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# Squeeze, Twist, Stretch: Exploring Deformable Digital Musical Interface Design Through Non-Functional Prototypes

## ABSTRACT

Deformable interfaces are an emerging area of Human-Computer Interaction (HCI) research that offers nuanced and responsive physical interaction with digital technologies. They are well suited to creative and expressive forms of HCI such as Digital Musical Interfaces (DMIs). However, research on the design of deformable DMIs is limited. This paper explores the role that deformable interfaces might play in DMI design. We conducted an online study with 23 DMI designers in which they were invited to create non-functional deformable DMIs together. Our results suggest forms of gestural input and sound mappings that deformable interfaces intuitively lend themselves to for DMI design. From our results we highlight four styles of DMI that deformable interfaces might be most suited to, and suggest the kinds of experience that deformable DMIs might be most compelling for musicians and audiences. We discuss how DMI designers explore deformable materials and gestures input and the role of unexpected affordances in the design process.

## Author Keywords

deformable interfaces, digital musical instruments, musical gesture, NIME. design practice, non-functional prototyping

## CCS Concepts

•**Human-centered computing → Interaction design;** Interaction design process and methods; Interface design prototyping; •**Human-centered computing → Interaction design;** Interaction design theory, concepts and paradigms;

## Introduction

Human-Computer Interaction (HCI) research has moved beyond concerns of rigid interaction devices to explore deformable materials and interfaces [1][2][3][4]. These deformable interfaces offer new opportunities for Digital Musical Interface (DMI) design [5][6][7]. For example, an advantage of using deformable interfaces for DMIs is that deformable materials have a guiding effect on their use, making them intuitive and easy to learn [8][9][10]. However, the nascent nature of deformable DMI design practice means that it is unclear how DMI designers design with deformable materials and how deformable material properties might influence DMI design practice. Furthermore, as there is no established design practice for deformable DMIs it can be difficult to design the mappings between gesture input and sound output [6]. In this paper we take a step back from deformable DMI implementation to reflect on deformable DMI **design** and ask *How might people design digital musical interfaces with deformable materials?* To explore this question we present a design exploration workshop in which we let designers explore the potential of deformable materials and deformable input in DMI design, and reflect on their design explorations. The primary contributions of this paper are: 1) A set of potential gesture mappings found in the deformable DMI design exploration workshop; 2) A description of the kinds of deformable DMI that emerge from the design exploration; 3) Suggestions for the role that deformable interfaces might play in DMI design and use.

The rest of this paper is organized as follows. First, deformable interfaces in DMI design and HCI are introduced. Then we present our design exploration workshop approach. This is followed by analysis of workshop outcomes. Finally, we discuss our findings and conclude the paper.

# Background

## Deformable Interfaces in Music

Deformable interfaces use “dynamic changes in a device’s physical shape for input and output” and offer new opportunities for HCI research [5][11][12]. Such interfaces offer hand-based, body-based, and multidimensional deformable input opportunities [7][13], using “dynamic changes in a device’s physical shape for input and output” [11]. The most common hand-based deformable inputs include bend, squeeze, stretch, twist, and push [7].

Digital Musical Instruments (DMIs) have been identified as one of the most creative and expressive forms of Human-Computer Interaction (HCI) [14][15], and DMI designers and researchers have explored the use of deformable materials in musical instruments and interfaces [1][16][17][18] [19][20]. Typically, deformable interfaces for music are used to control sound parameters, such as speed, pitch, and note duration [5]. For example, NoiseBear allows non-musicians and musicians to easily control various sounds by simple squeeze interaction [20]. Similarly, interfaces such as Zstretch demonstrate that stretchable controllers could be used to manipulate volume, pitch, and speed [17]. This design of mappings between deformable input and sound output is becoming a mainstream topic for both DMI designers and researchers [5][6].

