts of their hands. The construction of the bend sensor is similar to the pressure sensor in Figure 2a. The bend sensors were made in finger size (small 1.5 * 10 cm) and hand size (medium 3 * 20 cm).

There are different methods to construct stretch sensors, such as knitting and stitching with resisted thread, mixing conductive fabric with stretchy fabric glue, and stretching various conductive materials [63, 66]. The researcher tested these three methods and decided to use stretch fabric (Shieldex TechnikTex P-130+B) to make the stretch sensor [40], as (1) this type of material has been used as stretch sensors in other E-textile research, (2) it could be stretched in multiple dimensions, and (3) the output data was found to be stable compared to the other approaches. The construction of this stretch sensor was to stitch both ends of the conductive stretch fabric to copper fabric, one end to 3.3V and another to the ground (see Figure 2c). The stretch sensors were made to a small size to ensure that they could generate good value from stretching. Table 1 lists all the information on the sensor materials provided in our study.

3.1.2 Hardware. In our settings, the embedded computing platform is Bela [47], which provides ultra-low latency, and integrates audio and sensor processing. Bela also supports multiple audio programming languages, such as Pure Data [62], making it ideal for DMI projects.

3.1.3 Software and Sound Design. To explore how participants response to the materials and musical interaction, the sound was constrained in the study settings. The audio code is developed in Pure Data (an open source music making software) [62] and was modified from the FM (frequency modulation) synthesis algorithm based on examples from Bela's tutorial website [6]. FM or Frequency Modulation Synthesis uses at least two oscillators – a Carrier and a Modulator. The modulating oscillator is used to alter the frequency of the carrier oscillator (hence FM). The first analogue input is mapped to the carrier amplitude in our example. The other two inputs are mapped into the modulator frequency and amplitude. These mapping are commonly known as the harmonic ratio and modulation index, respectively. We choose FM synthesis because its a computationally efficient and relatively simple technique, yet can

Table 1: A list of sensor materials provided in the study. The resistance (ohm) of the sensors are approximate values measured by a multimeter as the values fluctuate. The working range indicates the initial value (first value) to the maximum/minimum value (second value). For example, the initial resistance of pressure and bend sensors is pretty high and decreases when pressured or bent. For stretch sensors, the initial value is low and increases when stretched.

Type	Material	Size	Initial Resistance (ohm)	Working Range (ohm)
Pressure Sensor	Rubber	2.5*2.5cm (s)	180K ohm	180K ohm-280 ohm
		5*5cm (m)	170K ohm	170K ohm-1K ohm
		10*10cm (l)	150K ohm	150K ohm-1K ohm
	Foam	2.5*2.5cm (s)	100K ohm	100K ohm-200 ohm
		5*5cm (m)	150K ohm	150K ohm-350 ohm
		10*10cm (l)	150K ohm	150K ohm-300 ohm
	Fabric	2.5*2.5cm (s)	20K ohm	20K ohm - 400 ohm
		5*5cm (m)	20K ohm	20K ohm-100 ohm
		10*10cm (l)	40K ohm	40K ohm-200 ohm
	Foam-filled fabric	2.5*2.5cm (s)	2M ohm	2M ohm-300 ohm
		5* 5cm (m)	2M ohm	2M ohm-200 ohm
		10*10cm (l)	2M ohm	2M ohm-100 ohm
Bend Sensor	Rubber	1.5*10cm (s)	3K ohm	3K ohm - 100 ohm
		3*20cm (m)	2.5K ohm	2.5K ohm - 100 ohm
	Foam	1.5*10cm (s)	2K ohm	2K ohm - 100 ohm
		3*20cm (m)	2.5K ohm	2.5K ohm - 200 ohm
	Fabric	1.5*10cm (s)	1.6K ohm	1.6K ohm - 300 ohm
		3*20cm (m)	2K ohm	2K ohm - 300 ohm
	Foam-filled fabric	1.5*10cm (s)	1.8K ohm	1.8K ohm - 270 ohm
		3*20cm (m)	2K ohm	2K ohm - 300 ohm
Stretch Sensor	Stretch fabric	3*25cm (s)	14 ohm	14 ohm - 30 ohm
		6*25cm (m)	8.7 ohm	8.7 ohm - 85 ohm
Total	22 sensors			

recreate complex timbres similar to those from acoustic instruments. However, the same synthesis process attached to a different material will probably sound different when the instrument is played because the relationship between sound and interaction cannot exist entirely independently of materials. In our study, we consider this difference as one type of material's property, which will be discussed later from the perspective of material controllability.

