Deformable Interfaces for Performing Music

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ABSTRACT
Deformable interfaces offer new possibilities for gestures, some of which have been shown effective in controlled laboratory studies. Little work, however, has attempted to match deformable interfaces to a demanding domain and evaluate them out of the lab. We investigate how musicians use deformable interfaces to perform electronic music. We invited musicians to three workshops, where they explored 10 deformable objects and generated ideas on how to use these objects to perform music. Based on the results from the workshops, we implemented sensors in the five preferred objects and programmed them for controlling sounds. Next, we ran a performance study where six musicians performed music with these objects at their studios. Our results show that (1) musicians systematically map deformations to certain musical parameters, (2) musicians use deformable interfaces especially to filter and modulate sounds, and (3) musicians think that deformable interfaces embody the parameters that they control. We discuss what these results mean to research in deformable interfaces.

Author Keywords
Deformable interfaces; user interfaces; music; controller; usefulness; user study.

ACM Classification Keywords
H.5.2 [Information Interfaces and Presentation]: User Interfaces.

INTRODUCTION
Deformable interfaces are emerging in the field of HCI, for instance as elastic displays [19], bendable smartphones [5], or soft controllers [11]. Because they are made of flexible materials, deformable interfaces allow for unique gestures such as crumpling [30], squeezing [9], and stretching [29], all of which would be impossible with rigid interfaces. Yet, it is unclear how and when deformable interfaces might be advantageous compared to rigid interfaces.

Existing prototypes of deformable interfaces have been used and evaluated mainly in the lab during controlled experiments [16]. While lab studies have helped to test prototypes in a systematic way, they provided little data on users' reactions in the wild or on the usefulness of deformations in a particular domain.

The present paper argues that a study of deformable interfaces conducted out of the lab would show more realistic use and responses from users, indicating when these interfaces can be useful and how they are used. We report such a study in the context of electronic music. We chose the music domain because much earlier work have explored deformable interfaces for music [4,7,10,26,35], and because performing music is a highly challenging and expressive real-time activity. Such a study will help understand how users take advantage of different materials, shapes, and deformations to control sounds.

To investigate the use of deformable interfaces for performing music, we run three workshops borrowing techniques from participatory design [3] to receive input from musicians on how to use deformable interfaces in music. Next, we give a set of interactive deformable interfaces to professional musicians, and ask them to use those to perform music at their studios. Also, to understand how musicians would incorporate deformable interfaces with their existing equipment, we allowed them to integrate the use of non-deformable interfaces (e.g., MIDI controllers) in their performances.

The present paper makes two contributions to research on deformable interfaces. First, we contribute design implications for deformable interfaces by reporting findings from three workshops on how different materials and shapes relate to musical features. Second, we contribute findings on the use of deformable interfaces out of the lab by reporting results from a performance study where musicians used deformable interfaces to play music and commented on their experiences. Since our primary goal is not develop new musical interfaces, we discuss how the results of the workshop and the performance study extend beyond the music domain and what they mean to research on deformable interfaces.

RELATED WORK
Deformable interfaces have been proposed as elastic displays [6,18,21,34], flexible and elastic hand-held devices [7,9,20,24,31,32], bendable smartphones [1,5,12,13], sponge and foam controllers [21,23], and music controllers [4,7,10,26,35]. Studies have shown how deformations can be used as input techniques for various applications in HCI,

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including depth navigation on mobile devices [5], animation [28], and 3D modeling [25]. Several studies have evaluated deformable interfaces, for instance by exploring the effect of interfaces size and materials stiffness on users' interaction [14,16], users' preferred gestures [15,17,29,32], and the use of multi-touch input on deformable surfaces [2]. However, deformable interfaces have not yet proven to suit a specific domain and possibilities for experimentation are still open. Since we evaluate deformable interfaces in music performances in the present paper, we focus the rest of this section on reviewing related work that introduces deformable interfaces to music.

Deformable Interfaces in Music

Table 1 shows a summary of the key related work on deformable interfaces used in music. We choose these papers in particular because they appeared either at NIME or CHI conferences, providing results for research on both musical interfaces and deformable interfaces. We discuss these deformable interfaces focusing on: (1) materials and deformations, (2) sensing technology, and (3) their use in relation to music.