As well as experimenting with the design of sound mappings, research has explored the design of deformable musical interfaces for different music activities. For example, Troiano et al. investigate the use of deformable interfaces for **performing music** which highlights the “usefulness of deformable interfaces in the musical context” [5]. Researchers have also shown that deformable musical interfaces can create “playful, visceral, and exploratory music experiences”, which have the potential for the public to have an **exploratory music** experience instead of designing for musicians only [1][19][21]. Whilst the research outlined above has explored deformable interfaces in mappings design and different musical activities, there is little current research on how deformable materials might inspire DMI design itself.

## Materiality in Design Research

The form and materiality (i.e. shape, colour, texture) of an interface plays an increasingly significant role in HCI research as attention is directed to the aesthetic dimension of interaction [22][23]. Form can be defined as “visual, physical, or temporal manifestation and/or configuration of a design” [24]. Form and materiality are inseparable for an object, therefore researchers consider form from three perspectives: material, meaning, and making [25]. Materiality is one of the critical features to consider when designing tangible interaction and deformable interfaces [26] as the physical properties of the interface suggest its functionality and the connections between digital representation and physical interaction. Indeed, the materiality of an artefact has been identified as a significant part of HCI design in terms of its tactile and embodied presence [25][27][28][29].

One approach to investigating materiality is through workshop methods, which have had a long and critical role in HCI research, allowing researchers to explore the creativity and new ideas of participants [30][31]. For example, Wilde et al. used workshops to explore the relations between embodiment, materiality and performativity [32], and Ratto reconfigured materials, users, and prototyping as critical making [33]. Andersen argues that material experimentation is an “under-described factor” in recent HCI research, and that material improvisation in their workshop approach could shift designers’ attention from design results to design process and to focus on reflections on the material [30].

## Exploring Design

One challenge for exploring deformable interface design is that there are currently many technical barriers to overcome when implementing deformable interfaces which distract from an open and exploratory design process, such as finding robust sensors and materials [18][19][34][20][35]. To be freed from such technical constraints, designers need to explore deformable interfaces in open-ended design contexts [36].

Open-ended design thinking can help designers create artefacts without implementation constraints and let their imagination run free, offering a novel and rich creative practice for designers [37][38][39]. Open-ended design approaches have been applied in material exploration research and musical instrument design research. For example, Lepri and McPherson [40] presented design value discovery through a hands-on design activity with open-ended design in communities of musical practice. Nordmoen et al. [41] explored the craft practice of designers exploring unfamiliar and ambiguous sensor material with an open-ended design context. 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 [30][41][42].

### Research Questions

In light of the potential for deformable interfaces in DMI design highlighted above we explore the following research questions (RQs) in this paper:

- RQ1: What mappings might DMI designers make between deformable input and sound output?
- RQ2: What kinds of DMIs do deformable materials inspire?
- RQ3: What uses of DMIs might be more suited to deformable materials?

## Design Exploration Workshop

We developed an open-ended design thinking workshop building on Andersen’s Magic Machine Workshop [30] to explore our research questions. In our workshop we focus specifically on how DMI designers think of deformable materials and deformable input in musical contexts without technical constraints. In our workshop we focus specifically on how DMI designers think of deformable materials and deformable input in musical contexts without technical constraints -- designers were invited to make an imagined instrument with different non-functional deformable inputs. Our motivation for taking this approach was to explore subjective design experiences through the process of making, and to also liberate participants (the DMI designers) from technological concerns and limitations and allow them to ask themselves ‘why’ instead of ‘how’ to design DMI with deformable input [30][40].

As the workshop took place in the UK during a period of lockdown in which in-person social interaction was heavily restricted we structured our workshop to take place remotely with participants taking part on their own and in their own home, connected to fellow participants and the workshop facilitator using Zoom video-conferencing software.

Before the workshop started, participants completed a questionnaire about their background and experience in DMI design. Then 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. The overall duration of the workshop was around 60 minutes.

## Participants

Twenty-three participants (17 male, 6 female) were recruited by academic mailing lists (NIME community: community@nime.org) and social networks. Based on the questionnaire results, participants experience in designing DMI ranged from novice designers to experienced designers. Regarding the level of DMI design expertise, 4/23 of the participants did not have much specific knowledge and experience related to digital instrument design. Most of the participants (20/23) had never used deformable input in DMI design before. All participants had experience either in playing an acoustic instrument or recording/producing music. There were eight workshops on Zoom with an average of 3 participants per workshop.