3.2 Participants

Participants were recruited using the institution's academic mailing lists and the researcher's social networks. Eleven participants (4 female, 6 male, and 1 non-binary) between the ages 23 and 40 (mean 29.9) were recruited to participate. After recruitment, detailed information about each participant's musical background and design experience was collected through a pre-study online questionnaire summarised in Table 2. All participants reported having studied music through self-taught, formal, or informal training. All participants had experience making music with DMIs and all participants had experience designing DMIs from 1 to 6 years (mean 3.8 years). Only P1 and P9 had experience with interacting with deformable interfaces before the study.

3.3 Procedure

Before the study, participants signed a consent form, completed a pre-study questionnaire, and were informed of the institution's ethics policies. The facilitator led the study activity, which was structured into three parts as follows (the detailed study script and interview question can be found in the supplementary material).

Table 2: Participant Demographics and Musical Background (Total Years of Experience in DMI Design)

P	Age	Gender	DMI Design	Primary Expertise	Secondary Expertise	Musical Genre
P1	26	F	6 years	Music Technology	Performing Music	Classical
P2	29	F	2 years	Performing Music	Musical Instrument Designer	Electronic
P3	28	M	2 years	Music Technology	Programming	Electronic
P4	29	Non-binary	5 years	Music Production	Composition	Electronic
P5	25	F	1 year	Music Production	Music Technology	Electronic
P6	31	M	5 years	Music Technology	Programming	Electronic
P7	23	M	3 years	Music Technology	Composition	Electronic
P8	34	M	4 years	Composition	Music Technology	Improvisation
P9	40	F	5 years	Performing Music	Music Technology	Electronic
P10	32	M	6 years	Programming	Music Technology	Improvisation
P11	32	M	3 years	Music Technology	Programming	Electronic

3.3.1 Part 1: Introduction and Practice (20 min). The facilitator introduced the study process to the participants and guided the participants to become familiar with the tools (i.e. Bela IDE, Pure Data, a collection of sensors) and materials. The facilitator explained how to connect the sensors to the breakout board and how they work. The facilitator then gave the participants an example task to practice and get familiar with the tools before the design task - participants were asked to play with two audio samples with the sensor materials to get familiar with the tools. This example task was different from the later design task.

3.3.2 Part 2: Design and Demo (50 min). In this session, participants were given a design task - to design a physical interface with the provided materials for an FM (frequency modulation) synthesis, which includes three analogue inputs. We acknowledge that a "raw" continuous manipulation of the modulation parameters would be quite musically distant from how we usually hear FM synthesis. The sound of the prototype instruments can be experimental and not necessarily "fully anticipated by the musician" [55]. The sound synthesis was pre-defined for the study, and participants were not asked to do sound design. Participants were invited to 'think aloud' during the design task. After the design practice, participants were invited to do a short demo with their piece, to show how it should be played and the musical gestures they would like to use. This part was video recorded for further analysis.

3.3.3 Part 3: Semi-structured Interview (15 min). At the end of the study, a semi-structured interview was conducted to investigate why participants chose the materials they used, their design processes, and how they understood the relations between materials, sound, and gestures. Then, participants were invited to talk about the problems and difficulties in the design activity, and expectation and overall feeling of the activity. Each design output was then photographed and documented by the facilitator. The interview questions can be found in Appendix A.