Materials and Deformations

Deformable interfaces need to resist extreme deformations while being able to be controlled effortlessly. Therefore, materials used to build them need to be both robust and flexible. Foam is soft, robust, and affords well deformations like squeeze, push, and twist. Foam has been used to build cubic [11] and spherical [9,10] deformable music interfaces, which sometimes were also covered with fabric [35] or woolen yarn [9], so as to deliver organic feel in touch. However, foam is not very stretchable and stretch deformation, if too extreme, might feel uncomfortable or even break the material. Fabric can be more flexible than foam; for instance, materials like lycra or elastane can be allow for extreme stretching because they are very elastic. However, fabric can wear or tear with prolonged use [7]. Rubber and silicone can endure more than fabric with repeated use and have been used to build shape-retaining deformable interfaces [26,37]. They allow for easy bending or twisting, but they can be hard to stretch. Sculpton [4] used flexible metal springs and wooden spheres covered in latex to create a soft music controller in the shape of tetrahedron, allowing for squeezing, stretching, and pressing. Clay has also been used for musical interaction [33]; it is shape-retaining and can be broken and rejoined. However, the above listed materials have been presented to users only individually and no previous studies attempted to investigate how users understand or react to different shapes and materials that deform.

Paper	Materials and Deformations	Technology	Use
Sonic Banana [21]	Rubber, (bend, twist, stretch)	Bend sensor	MIDI Controller
The Embroidered Music Ball [29]	Fabric, conductive thread, (squeeze, stretch)	Pressure sensor	MIDI Controller
A Malleable Interface [11]	Conductive foam, (poke, twist, press, squeeze)	Conductive foam, copper wire	Sound Controller
A Malleable Device [18]	Paper board, rubber, wood, (press, push)	Camera sensor	Data Sonification
Clay Tone [27]	Clay, (stretch, twist, squeeze, press)	Camera sensor	Sound Controller
Zstretch [7]	Fabric, wood, (stretch, squeeze, twist)	Resistive strain gauges	Sound Controller
MARSUI [30]	Silicone, metallic wire mesh, (bend)	Bend sensor	Auditory Feedback
The Music Ball Project [10]	Sponge, (squeeze)	Microphone	Sound Controller
NoiseBear [9]	Conductive foam, woolen yarn, (stretch, squeeze, twist)	EEG electrodes, conductive thread	Sound Controller
Sculpton [4]	Wooden spheres, metal springs, latex, (squeeze, stretch, press)	Slide potentiometer, light dependent resistor (LDR)	Sound Controller

Table 1: Key related work and their main four characteristics

Sensing Technology

Sensing deformations presents various challenges. To sense deformations, a camera-based approach may be used, or materials need to be either conductive or embedded with sensors. Bend sensors were embedded in Sonic Banana [26] to sense bend and twist. However, bend sensors are fragile at their terminal part and can break with frequent use. To overcome this problem, MARSUI [37] used electrical semi-conductive tape as custom-made bend sensor. Kiefer used conductive foam to sense various degrees of pressure and squeeze [11]. NoiseBear [9] improved the robustness of Kiefer's design by adding conductive threads and cushion stuffing, so as to lower the latency of the conductive foam. Zstretch [7] used resistive strain gauges sewn at the edge of a lycra cloth in order to detect stretch. However, this approach presented problems over time, such as lowered sensitivity and the need for frequent repairs. Sculpton [4] embedded a slide potentiometer in its first version and light dependent resistor (LDR) in its second version, so as to detect when the springs are stretched. The configuration with LDR was functional but required several connections. Finally, two deformable interfaces have used a camera-based approach in order to sense deformations [19,33]. Camera-based approaches are good for prolonged use and can be effective, but deformations are sensed only when the interface is in the visual field of the camera.

Use and Evaluation

Earlier deformable interfaces for music, like Sonic Banana [22], were mostly used as MIDI controllers to manipulate sound parameters such as speed, pitch, and note duration. One quality that deformable interfaces showed in relation to music was their intuitiveness and ease of control. For instance, NoiseBear [35] supported simple squeeze interaction to control various sounds and it could be easily used by novices as well as experienced musicians. Other interfaces like Zstretch [7] showed how a stretchable controller could be used to manipulate volume, pitch, and speed in an alternative way. Sculpton [4] was used to control and generate sounds by stretching and squeezing the body of a soft tetrahedron and it was used by its creator for several live performances [39]. Kiefer used conductive foam to build a small cube-shaped interface [11] and evaluated it with eight musicians, who described Kiefer's interface as more expressive compared to regular knobs or faders. However, his study evaluated the interface only based on qualitative information, where participants were constrained to modify only specific sound parameters (i.e., phase modulation).