## Workshop Design

Following Andersen's methodology in which workshop materials should remain mundane and everyday [30], participants in our workshop were invited to search for everyday objects in their home. Participants were asked to prepare the materials before the start of the workshop and were informed that the key aim of the material searching was to find materials that provide some deformable gestures (i.e. stretch, bend, press, twist, and squeeze). These gesture inputs were selected as Troiano et al. [5] found them to be the gestures most commonly used by musicians in a study on the use of deformable interfaces for performing music.

We primed participants with the material search aims with an intention that as they began to look for the appropriate materials, they would hopefully start to unconsciously think of questions such as 'what kind of materials could provide such deformable input' and 'what kind of everyday materials will be suitable for a design activity'. The task of searching available materials became the first source of insights about participants' assumptions about deformable input. Unlike Andersen's approach [30], we invited participants to have an open discussion before the Prompt activity to discuss their general expectations and ideas on the design activity. The six steps of our workshop were:

1. A brief introduction of the aim and procedure was presented. With participants' permission, the facilitator started the video recording.
2. Participants were then given 10 minutes of open discussion of their understanding of the materials they had collected and the design activity.
3. Participants were then provided with Prompt Activities: connect words and drawings to deformable input gestures including bend, press, stretch, twist, and squeeze.
4. The participants were then asked to use their available materials to build imagined instrument(s).
5. Once the group finished building the prototypes, each participant was invited to 'play' their instrument(s) and explain the sound they imagined.
6. Then, each presentation was discussed within the group.

## Data Collection and Analysis

The workshop sessions were audio and video recorded and then transcribed to facilitate thematic analysis. The data analysis included the analysis of workshop outcomes (i.e. design output), interview transcriptions of the group discussion, and observations during the study. We followed the guidance of thematic analysis [43] and conducted a data-driven approach to extract participants' ideas about using deformable input. We generated around 90 codes and identified six themes which are presented in the following section.

In total, 28 prototypes (5 participants built two prototypes) were built in the design activity of the study. Note that some participants only presented a prototype design concept and did not include the details such as the mapping design. Table 1 presents some examples of prototypes built during the workshop with the description of the construction, the materials and the input gestures they used, and manipulation of the prototypes.

**Table 1: Some examples of the prototype built during the workshop**

| P | Construction | Manipulation and Gesture Input | Materials |
|---|---|---|---|

| | | | |
|---|---|---|---|
| P2 | A MIDI controller that maps the shapes and sound parameters. | Control the sound by changing the shapes of the rubber bands. (stretch, press) | Rubber bands, metal box, clips |
| P3 | A tangible synthesizer box that the controls of sound parameters via some tangible components. | Use a tangible way to control the sound(e.g. squeeze a pink foam to change the pitch). (twist, press, squeeze, touch, stretch) | Clay, tinfoil, foam, paper, rubber band |
| P4 | A wearable musical interface that allows people to use two hands to control the sounds. | Wear the interface on the left hand and control it via right hand (or versa). (stretch) | Paper, spring |
| P5 | A Hand Theremin that allows people to control  the sound by touching and manipulating the material. | Interact with the material via hand gestures. (squeeze, bend, twist) | Paper plate, fabric, metal wire, clay |
| P9 | A harmonica style instrument made in clay straw which allows user to blow into it with two hands manipulation. | People could play with it by pressing the buttons, and stretch the twine. (press, stretch) | Clay, twine, straw |
| P12 | A spring shaped structure and a fabric covered box as base. | Controlling the pitch through touching different area of the shape, and push/stretch the handle to create some sound effects. (squeeze, touch, push/stretch) | Foam, clay, metal wire, fabric, twine, paper clips |

| | | | |
|---|---|---|---|
| P14 | A bendable clarinet which made in plastic bottle and elastic bands. | Using deformable inputs such as bend and stretch to add sound effects. (twist, press, twist) | Plastic bottle, rubber bands |

# Findings

Six themes were identified from participants' feedback and observation of their design work: i) Design inspirations and processes; ii) Deformable input in musical context; iii) Interaction styles; iv) Tangible manipulation of sound; v) Music perception; vi) Imagined instruments in open-minded design context.