3.4 Data Collection and Analysis

All participants' design sessions, presentation (demo), and interviews were audio and video recorded and transcribed to facilitate thematic analysis. Data analysis comprised of i) analysis of the gestures people used to play their instruments evident in the video recordings; ii) analysis of the transcripts of interviews and design sessions captured in the video recordings. We followed the guidance of thematic analysis and conducted an inductive (bottom-up) thematic analysis approach to extract participants' ideas about the development of musical gestures with the sensor materials [11]. We acknowledge that the topics of our interview questions may introduce some bias in participants' answers and subsequent coding. However, the data-driven approach employed in this study minimizes any preliminary assumptions about the participants' design process. Following the step-by-step guide with six phases of analysis, which are (1) getting familiar with the transcripts, (2) generating initial codes, (3) searching and (4) reviewing themes, and finally (5) defining and (6) naming themes [11]. This process was carried out using MAXQDA software.

4 FINDINGS

We identified 78 codes, and 331 coded segments in the thematic analysis of the interview data and the video observations which were clustered into six themes: *Interpretation of Materials, The Instruments, Gesture Development, The Design Approaches,* and *Participants' Reflection on their Approaches*. The themes reported below are illustrated with representative participant quotes (Participant ID is included in brackets).

4.1 Interpretation of Materials

The study found that participants' understanding and interpretation of the sensor materials used in building an instrument can be divided into two categories: physical properties (e.g. hardness, stretch, texture) and functional properties (e.g. pressure sensor, bend sensor, stretch sensor).

The first way of interpreting materials was from physical properties to functional properties. Under this approach, participants

(P4, P7, P8, P10) tried to interact with all the sensor materials without technology and chose those which "feel good". The interaction only involved understanding materials' physical properties, such as sensation feedback and softness. P2 explained as "I was looking for something that would be nice to squeeze. So like this one, you can like really feel that much tactile response when you press it".

The second approach was that participants (P1, P2, P4, P6, P9) with more DMI experience (average 4.6 years, compared to the overall mean of 3.8 years), made their design decisions from functional to physical properties. In this way, participants tried to connect each sensor material to Bela and tested whether they could have "good control". If the sensor material did not work as they expected, then participants would try the sensors made in other materials. P1 explained the process as "I think ultimately it was the sensor itself first and then a bit more with these two (sensors) about the actual texture and material of it". P9 mentioned she was looking for sensor materials that could afford "repeatable and performable" controls and "feels good to press" by gently changing the pressure to find the pitch she wanted to play, because the mapping of the sensor material deformation and the pitch it generated "feels good".

However, there were participants who acknowledged the different properties and affordances of the materials, but thought that it was unimportant to their design. P11 designed an instrument controlled by a ball instead of hands, and he said, "my touch with the materials was not so necessary. I do not think the material itself has informed my instrument making".

4.2 The Instruments

Table 3 shows a summary of the prototype instruments pictured in Fig 5. Eleven instruments were created by participants in the design activity. We categorised the design prototypes into three types: sensor-based instruments, experimental instruments, and multi-controlled instruments. There were four instruments (P2, P9, P10, P11) identified as sensor-based instruments since participants were focused on learning a "good control" of the sensors during the design process. P2 and P9 gave up one control of the sound settings (three parameters of an FM synth) but focused on two parameters only. Because within the limited time, they wanted to "develop the knowledge of how to play with the sensors" (P2). Three participants (P5, P7, P8) designed their instruments as experimental instruments to explore how to interact with music in a way that they never tried before. In particular, they enjoyed the unpredictable interaction with the sensors and saw its as an "inspiration source in the design and performance" (P5), which will be discussed in more detail in Section 4.4. Some prototypes (P1, P3, P4, P6) were designed as multi-controlled instruments that allowed musicians to play in multiple ways. For example, the instruments developed by P1 and P3 could be played by holding the object on their hands and playing with fingers, or placed the instruments on a surface and played by multiple players.

4.3 Gesture Development

When we invited participants to talk about how they developed the musical gestures (see Table 3), three approaches emerged throughout the design practice. The first approach is *Gesture Came from the Musical Intention* in which participants thought about what kind of gestures would be suitable for the control of particular sound parameters. P3 designed his instrument because he "liked the stretching for volume". P6 explained that the initial idea of the design was to "have the possibility to switch off the amplitude to have no sound and then get louder linearly, so the pressure sensor is the best choice". P7 mentioned that the design of gesture control was based on the idea of "holding down a note and then roll[ing] up the volume (bend)".