The deformable interfaces described above were mainly evaluated and used in the lab. Only few studies exist that are not lab-based (see [10,33]). Furthermore, users were never presented with different interfaces together, or asked how different materials and shapes affect musical interaction. Therefore, the empirical understanding of the use of deformable interfaces in music is rather one-sided in terms of methodology. To address these shortcomings, we organized three workshops to gather insights from professional and amateur musicians and a study out of the lab to investigate the use of deformable interfaces. In the next section we describe the workshops.

WORKSHOP

We conducted three workshops with nine musicians (three musicians for each workshop) on how to use deformable objects for music performances. The aim of the workshops was to inform us on how deformations could map to musical parameters and how different shapes and materials invite to musical interaction.

The structure of the workshops was based on principles of participatory design, focusing especially on activities such as experimenting with mock-ups, horizontal prototyping, thinking aloud, and brainstorming [3]. We decided to use the workshop method because it has proven to be effective when wanting users to explore and generate ideas on new technology [31]. Findings from the workshops were used for designing the deformable interfaces to be used later in the performance study.

Participants

Participants were recruited among professional and amateur musicians experienced with electronic music. We recruited a total of nine participants. Four participants were DJs, while five were performing live electronic music; all of them were experienced with music production. Furthermore, four participants were experienced with building MIDI controllers and modifying electronic music devices through circuit bending. Eight participants were male and the average age was 29.7 ($SD = 4.5$). We ran three workshops with three musicians per workshop. At the end of each workshop, participants received a small gift as a compensation for their time.

Materials

Based on related work we developed a set of 10 non-interactive mock-ups (see Figure 1). Participants used the 10 mock-ups as the main inspirational tool throughout the workshop. Table 2 indicates the similarities and differences between the mock-ups and related work.

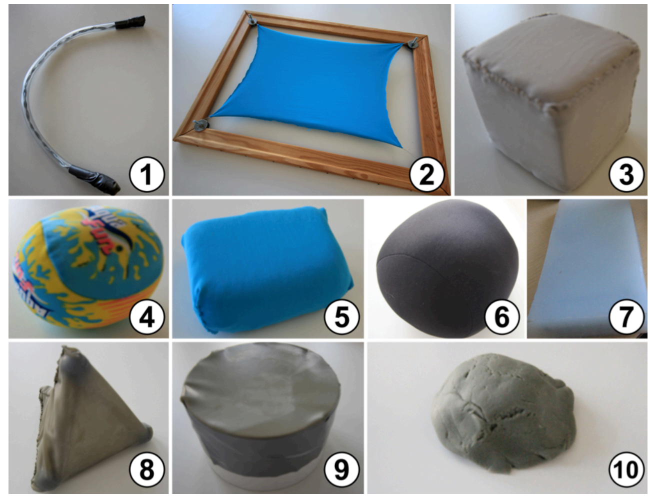

Figure 1: The object used during the workshop inspired by related work.

Workshop Set-Up

Each workshop was divided into three phases: (1) a *familiarization* phase, (2) a *simulation* phase, and (3) a *brainstorm* phase.

The *familiarization* phase was designed to introduce participants to the deformable objects. The goal of this phase was to let participants explore different materials and the deformations that they afforded. We encouraged the participants to start thinking about deformable objects as music interfaces already in this phase.

The *simulation* phase was designed to simulate possible real uses of the deformable objects for controlling sound. The goal of this phase was to receive suggestions from

No.	Paper	Original	Our Objects
1	Sonic Banana [21]	Orange rubber, 60 cm length	Transparent rubber, 60 cm length
2	Zstretch [7]	Green lycra fabric, wooden frame (36 cm length)	Blue lycra fabric, wooden frame (60 cm length)
3	A Malleable Interface [11]	Conductive foam, cube shaped, hand-sized	Foam, cube shaped, fabric covered, hand-sized
4	The Embroidered Music Ball [29]	Cushion stuffing, conductive foam, woolen yarn covered, hand-sized	Cushion stuffing, foam, fabric covered, hand-sized
5	The Music Ball Project [10]	Ball shaped sponge, rectangle shaped sponge, hand-sized	Ball shaped sponge, rectangle shaped sponge, hand-sized
6	NoiseBear [9]	Conductive Foam, Woolen Yarn	Stretch, Squeeze, Twist
7	MARSUI [30]	Blue silicone + metallic wire mesh, size N.A.	White silicone + metallic wire mesh, 18 cm
8	Sculpton [4]	Wooden spheres, metal springs, red latex, hand-sized	3D print spheres, metal springs, grey latex, hand-sized
9	A Malleable Device [18]	Paper board cylinder (16 cm radius, 7 cm height), transparent rubber, wood	Plastic cylinder (16 cm radius, 7 cm height), grey latex
10	Clay Tone [27]	Clay	Clay