## Design Inspirations and Processes

Three types of design inspiration for deformable DMIs emerged from our workshop:

1. Design based on existing instruments (including acoustic and digital instruments),
2. Design based on the material properties, and
3. Design based on the way of interaction.

For those prototypes which were designed based on existing instruments (P5, P9, P14), participants explained that they wanted to create different interactions for the existing instrument when they presented where their ideas came from. Participant 3 described the prototype as "a Hand Theremin" which allows people to control the sound by touching and manipulating the material. The second type of instruments (P3, P4, P10, P12) are described as design based on the material properties since participants connected the properties of the materials to the sound design and interaction method. P3 and P5 described materials such as foam and clay that make people subconsciously want to squeeze and press. P15 mentioned that material such as paper reminiscent a crisp and clear sound as the material itself is very light. The third type of instrument was designed for specific interaction. One example is a wearable instrument (P3) which shows a way of playing with two hands, more like one hand is responsible for chords, and the other hand is responsible for melody.

## Deformable Input in Musical Context

In selecting the materials, participants' material selection showed their initial understanding of deformable input, which is the consideration of 'what kind of materials could provide such deformable input'. From the results, participants not only used soft materials to achieve deformation, but they also used material such as cardboard to build a physical structure to allow them to stretch and bend (one example in Figure 1 (e)).

**Table 2: Mappings between gesture input and sonic/musical response in Prompt Activity** (Numbers indicate the number of participants referring to each category)

| Sound | Squeeze | Twist | Stretch | Press | Bend |
|---|---|---|---|---|---|
| Pitch Control | 5 | 6 | 6 | 2 | 14 |
| Timbral Changes | 1 | 2 | 2 | 1 | 1 |
| Volume/Amplitude | 5 | 5 | 4 | 3 | - |
| Filtering | 2 | 2 | 2 | - | 1 |
| Speed/Tempo Changes | - | 1 | 4 | 1 | 1 |
| Distortion | - | 2 | 2 | 1 | 1 |
| Modulation | - | - | 1 | 1 | 2 |
| Panning | - | 1 | - | - | 1 |
| Envelope (ADSR) | 1 | - | - | - | - |
| Trigger Sound | 3 | - | - | 4 | - |
| On/Off | - | - | - | 4 | - |
| Percussive Sounds | - | - | - | 3 | - |
| Spectral Content | - | - | 1 | - | - |

| | | | | | |
|---|---|---|---|---|---|
| Dynamics | - | 1 | - | - | - |
| Delay | - | 1 | - | - | - |
| Reverb | 1 | - | - | - | - |
| Far/Close | - | - | 1 | - | - |
| Wet Mix | 1 | - | - | - | - |

Table 2 and Table 3 present the mappings between deformable input and sound output identified in responses to the prompt activity and the design activity. In terms of the results of Prompt Activity (see Table 2), the design of the mapping is mainly in terms of two aspects. Firstly, the imagination of mappings design is emerging from the understanding of the gesture inputs—considering the meaning of gesture input in the prompt activity inspired participants creativity in design activity. Participant 15 indicated that the final design came from “by starting to think about gestures and interacting with a possible instrument”. Seven participants (Participant 4, 5, 6, 10, 12, 13, 15) reported thinking about what those gestures might mean to music inspired them to think about the kind of interfaces they want to build, and to think about “what could modify with gesture” (Participant 10). The second aspect of inspiration in the mapping design of Prompt Activity is developing ideas from the existing musical instruments. Four participants (Participant 3, 5, 7, 8) mentioned that the ideas of mappings design came from the gesture input on existing musical instruments they had played or known before.