The second approach was *Gesture Came from Manipulating Materials*, in which some participants designed gestures based on their physical interaction with the sensor materials. When participants talked about their instruments, they talked about the materials' affordances as a source of ideas in gesture design. Nine participants (P1, 2, 3, 4, 5, 7, 8, 9, 10) commented that the texture and tactile feedback of the material not only gave them ideas of design gestures for the instruments but also invited them to think about what would be the "best control" of the instrument. P8 said that directly manipulating materials "invited me to think about how the materials allow them to be translated into a sound" (P8). For example, P1 mentioned that the foam was soft and suitable for pressing, but the rubber is more rigid, which would be better for an on/off button. Or, P10 mentioned that because of the weight of the rubber, the instrument was designed by shaking to control the amplitude.

The third approach can be summarised as *Gesture Came from Intuition*, in which participants reported that gesture development was following their feelings. P4 designed an instrument based on one basic gesture and "then everything else (other gestures) comes". P1 commented that the gestures and the way she held the instrument naturally came out by "controlling everything and making it feel quite natural" (see Figure 3). P7 cannot explain where the gestures came from, "might be the sensors or materials intuitively, which just feels right without technical reason".

4.4 The Design Approaches

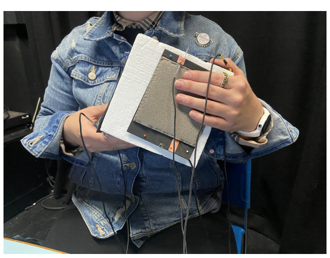
Another theme emerged from the video observations of the design activity and the interview feedback was about participants' design approaches. We found several design approaches that participants took in the design process.

4.4.1 Exploration, Experimentation, and Learning. All participants described the design process as one in which insights emerged from action: Participants frequently used the terms *problems (6/11), experiment (8/11), discovery (4/11),* and *exploration (7/11).* The participants described their process as "playing around," and then finding, "realizing" what works and what does not. As most participants (9/11) had no prior experience with deformable materials for DMIs, we assume that they did not know in advance what would work well and what would not, but discovered this over the activity process. This result reinforced the findings from previous research, which was new design or interactive techniques emerged when people were presented with unfamiliar technology, particularly in the context of deformable interfaces [70].

Seven participants (P1, P5, P7, P8, P9, P10, P11) described exploring sensor materials as the first step in the design process. One exploration aspect was finding the sensors with "good control" (P11). P1 described this process as "I swapped this one (the pressure sensor) out a couple of times to find out what I like the best". In

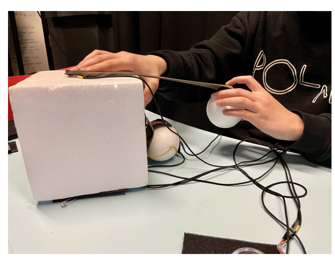
Table 3: Musical Gesture or Technique Developed by Participants (Complementary to Figure 3). The description of the musical interaction was a summary of the participants' descriptions from the interview.

Participant	Musical Interaction
P1	Hold the cube and hug it against the body. Use the left-hand thumb to press the pad (pressure sensor) to turn it on and off, and fingers for the modulation. Then the right hand is to brush through the rubber pad, push it down, or bend them to push on the other side to control the pitch.
P2	Use fingers (right hand) to push the small pad (pressure sensor) for the pitch and the left hand to hold a strip (flex sensor) to control the modulation.
P3	The instrument is called the FM wear-cube as a percussive interface that accommodates the parameters using percussion. Use the left hand to keep the pressure at a certain value. The right-hand palm controls the harmonic ratio. The stretching was more like an accordion to control the brightness of the sound.
P4	A pressure sensor controls the amplitude for only one hand (left hand). The stretch sensor is to be controlled the harmonic ratio with the fingers (right hand) and the thumb to control the modulation.
P5	A shooting game inspires the instrument. It targets the pressure sensor with this ball attached to this stretch sensor. It will generate a different sound when it is hitted.
P6	Hold it (the cube) close to the body and use palms and fingers to control the three parameters.
P7	There are two flex sensors between two sticks. The amplitude on the top and the bottom is the pitch. It is not just forwards and back; performer can bend them and explore the gestures.
P8	Wear the bend sensors on two arms; the left arm will map into the harmonics. While the right one is the amplitude, and the left one to harmonics. And the stretch sensor in between two hands for the modulations.
P9	Use two little pressure sensors on hands: the one made in rubber control the amplitude, and the one in foam changes the pitch.
P10	The left hand has two bend sensors, one mapped to pitch, which creates a constant note, and one mapped to harmonic—the right hand has a bend sensor in rubber to change the amplitude by shaking.
P11	Have the pitch control on the big pressure pad with the left hand, and control with the ball for easy control. The right-hand control the amplitude (on/off) like a percussive instrument.