Table 2: Differences and similarities between related work and our objects.

participants on how deformations could map to different musical parameters. During this phase a selection of sounds was played, which participants were asked to map to deformations. Each time a sound or an effect was played the participants picked a deformable object and suggested a potential deformation for that specific sound. Participants explained their choices by thinking aloud. The sounds played during this phase were: (1) generative sounds (keyboard, drums), (2) samples and loops, (3) sound modulations (volume, pitch, tempo, frequency), (4) filters (low pass, band pass, high pass), and (5) sound effects (delay, reverb, chorus, flanger, distortion, bit-crush). We used sounds from the default set of most electronic music software (e.g., Ableton Live®, Logic Pro®).

Finally, the *brainstorm* phase was included to let the participants generate ideas on how to use deformable objects for performing music. The goal of this phase was also to understand which of the 10 deformable objects the participants would use for real music performances. To help participants generate ideas, we used various support tools such as big paper sheets and colored post-its. We instructed participants to only generate ideas based on the 10 deformable objects used in the workshop.

Procedure
The participants were welcomed and introduced to the set-up, the workshop's purpose, and its structure. The workshop started with the *familiarization* phase, where participants could explore the deformable objects for 15 minutes. Then after a five minute break, participants went through the *simulation* phase for 50 minutes. After this, participants took another five minute break before going to the *brainstorm* phase. The *brainstorm* phase lasted 40 minutes.

Analysis
We used Microsoft Excel to code the videos recorded during the workshops. We coded each instance of deformation suggested by participants that related to musical parameters. For instance, if a participant suggested a twist deformation to apply more effect to a sound we would code this as "Twist to Increase Effect". All the instances of deformation were coded by one author and grouped into clusters, where each cluster contained identical instances of deformation-to-musical parameters.

We transcribed participants' think-aloud comments on how physical features of materials and deformations related to music (e.g., stretching the surface of a cloth would change the speed of the tempo). From those transcriptions, we identified trends and report the most interesting comments. We discuss these findings in the next section.

FINDINGS FROM THE WORKSHOPS
In this section we discuss: (1) how the participants mapped deformations to musical parameters, (2) how the participants described physical properties of deformable objects in relation to music, and (3) what deformable objects from the set the participants would use for real music performances.

Deformations to Musical Parameters
During the *familiarization* and the *simulation* phases the participants provided many suggestions on what actions to perform when playing music with deformable objects. We have identified two major trends among their suggestions, namely using simple surface contact (e.g., tap, poke, push) to generate sounds, and using object deformation (e.g., twist, stretch, bend) to modulate or applying effects to sounds..

Sound Generation
When suggesting how to play keyboard notes or drum sounds, the participants mostly tapped or poked the surface of deformable objects. Participants explained that in order to generate sounds one does not need to use complex deformations. Instead, a simple contact with the object would be enough to play a sound. Participants said that any of the objects could be used for that purpose. These results are obvious with respect to the participants' previous experience with rigid musical interfaces, in which they mostly use tapping, poking, or plucking strings to generate sounds.

Sound Manipulation
While sound generation involved mostly tapping and pushing, the participants deformed the body of the objects in many different ways when simulating sound effects and modulations. Participants generally explained that applying effects or modulating sounds has a strong analogy with sculpting or modeling physical objects.

Six participants twisted an object to increase or decrease the amount of a sound effect. According to a participant, this deformation was inspired by previous experience with knobs embedded in synthesizers and MIDI controllers. Six participants suggested stretching to modify the pitch of a sound. One participants said that pitch can be stretched to become higher or squeezed to become lower: *"I think that a stretched surface 'feels' and 'looks' like a high pitched sound, because the sound also sounds stretched"*. Two participants also showed how stretching could be used to apply reverb effect to sounds, where stretching would increase the room size or the amount of reverb.

Three participants suggested *pressing* down the body of an object to increase tempo and three participants suggested the same deformation to filter sound frequencies with high pass (HP) or low pass (LP) filters. In the case of tempo, they all explained how compressing an object should also compress the duration of a sound, thereby increasing its speed. In the case of filters, participants explained that by pressing down the body of the object they would either cutoff sound frequencies or emphasize them.

Six participants showed how *squeezing* an object in one or two hands could be used to crush or distort a sound. One participant explained the relation between squeezing and sound destruction like this: *"I can imagine that if I squeeze the object completely I will have a distorted or crushed sound. I think it's because it physically resembles the sound that I hear, because it feels like I'm destroying the sound in my hands"*.