**Table 3: Mappings between gesture input and sonic/musical response in Design Activity**

| Sound | Squeeze | Twist | Stretch | Press | Bend |
|---|---|---|---|---|---|
| Pitch Control | 2 | 3 | 8 | 3 | 4 |
| Timbral Changes | 2 | 1 | 2 | 4 | 1 |
| Delay/Time Changes | 1 | - | 3 | 2 | 2 |
| Sound Effect | 3 | 1 | 2 | - | - |

| | | | | | |
|---|---|---|---|---|---|
| Volume/Amplitude | - | 2 | - | 1 | 2 |
| Distortion | 2 | 2 | - | - | - |
| Reverb | - | 1 | 2 | - | - |
| Modulation | - | - | 1 | - | - |
| Harmonies | - | - | - | - | 1 |
| Trigger Sound | - | - | - | 2 | - |
| Mute | - | - | - | 1 | - |
| Spectrum | - | - | - | - | 1 |
| Mix | - | - | 1 | - | - |

Regarding the results from the Design Activity (see Table 3), most (59/62) of the deformable gesture input (i.e. squeeze, twist, stretch, press, and bend) are designed as continuous feature modulation  (e.g. timbre, amplitude or pitch). Participants described this continuous modulation as “gradually go down and go up” (Participant 12). The changing of sound parameters depended on the amount of force exerted by the users (i.e. the greater the stretching force, the more significant the change in output). The mapping design like this was suggested to make the musical interaction more “intuitive and understandable” (Participant 3). Another type of mapping design is discrete triggering modulation, for example triggering on/off events. Only press gesture was designed into discrete triggering modulation (e.g. two designed for trigger sound, one designed for mute).

## Interaction Styles

We categorised the design prototypes into four types from our analysis of our observations and interviews: hand-held instrument, surface-based instrument, wearable instrument, and hybrid-mode instrument.

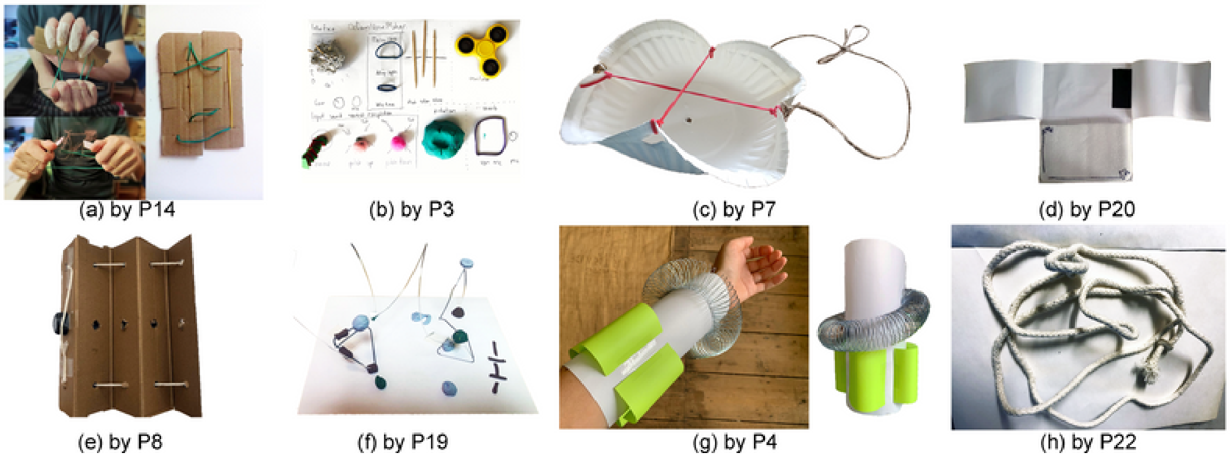
(a) by P14 (b) by P3 (c) by P7 (d) by P20
(e) by P8 (f) by P19 (g) by P4 (h) by P22

Figure 1: A selection of the outcomes from the workshop. From left: (a)(e) Hand-held Instrument, (b)(f) Surface-based Instrument, (c)(g) Wearable Instrument, (d)(h) Hybrid-mode Instrument.