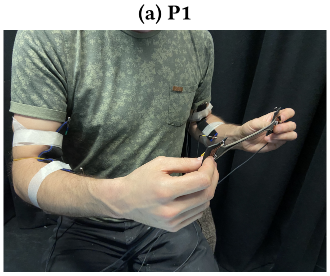
(a) P1

(b) P3

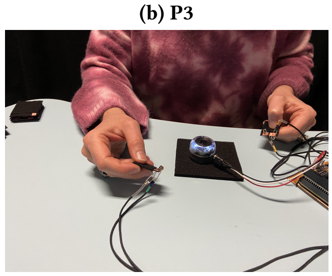


(c) P5

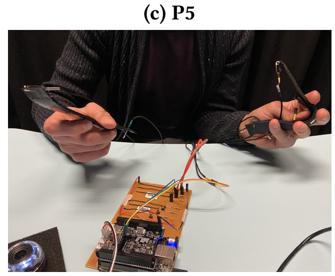
(d) P6



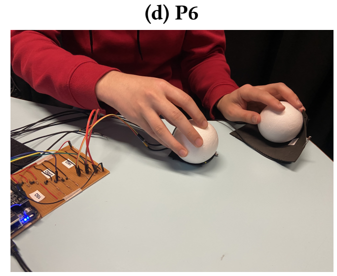
(e) P8



(f) P9



(g) P10



(h) P11

Figure 3: Examples of Participant's Construction.

another aspect, some participants mentioned they started by touching and interacting with the sensor materials to find materials that give them tactile feedback. Four participants (P4, P7, P8, P10) tried to interact with all sensor materials without technology and chose those they "feel good" (P4).

Because of the unfamiliarity with the sensor materials, all participants described learning as part of designing their deformable DMI. Five participants (P1, P4, P8, P9, P11) specifically mentioned exploring how each sensor works as an input device. Three participants (P8, P9, P11) said "had to explore the coupling between gestural signals from the sensors" (for example, how much pressure will reach their expected output and pressing and bending at the same time would increase the value of the bend sensor quickly).

4.4.2 Intuition. As mentioned in Section 4.3, another approach can be described as designing following their intuition, feelings, and previous experience with playing/designing DMIs. Participants were asked questions including "how did you design your instrument?" P7 commented that the design followed his "ears and feelings", which he supposed was a more important part than "reading any technical documentation". P10 developed a musical gesture that he had never played before and said that the technique to play the instrument was "following my intuition" (P10).

4.4.3 The Role of Unpredictability in Design. As the provided stretch sensors are not linear in their control (values of stretch and sound output), participants had different opinions about the unpredictable sound output. Some participants (P1, P3, P9, P10) who wanted more control of their instruments did not like the "chaotic", "unstable", and unpredictable sound output. On the contrary, some participants (P5, P6, P7, P8, P11) saw the unexpected control as an opportunity in design and performance. P5 said "for the stretch (sensor) because I like the range, the stretches are generated and this non-linearity", and she believed "design with the unpredictable materials would produce surprising results". This extends the findings from previous work on how musicians appreciate the potential of serendipitous discoveries in music performance [9, 70]. Our results indicate that the unpredictable control offered by deformable interfaces not only demonstrates potential in performance but also inspires designers with novel design ideas during the design process.