One participant showed how pushing a latex membrane upwards would emphasize certain frequencies, while pushing it downwards would cut frequencies (see Figure 2). The participant explained: "*When I push up, the latex has the shape of a peak, so I imagine this would emphasize the frequencies, whereas pushing it down should do the opposite and cut the frequencies"*.

Figure 2: A participant pushing upwards and downwards on a latex membrane to manipulate sound frequencies.

We can conclude that the participants saw the deformable objects and their deformations mostly as tools for sound filtering and modulation. This suggests that a deformable interface may be useful in music performances to model and dynamically change the sonic characteristics of pre-generated sounds.

Physical Properties of Objects Related to Music

Participants were presented with both objects that retained shape and objects that did not. Participants used this property in order to simulate different musical interactions.

Non Shape-Retaining Objects

Some materials would return to their default state (shape) after being deformed. Participants explained how this property could be used to generate dynamic or automated sound events. For instance, two participants showed how non shape-retaining objects could be used to generate dynamic changes of volume. They did so by pressing on the surface of an object and explained: *"While I press down the volume is loud and we can hear the note. Then I release the surface and the faster the material goes back to its default state, the faster the volume decreases"*.

Figure 3: A participant modeling the silicone object to generate different waveforms.

Surface vibration was suggested to control dynamic sound modulations, for instance like vibrato or low frequency oscillations (LFO). One participant commented: *"I can shake the cloth and control sound oscillations in this way. But it also vibrates for a while after I touched, and somehow it feels like the surface is alive"*.

Shape-Retaining Objects

Participants explained how shape-retaining objects could be used to "lock" sound parameters or to generate sound automations. For instance, one participant showed how the silicone object could be bent and locked in place to generate loops or modeling waveforms (see Figure 3).

Because clay can be torn into pieces, participants showed how this material could be used to break a sound into smaller parts (i.e., smaller sound samples). For instance, one participant showed how this feature could be used to perform what in electronic music is known as "granular synthesis".

We conclude that participants would make a distinct use between objects that retain and do not retain shape, were the former would be used to lock sound parameters, and particular types of synthesis or automated looping events, while the latter would be used for expressive control and dynamic events. However, we have noticed that participants slightly preferred non shape-retaining objects, which were mostly inspiring participant's ideas in the *brainstorm* phase.

Preferred Deformable Objects

During the *brainstorm* phase participants showed a particular interest for 5 of the 10 deformable objects, especially objects number 2, 3, 6, 7, and 8 from Figure 1. Most of the ideas produced during the brainstorm focused on these objects. Also, participants suggested what deformations would be best to use with those objects. Object 2 was preferred for stretching, while 8 was preferred for twisting. Objects 3 and 6 were preferred for pressing and squeezing, respectively. Finally, object 7 was preferred for bending. Therefore, we embedded sensors into the five objects that were preferred by the participants and made them interactive for the performance study.

PERFORMANCE STUDY

The performance study aimed to investigate how deformable interfaces are used for music performances out of the lab. Our approach to the performance study was inspired by studies of interactive interfaces in the wild [22]. We were particularly interested in how musicians perform music with deformable interfaces in a realistic environment and how they describe their experiences about using them. We asked six musicians to use five deformable interfaces in order to perform some music piece at their studios. With this study we wanted to investigate the following questions: (1) How are deformable interfaces used out of the lab to perform music? (2) What are they used for? (3) Do they change the feeling of control? (4) Are deformations systematically mapped to specific parameters? (5) Do musicians find deformable interfaces useful to play music?

Participants
Six professional musicians, all male, with an average age of 35 (*SD* = 8.8) participated in the study. Participants had between 5-25 years of experience with live performance or studio production of electronic music. None of the participants took part in the workshops or had previous experience with deformable interfaces. At the end of the session, participants received a gift to compensate for their time.

Apparatus
The set-up included interactive versions of the five preferred deformable objects (see Figure 4) as well as the musicians' own equipment (e.g., MIDI controllers, studio recording devices, laptops).

We embedded force resistive sensors (FRS) into objects 1 and 2, in order to sense when participants pressed or squeezed them. Two conductive rubber chords were sawn on the back of object 3 to sense stretch in both vertical and horizontal orientations. A single flex sensor was embedded into object 4 to sense bend deformation. Finally, we placed a rotary potentiometer inside object 5 to sense twist deformation. All the sensors were soldered to cables, plugged into a breadboard and connected to an Arduino Mega 2560, in order to send sensors' signal to the laptop. We enclosed the Arduino Mega and the breadboard in a laser cut casing.