### Hand-held Instrument

There were 12/28 prototypes identified as hand-held instruments since they were played by two-handed input (two examples in Figure 1 (a)(e)). When participants presented this type of prototype, they performed the way of playing such an instrument. Participants’ descriptions referred to traditional acoustic instruments, and some unique modulations of deformable input were emphasised. For example, P8 introduced the instrument as “holding like an accordion”.

### Surface-based Instrument

Some mock-ups (4/28) were designed as surface-based (or table-based) instruments that allow uses to interact by shaping, moving, and manipulating different components on it (two examples in Figure 1 (b)(f)). In particular, one type of surface-based instrument can be described as tangible manipulation of some sound parameters (see Figure 1 (b)). One prototype that emerged in our workshop was like a “tangible synthesiser desk”, which allow users to control the sound parameters tangibly instead of pressing buttons or moving sliders.

### Wearable Instrument

Some prototypes (3/28) are presented as wearable instruments which provide one-handed or two-handed input accordingly  (two examples in Figure 1 (c)(g)). One type of wearable instrument that emerged in the workshop are head-mounted (see Figure 1 (c)). Two designers wore the prototype as wearing masks and manipulated the prototype with two hands. One designer pointed out that singers could play this artefact by manipulating their voices. Another type of this kind of prototype is which could be worn with one hand/arm and interact with it by the movement of the hand/arm and the fine control by the other hand (see Figure 1 (g)).

### Hybrid-mode Instrument

Some prototypes (9/28) were categorised as a hybrid-mode instrument as they are presented to be played flexibly (two examples in Figure 1 (d)(h)). Participants also described this type of instrument as “no strict method to play” (Participant 17). These kinds of prototypes mainly are constructed or designed based on the material itself—the way of playing them thus varied the properties of the materials. One example that emerged in our workshop is controlling the sound by folding, crumpling, and placing paper (see Figure 1 (d)). Although it was argued that this prototype did not include any deformable input, it contributed to a way of thinking that simple materials produce complex actions and results.

> “It has a memory because once you fold it and you play a bit with it, it will keep some scratches on it. So, this could also be something interesting, like an instrument with a memory (see Figure 1 (d)).” (Participant 20)
>
> “The thing that actually got me more excited, was just playing with a piece of rope. It’s just really complex, like you can put a lot of gesture into it, you end up with such complex shapes (see Figure 1 (h)).” (Participant 22)

## Tangible Manipulation of Sound

As expected, designing non-functional prototypes focusses DMI designers attention to the materials, tangible interaction, deformability, and physical expressiveness. Our data suggests that interaction with materials can also stimulate designers’ imagination. The quote from Participant 7 exemplifies this point: “playing with the materials because it is also tactile and gestures, that is when you start to imagine possibilities that maybe do not already exist”.

Participants mentioned design feedback that can be linked with direct material manipulation and spatial interaction. Six participants (Participant 4, 7, 9, 12, 22, 23) mentioned that they came up with the design ideas when they started to “play” with the materials. Eleven participants (Participant 5, 7, 9, 10, 11, 12, 13, 16, 18, 21, 23) considered the interaction and input as to their first step in designing such interfaces. Five participants (Participant 3, 7, 10, 18, 21) reported that they designed the sound and the functionality of the interfaces based on the haptic manipulation. Participant 21 mentioned that “different tactile sensation” offers “different ability to manipulate the tone”, similar in acoustic instruments.

From participant feedback, we suggest that there were primarily two aspects of physical expressiveness explored in the design workshop. The first aspect is the rich expressiveness of the material itself, which allows designers to think about using the material’s affordances and constraints, e.g. building a DMI by “reassemble the physical constraints of different ranges” (Participant 20). Another reason was the variety of gestures that could be imagined. Eight participants (Participant 3, 5, 11, 12, 16, 19, 21, 22) reported that the objects’ substantial materiality inspired them to explore the relationship between different gestures and material properties. For example,  “you can squeeze and bend the pitch literally by just like moulding in the clay”  because “the clay’s kind of lets you do so much” (Participant 5).