4.5 Participants' Reflection on their Approaches

During the study, we observed that participants felt differently about how they approached the design activity with the materials and tools. For example, seven participants (P2, P5, P6, P8, P9, P10, P11) mentioned that they generated design ideas by interacting with physical components, especially people who "often do not have many different materials to create an instrument" (P10). Sensor materials forced participants to focus on manipulating materials and exploring gestures, thus thinking about how to "translate it (the material) into sound" (P2). P8 felt that the provided sensor materials were more like "materials" instead of "sensors", which opened up his design thinking and was not limited to previous knowledge. As P8 noted, if participants were only provided with "the Bela (microcomputer) and Pd patches, maybe people would go to the path of a digital model or synthesizer".

All participants commented that conducting the design activity with the provided tools and materials was a reversal of their previous creative approaches because rather than focusing on the sound design, they focused on the relationship between the material and the gestural interaction. In this way, the design intervention allows participants to see the design of DMI from a fresh perspective by "testing different materials" (P1) and "having this option of materials to play with" (P9).

Although the settings constrained the design activity, seven participants (P1, P5, P6, P7, P8, P9, P11) indicated they felt the activity was an open-ended exploration. It was possible to "sit here forever and just play around with everything for a couple of days" (P1). P9 believed "the creative process is open enough, it is not like just press two buttons". Also, participants mentioned that presented tools and materials are important because "having something that kind of organic (sensor materials) in a way more than just piece of metal button" (P9).

5 DISCUSSION

Overall, this paper presents a study investigating the meaning of deformable materials in DMI through design practice. This section reflects on the emerging themes from the design activity and discusses the approach of exploring and analyzing the strongly entangled elements in broader areas of DMI design and HCI.

5.1 Entanglements in DMI Design: Sound, Gesture and Material

The design of DMI is dynamic and complex and involves the use of multiple disciplines and different areas of knowledge [75]. With the focus of "materials" in this paper, the deformable materials in particular, we propose three processes (see Figure 4) emerged in our study which all exhibit designers' response and understanding of material. Comparing our observations to previous literature on materiality in general HCI design, there may be several crossover between approaches [36, 57].

The Material-driven approach begins with the exploration of material which aimed to gain the knowledge and affordances to build the understanding of the materials (similar to a combination of Logical and Intuitive approach described by Nordmoen et al. [57]). As reported in Section 4.4.3, the non-linear control and surprising affordances of materials prompted creativity (i.e. improvisation) in our study. We have some reservations about whether the non-linearity and unpredictability of the deformable materials should be seen as a weakness in the technical foundations. This is because the non-linearity of the sensor materials could be seen as a learnable technique in musical interaction of an instrument, and also an "edge-like interaction" for music improvisation [50, 56]. The unexpected affordances of materials also could be seen as an inspiration for gestural interaction in DMI design [81]. Reflecting on this point, the non-linearity of the sensor materials related to the DIY approach and materials chosen to build the sensors. More industry-approved approaches, or other techniques for building deformable sensors coming from material science, or soft robotics, might alleviate this problem. On the other hand, this might then lose the value of the approach followed in this study.

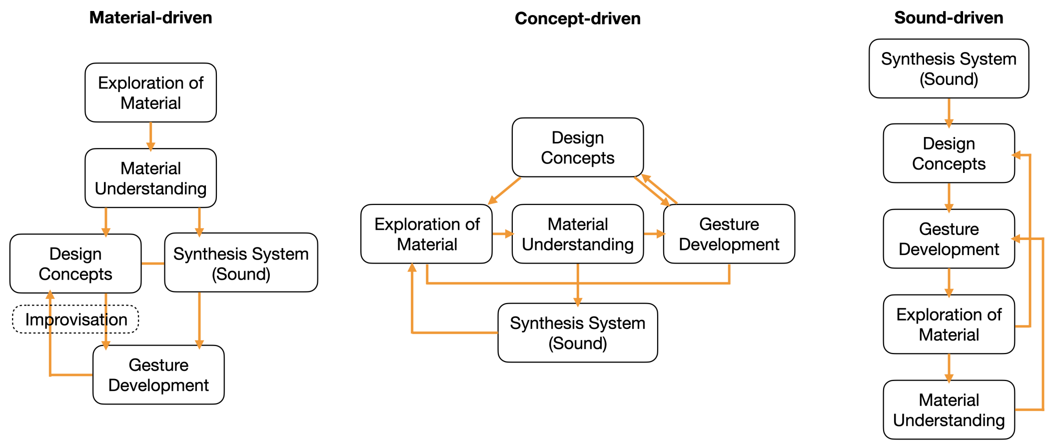


Figure 4: Three processes by which the participants responds to the material and develop musical gestures in the design process. As the sound synthesis system was constrained in our study, the diagram represents the participants' understanding of the synthesis system.