We processed the signal coming from the Arduino Mega with the software Pure Data, using the Firmata library and Pduino, before sending the signal to the computer. In order to broadcast input from the objects as MIDI data we scaled sensors' input to values between 0 and 127 (the standard MIDI value range). In order to reduce signal noise we averaged the sensors' values over 20ms. Since we deliberately did not investigate multi-dimensional input control in the performance study, we programmed each object to sense only one type of deformation.

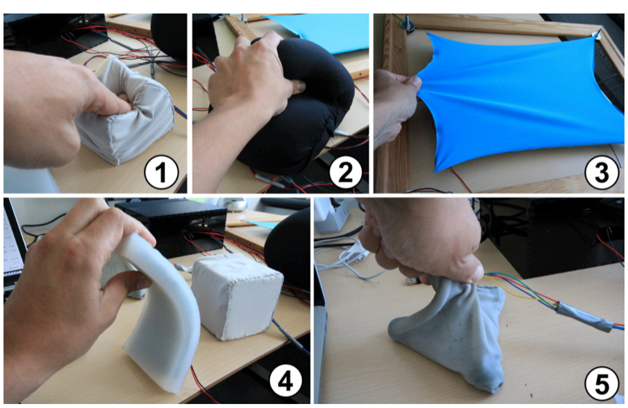

Figure 4: The deformable interfaces used during the performance study.

Procedure
The study had two primary activities: (1) mapping musical parameters to the deformations afforded by the deformable interfaces, and (2) using the mappings to perform a music piece of maximum five minutes.

Before the study, participants were asked to prepare musical material for their five minutes performance and make sufficient space in their studios to use the deformable interfaces. However, we did not ask the participants to organize their performance set-up in any particular way, but rather let them choose their own space configuration. Furthermore, we instructed all the participants to download and install the software required in order to receive input from the deformable interfaces (i.e., Pure Data, Arduino and Processing).

Once at their studios, we explained to the participants the purpose of the study and introduced them to the deformable interfaces. We started by showing the participants what deformations the interfaces could support and how to control MIDI events. We guided participants through the mapping of deformations to sounds until they could handle this process autonomously. We did not impose any constraints on which musical parameters participants could choose to map. Moreover, we allowed them to use their existing studio equipment together with the deformable interfaces.

All the participants choose to control MIDI events and sounds parameters with the music software Ableton Live®. When participants were satisfied with their configuration they could start performing music. As previously said, the performance could last for a maximum time of five minutes. We imposed this time constraint to emulate the pressure of a real performance and to force the participants to perform a coherent music piece rather than randomly exploring the objects.

Once participants finished their performance, we concluded by interviewing them on their experience about using the deformable interfaces.

Data collection
We collected data for further analysis by video recording the participants' performances, as well as by storing the sensors' values in log files. Log files included timestamps (milliseconds) and streamed values from sensors sampled at a rate of 100 samples per second. Finally, we collected qualitative information from participants by video recording their interviews.

Analysis
One author coded the videos and transcribed the interviews using Microsoft Excel. From the videos we coded instances of mapping between deformations and musical parameters. Moreover, we analyzed the videos of participants' performances, focusing on how deformable interfaces were used to perform music and how they were integrated with existing instruments. Finally, we analyzed the data from the

log files using MatLab, in order to investigate how long each deformable interface was used for and the how their values were controlled.

RESULTS FROM PERFORMANCE STUDY

In this section we report on (1) how participants performed music using deformable interfaces, (2) which deformations map to which parameters, (3) the time spent using each interface, and (4) how the interfaces were controlled.

Use of Deformable Interface

All participants took advantage of the haptic and tactile feedback of the deformable interfaces to quickly retrieve the sounds that they wanted to control. These observations were confirmed by the participants' comments. For instance, one participant said: *"I was looking for the low pass filter while I wanted to modify something in the program. I remembered that the filter was mapped to the squeezing ball, so I just touched the objects until I found the round shape and started to squeeze it to control the filter*" – P2.

We observed some cases where participants would use the flexibility of interfaces in a particular way. For instance, one participant mapped the pitch to bend deformation with the silicone object (Figure 4, object 4) and in order to generate a vibrato effect, he started to deform the interface with a wavelike movement. This particular use of the deformable interface supports the observation of some participants that these interfaces differ from knobs and faders present on most music controllers: *"This objects are different from faders and knobs. They make you feel like you are holding the sound in your hands and you can actually shape it"* – P3.