## Music Perception

A theme related to the perception, or more accurately, possible reception of deformable DMIs was also identified in our study. Specifically, how deformable DMIs might be perceived by musicians and audiences. Six participants (Participant 3, 11, 19, 20, 22, 23) argued that DMI with deformable input was more suitable for exploratory activities than performing in front of the audience. According to Participant 22, sometimes an instrument’s use in performance is unnecessary if it is “enjoyable to use” and “as expressive in a particular way”.

Another aspect of the experience for deformable DMI is coming from the audience’s perspective. As suggested by Participant 23, one potential issue of using deformable musical interfaces in performance was that it was “extremely difficult to perceive from the audience”. Five participants (Participant 3, 15, 20, 22, 23) reported that the experience of interacting with deformable interfaces was associated with interacting with the material. When the audience cannot touch the interface, they will not be able to perceive the interaction. Participant 15 pointed out that the design challenge of using deformable interfaces in DMI might be “how do we make an instrument that is interesting to play with, and also interesting to listen to”.

Three participants  (Participant 20, 22, 23) suggested that an “instrument created with no intention of performing to an audience” might be one solution, which means “a musical instrument for creating music for the musicians” (Participant 22). For performers, “it feels more of a personal experience or less of a spectator experience”

(Participant 23). This result is similar to findings in current literature about the problem of audience understanding and engagement of DMI [44].

## Imagined Instruments in Open-minded Design Context

From observations in our study, participants' design process could be summarised in four phases: (i) the conceptual phase (prompt activity), (ii) the experimenting phase (design activity), (iii) the implementation phase (design activity), and (iv) the performance phase (presentation and demo). The design inspirations emerged in different design phases, and some overlapped within the design process.

Our data indicates that the open-minded design context allows participants to imagine the possibility of interactive gestures and materials properties in a musical context. This design environment helps designers consider different aspects of materiality during the design process. In the ideation phase, the understanding of the material allowed participants to evaluate their design requirements and make the design decision with the available materials (Participant 2, 3, 6, 13, 16, 21, 22). More than half of the participants mentioned that the results had exceeded their expectations; they did not expect they could make any design decisions in such a short time with those unfamiliar materials.

Another aspect is that "without technical constraints", participants had more freedom to deeply think of the gesture input and interaction (Participant 23). Participant 23 viewed design without any technical constraints as "a great opportunity because it is imaginary". This design approach was reported to be helpful to get more inspiration with no bound of technical limitations. For example, Participant 5 reported that when she designed without thinking of implementing the prototype, she found she would more focus on "thinking the design of gestures and interaction". Moreover, design ideas were generated quickly through interacting with materials, which surprised many participants (Participant 2, 3, 4, 5, 6, 7, 8, 13, 15, 16). Five participants (Participant 2, 13, 15, 20, 23) identified themselves as "not a tangible guy", "usually work digitally", and "do not build much stuff", but after the hands-on activity, they reported "something on my adopt in the future", and "motivated to maybe try to turn this into a real instrument".

Participants who enjoyed the design activity also reported the problems of other kinds of design workshops. For example, the typical format of DMI design workshops was suggested to be "take the script, go to GitHub, do this, do that", which participants noted "did not have much space for imagination" (Participant 23).

# Discussion

Reflecting on our findings we suggest that participants generated unique design ideas from everyday objects in three ways: i) rethinking the materials in a specific context (music in this study); ii) exploring design concepts with concrete objectives (making a non-functional DMI and demo); and iii) encountering unexpected affordances during design exploration.

From the results, some participants emphasized their reflection on the interfaces' materiality and how the material properties connect to their design concepts during the discussion (after the design activity). In this way the prompt activity and pre-discussion in this study allowed participants to talk about and re-think the meaning of the materials which led to the prototype's interaction design and physical form becoming clearer. This process is similar to the description of material driven design methods in the literature, such as understanding the material, creating materials experience vision, manifesting materials experience patterns, and designing material concepts [45].