The Concept-driven approach begins with a clear design concept of the instrument in which participants explore the materials to achieve the concept. In our observation, the concept was mainly based on the understanding of materials instead of the sound synthesis system. Designers tried to test each sensor and accumulate experiences about the controls, mappings, and gesture interaction. However, if unexpected affordances occurred, they returned to the beginning (acquiring the knowledge) of the creative process and repeated the whole process. Interacting with different materials gave participants a chance to compare and test their ideas. Compared to Nordmoen et al.'s [57] Conceptual approach, we found the process of realising the concept also involved the re-thinking of concepts after the gesture development. Also, when participants start to approach the idea with sound, this sometimes lead them to re-run the exploration of materials.

The Sound-driven approach starts with the understanding of the sound. Participants reported that the sound reminded them a musical idea (design concept) in which they started to think about the musical gesture to control the sound. Then, they went to explore the materials to find the suitable sensor materials to achieve the idea. This process is similar to the Sound-Gesture-Object approach described by Pigrem et al. [60]. However, in our observation, some participants brought some insights from the exploration of materials and started to re-consider the design concept and gestures (similar to the Sound-Object-Gesture approach [60]). Some properties specific to deformable materials (e.g. the difficulty of precise control, high learning curve [10]) become opportunities for the creative process in DMI design. When designers cannot control sound parameters through simple actions (e.g. press buttons, move sliders), they begin to think about why they are designing such gestures [80].

Through the constraint of sound, we find the insights into the material form the basis for the establishment of musical gestures (in Material-driven and Concept-driven approach). However, participants' different approaches to interpreting materials and design activities highly depended on their "personal background and aesthetic priorities", which reinforced the findings from previous work [46]. We found an association between disciplinary background and approach, which suggests that participants with more experience in DMI design and performing music adapted a sound-driven approach and thought more about the functional properties of the sensors over the physical properties. Participants who had to perform music experience looked for "repeatable performance" and "precise control" instead of discovering design ideas through the materials. It follows that experience may sometimes lead designers to miss opportunities of exploring new ideas and thus fall into the trap of experience.

5.2 Values and Lessons for Exploring the Strong Entangled Elements Separately in DMI Design

The strong entangled elements in DMI design are those that are tightly integrated and interdependent with one another, such as sound synthesis system, the physical interface, and musical gestures. Because of the entanglement of these elements with each other, it is difficult for researchers to analyze the role of some of them in the design and their relationship with other elements in the design separately. In our study, we focus on the physical interface and find the properties specific to deformable materials may have an irreplaceable role in encouraging more thoughts about materiality in DMI design. Some properties are desirable in general, such as materials' sensation feedback, but some are not, such as the difficulty of control. It is worth mentioning that the properties seen as weaknesses in the technical foundations, such as the non-linearity and unpredictability, are a source of design creativity. For example, the unpredictability of the stretch sensor was used as the core of improvisation in performance (P5). In this aspect, we suggest researchers and designers embrace the indefinite and unfamiliarity and see them as opportunities, which reinforced the idea of "ambiguity as a resource for design" [21].

We suggest below approaches to conduct the research and analysis of entangled elements in DMI design and broad HCI. These reflections could help researchers to structure a material-oriented study, or could be used to inform the design of tools or toolkits that aim to analyse one particular element in DMIs.