Because one deformable interface had springs inside and it would spring back fast if released (see Figure 4, object 5), one participant used this feature to generate quick changes in pitch; he commented like this: *"It is nice that this one springs back so fast to the center, it's dynamic and I can modulate the pitch fast. It generates an interesting conversation between the performer, the interface, and the sound"* – P1.

When we questioned participants about precision of control, they all said that it was not a concern for them during the performance, and that they rather focused on the expressive possibilities of the interfaces. We observed, however, that participants would initially monitor the sensors' values on the display. As they progressed through their performances they focused more on using the deformable interfaces and stopped looking at the display.

We observed that sometimes participants would use two or more interfaces simultaneously to modify different sounds at the same time. Five participants often used the pressing and squeezing interfaces simultaneously (Figure 4, object 1 and 2) in order to control two parameters of the same modulation or filter (e.g., the rate and the amount of a LFO). Twist and bend were also controlled together by four participants, where bend was used to modulate a sound (e.g., pitch, filter) and twist to apply effects (e.g., delay, distortion). Eventually, two participants managed to use three interfaces simultaneously, involving the use of one hand and the forearm to press and squeeze two interfaces at the same time while bending another one in the other hand.

Finally, it was interesting to notice that, even though participants were never instructed to use deformable interfaces only to control filters, effects, or modulations, they used them exclusively for those purposes. Therefore, the way participants incorporated deformable interfaces in the instrumental set-up was mainly as tools to filter or manipulate sounds, whereas the MIDI controllers and keyboards were used only when the participants wanted to trigger notes or samples.

Further Comments

All participants described the deformable interfaces as objects that embody the sounds, stressing out how the elements of a sound would be directly transposed to the interface and become physical: *"It feels like the object itself is somehow embodying the sound"* – P3.

All the participants found the deformable interfaces useful for playing music and also more inspiring and expressive than rigid interfaces. Four participants said that they would use deformable interfaces as a performative tool during live performances, while two participants would use them as creativity tools in the studio to be inspired during composition. All participants described deformable interfaces as very intuitive, easy to learn, and fun to play with. Finally, all participants described the deformable interfaces as having a more organic feel compared to rigid interfaces.

Mappings

Table 3 shows mappings between deformations and musical parameters defined by the participants. Participants mostly used the deformations to control filters and modulations.

Filters were used the most with high pass filter (HP) and low pass filter (LP), mapped overall eight times. These filters were mapped mostly to press, squeeze, and bend

P	Press	Squeeze	Stretch	Bend	Twist
P1	Volume (Increase)	Bit Crush (Amount)	Reverb (Amount)	Pitch (Transpose)	Pitch (Transpose)
P2	LFO (Amount)	LFO (Rate)	LP Filter (Cutoff)	LP Filter (Cutoff)	Delay (Feedback)
P3	HP Filter (Cutoff)	FM(Rate)	Beat Repeat (Note Interval)	LP Filter (Cutoff)	Delay (Feedback)
P4	LP Filter (Cutoff)	LP Filter (Cutoff)	Delay (Feedback)	Pitch (Transpose)	Distortion (Amount)
P5	LFO (Amount)	LFO (Rate)	Reverb (Amount)	Pitch (Transpose)	Panning
P6	LP Filter (Volume)	LP Filter (Cutoff)	LFO (Rate)	LP Filter (Cutoff)	Beat Repeat (Note Interval)

Table 3: Mappings between deformations and musical parameters.

deformations. Participants modulated the volume and the frequency of sounds with low frequency oscillation (LFO); this modulation was mapped five times to either press or squeeze deformations. The predominance of filters and modulations among the mappings confirms the idea emerging during the workshops that deformable interfaces are best for sound manipulation.

Bend was the most frequently used deformation to control pitch, while twist was used the most to control effects, such as delays, distortions, and beat-repeat. These uses also relate to findings from the workshop, where participants associated bend with pitch modulation and highlighted twist as a good deformation to control the amount of effects. Finally, stretch deformation was mostly used for effects such as reverb and delay.

Usage Time
Figure 5 shows how much each interface was used on average. This results shows that participants tend to use all the interfaces during their performance, with a slightly higher preference for pressing interaction (22.2% of the time) and less preference for stretching (15.9% of the time).

Control of Values
To understand how participants controlled the interfaces during their performances, we looked at the values registered by the embedded sensors, expressed as a percentage from not actuated (0%) to fully actuated (100%). Results showed clear trends for press, squeeze, and stretch, where most time was spent on the highest value (i.e., 100%), with respectively 9% of the time for press, 24% of the time for squeeze, and 26% of the time for stretch. These results suggest that press deformation was used less aggressively compared to squeeze and stretch.