We suggest that the time pressure and the concrete objective for demonstration encouraged more focused and concrete design output. The limited time forced participants only be able to capture the most significant, such as finding the most suitable materials to fit their ideas within the time, and the use of significant properties of the materials. As reported in the previous section, results show that eight participants reported that the objects' materiality inspired them to explore the relationship between different gestures and material properties. For example, Participant 22 mentioned that the "imperfect and complex of the materials" show the "real richness of expression" of the interface, and such richness of expression is coming from the material itself.

The constraints and affordances of materials have been shown to be a significant guide and influence on interactions [46]. In this study, the unexpected affordances of the material provided a unique design perspective. For example, Participant 15's design is a bendable piano made of paper. The effect is that the keys are very light as they are made of paper, so people can interact with it by blowing air, and even "let it go as a sort of instrument that is played by the wind". We found that the uncovering of unexpected affordances occurred the later stages in design process - when the implementation of initial idea was done.

## Design Approaches

Reflecting on our results we identified two main design approaches: i) gesture-guided design; and ii) form-driven design. We noted that there were two forms of gesture-guided design process: (1) designers re-thinking the meaning of deformable gesture input before the hands-on activity, and (2) designers focussing on gesture design during the design practice. For the first case, 10 participants noted that the prompt activity was helpful for them to generate ideas of how gesture inputs and sound output could be related. Participant 4 mentioned that “it is a good starting point to think about what possibilities there could be” with those gestures. One example for the second case is that some participants design their pieces with a clear goal. For example, Participant 18 wanted to make a guitar-like interface that allows people to interact with the prototype by plucking the strings made by multiple materials.

In terms of form-driven design we noticed that some participants focused on physical design or physical qualities during the design process. For example, the hand-held instrument and wearable instrument prototypes as reported in the findings section (see Figure 1). Such a design process leads to a more “visual” design result, and it is easy for others to understand the designer’s ideas through the appearance. In the presentation after the design activity, participants mainly talked about their pieces’ physical shape and how the physical design connects to the interaction. For example, Participant 8 noted that “I would usually start with the physical presence of the object and let that dictates how I would want to interact with it, and what gestures I would use”. Or, in Participant 22’s design the rich expressiveness of the material itself means that the prototype “ends up with such complex shapes”. Such reflection on the form of the design occurred throughout the design process, for example, participants 7, 8, 15 mentioned that when they interacted with their pieces for a while during the demo, new ideas emerged about the design form. We suggest that this approach is similar to a form-driven design approach widely used in the design domain (i.e. fashion design, architecture design, product design, and graphic design) [22].

## Limitations

There are some limitations to our work that might affect the results. One limitation of the study design is that participants were not given the same set of materials and tools to experiment with. Although an instruction of finding suitable materials were introduced at the beginning of the study, everyone’s understanding of appropriate materials was different. However, as discussed previously, participants’ material selection exemplified their initial understanding of what might be deformable input with regard to the implicit design question of ‘what kind of materials could provide such deformable input’.

The study was conducted online, and so the data collection of the video recordings was inherently problematic and there was no opportunity for in-person discussion and interaction. However, such an approach does allow for including participants who might not normally travel to take part in studies in design workshops and universities.

## Concluding Remarks

This paper presented a study which explored the design of deformable musical interfaces through non-functional prototype design practice. We found that participants generated deformable DMI design ideas through rethinking the materials and exploring unexpected affordances within a musical design context. We also observed both gesture-guided and form-driven approaches to designing deformable DMIs. Future research needs to explore how DMI designers might take such design decisions and approaches through to the implementation phase. For example, exploring how DMI designers implement the mapping between deformable input and sound output, examining whether design variations depend on the properties of the materials, or even how DMI designers would design the materials themselves.

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## Ethics Standards

This study was approved by anonymized institution’s Research Ethics Committee (Reference No: xx). All participants provided informed consent, and participants received £10 as compensation for their time. There are no observed conflicts of interest in this study.

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