- **Provide the same kind of sensor in different materials.** In our study we found that offering different materials for the same kind of sensing invited DMI designers to engage more in a 'material level of interaction' rather than a 'sensor level of interaction'. For example, the pressure sensor was provided in rubber, foam, fabric, and foam-filled fabric materials - see Figure 1b. The direct manipulation of materials sparked conversations about how materials influence DMI design, which echoes the methodology of the Material Probe approach [13].
- **Provide the tools or materials that participants are not familiar with.** As reported in the findings (Section 4.4), the unfamiliarity with the sensor materials (deformable materials) results in an open-exploration of the sensor materials to gain the knowledge of them. The unfamiliarity of materials lead to a type of experimental approach and participants were not necessarily "fully anticipated by the musician" instruments. This view is reinforced in our study as we found that the experimental musical interaction could stimulate designers' creativity.
- **Simplified the tools that provided to participants and avoiding the intervention of other materials.** Our study included supporting materials such as sticks, rubber bands, and polystyrene cubes. However, we discovered that these additional materials may have caused participants to concentrate on materials that were not the deformable materials being studied.

5.3 Limitation and Future Work

One limitation of the study design is that the presence of materials other than the deformable materials, such as supporting materials like sticks and polystyrene cubes, may have impacted the design ideas and resulted in outcomes that were not solely focused on the deformable materials being studied. It is unclear whether the findings would have been different if participants were asked to create a different type of synthesizer or produce different sounds. In this study, we only focus on soft materials that our participants are not familiar with. A potential future direction could involve conducting a comparative study to explore how DMI designers compare deformable sensor materials to "hard" materials in DMI design, and how the distinct material properties impact their design process and approaches. Additionally, this study only examined the prototyping stage of the design process. A potential future study could be a longitudinal study that tracks designers as they develop their designs over a longer period of time, providing deeper insights into how the design process evolves as the designer gains more experience and skill with the instrument.

Sound production is a critical aspect of any DMI. In this study, the sound was limited to provide participants with a consistent design task. Future studies could examine sound design and observe how participants approach the design task. For musicians, the motivation to perform, compose, and record with deformable DMIs is likely to be strong, whereas this study was limited to laboratory-based exploration. A future study could examine the design of deformable DMIs for musical performance.

6 CONCLUDING REMARKS

This paper presents a study that explores the potential of deformable sensor materials in the design of digital musical instruments (DMIs). Drawing on existing examination of materiality and research through design approaches in HCI, we focus on how DMI designers perceive and understand deformable materials and then translate this knowledge into design practice and musical interaction. The study, which involved eleven participants, showed that critical thinking about the properties of materials and technical weaknesses, such as unpredictability, can inspire design and improvisation in musical activity. We do not provide any straightforward answers to questions about the role of deformable materials in DMI design. Instead, we view deformable materials as a probe for investigating the complex relationships between different elements in DMI design. In this paper, we also reflect on our methodology and the concept of "research through design" in the design of digital artifacts for musical interaction and Human-Computer Interaction. We believe that the results and reflective discussions of this work are beneficial to multiple communities, including musicians, DMI designers, and researchers in the field of design research.

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A INTERVIEW SCRIPTS AND PROMPTS

Concept and Design Process

(1) Could you please introduce (explain) how your instrument works?
(2) How did you design your prototype? Could you talk a bit about your process or how you were thinking during the design?
(3) Why you chose these materials? (if it is not mentioned)
(4) What did you think of the relation between sound and material? (if it is not mentioned)
(5) How did you design the gesture? (if it is not mentioned)
(6) Suppose if you had to give someone to play with your prototype, what would you tell them?

Problems and Difficulties

(7) What were some of the things that worked really well? (Why, and how did you know?)
(8) What were some of the things you tried that did not really work? (Why didn't they work, or how did you know?)

Prospects and Expectations

(9) If you had all the time in the world to work on this, what would you do next?
(10) If I asked you to do it all again from scratch, would you do anything differently?
(11) At any point, did you feel limited by the pre-settings of software (Pd), or as if it got in your way?
(12) If you could change anything or add any functionality that you wanted, that you can imagine, how would you improve the settings of sound/hardware?

Overall Feelings of the Activity

(13) Could you talk about your overall feelings about this activity?
(14) Do you think the provided materials are enough? What other materials or tools that you wanted to use but I didn't provide?
(15) For the overall of the study, was everything clear and straightforward?
(16) Do you have any questions and suggestions about the study?