DISCUSSION
We have collected reactions from nine musicians to 10 non-interactive objects and investigated how six musicians would use deformable interfaces to perform music. Overall, our results confirmed the usefulness of deformable interfaces in the musical context. Next, we discuss our results in detail, point to limitations of the present paper and outline future work.

Feeling of Control
One goal of our study was to investigate how deformable interfaces change the perception of control. However, few musicians commented on the precision and level of control of the deformable interfaces. Instead, musicians highlighted their ability to inspire and how they allow for serendipitous discoveries and epistemic actions [24]. The musicians also valued the haptic and tactile feedback provided by the deformable interfaces. The analysis of the log files showed that the deformable interfaces led to different interaction behaviors. For example, squeezing caused more extreme interactions than pressing. However, more studies are needed to investigate whether these implied behaviors are

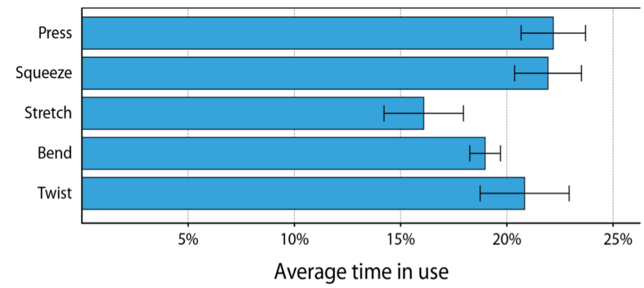

Figure 5: The average time spent by participants using each deformable interface.

specific to the musical domain or to deformable interfaces in general.

Embodiment and Strong Specificness
Another important finding from the performance study is that the musicians see a stronger relation between action and effect when using the deformable interfaces than when using a regular controller. The deformable interfaces left the impression of *"having the sound in the hand"* and some musicians reported that the deformable interfaces made it easier to remember mappings than regular controls. These comments are supported by our observation of clear trends in how deformations and filters were mapped – both across individual musicians and between the workshop and the performance study. This suggests that deformable interfaces share qualities described in studies of tangible user interfaces as embodiment facilitation [24] and strong specificness [36].

Shapes, Materials, and Deformations
We found that shapes and materials played a key role for participants in both the workshop and the performance study. The haptic qualities of different materials influenced the way in which participants generated ideas on deformable interfaces and how they used them to perform music. Also, different shapes and materials implicitly suggested what deformation they would be best for. We found that these three characteristics (i.e., shapes, materials, deformations) determined how participants choose to use deformable interfaces to perform music. These results suggest that the combination of shapes, materials, and deformations are key for the design of deformable interfaces.

Limitations and Future Work
The present paper has a number of limitations, for which we aim future work to compensate. The aim of our paper was to understand differences between atomic deformations. As a consequence, the deformable interfaces were deliberately designed to support only one type of deformation. However, the capability to support many degrees of freedom is often highlighted as the prominent feature of deformable interfaces [28]. A natural next step would therefore be to merge the functionality of our five interfaces into a single deformable interface and investigate if and how this changes our findings. Second, while the performance study sought to emulate some of the pressure

relating to performing music, it was still conducted in the relatively safe studio environment of the musicians. An interesting next step would be to perform a concert evaluation as Pedersen and Hornbæk [20], to investigate also how the secondary user group (i.e., the audience) experience the interfaces. Our study imposed a short time constraint (five minute) for musicians to perform with the deformable interfaces. With this approach we wanted to engage musicians in a realistic use of the interfaces rather than a random exploration. However, musical interfaces, especially if novel, may need a longer use to be assimilated by musicians. A logical next step would be to do a study where musicians train with the deformable interfaces for a longer period of time and finally go to perform live on stage with them.

CONCLUSION

Deformable interfaces afford new ways of interacting and open new possibilities for control. We have presented results from three workshops on deformable interfaces in music, and described how participants explain musical properties of shapes, materials, and deformations, and how they would use them to perform music.

With the performance study we investigated the usefulness of deformable interfaces for music performances out of the lab. We evaluated deformable interfaces with musicians performing music with a set of five deformable interfaces. The performance study showed that deformable interfaces are used mostly for sound manipulation and filtering, rather than for sound generation. They are also perceived as expressive and as embodying the sounds that they control. Finally, musicians used particular deformable interfaces for particular filters and effects.

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