Non-Rigid Musical Interfaces: Exploring Practices, Takes, and Future Perspective

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ABSTRACT

Non-rigid interfaces allow for exploring new interactive paradigms that rely on deformable input and shape change, and whose possible applications span several branches of human-computer interaction (HCI). While extensively explored as deformable game controllers, bendable smartphones, and shape-changing displays, non-rigid interfaces are rarely framed in a musical context, and their use for composition and performance is rather sparse and unsystematic. With this work, we start a systematic exploration of this relatively uncharted research area, by means of (1) briefly reviewing existing musical interfaces that capitalize on deformable input, and (2) surveying 11 among experts and pioneers in the field about their experience with and vision on non-rigid musical interfaces. Based on experts' input, we suggest possible next steps of musical appropriation with deformable and shape-changing technologies. We conclude by discussing how cross-overs between NIME and HCI research will benefit non-rigid interfaces.

Author Keywords

Non-rigid interfaces; musical interfaces, expert study

CCS Concepts

•Human-centered computing → Sound-based input / output;
•Applied computing → Sound and music computing;

1. INTRODUCTION

Research in human-computer interaction (HCI) is engaging with *non-rigid* materials and interfaces [34], to explore new interactive paradigms [3] and control possibilities [40]. In that respect, previous work has investigated non-rigid musical interfaces [38, 26, 6, 23, 24, 18, 17, 12, 45], showing how they allow for new ways of performing music [40, 29, 2, 42]. However, while *non-rigid interfaces* are now a research area in HCI [3, 1], their research within NIME is sparse and we lack both (1) systematic overviews of existing work and (2) clear guidelines for future research. For instance, while HCI has discussed the role of shape, material, sensing, and mapping in supporting user interaction with non-rigid interfaces [3], also within music [40], such discussion has yet to be formalized at NIME. We address the above shortcomings with a twofold contribution. First, we overview existing non-rigid musical interfaces and define them as a research area of NIME. Second, we survey 11 among experts and pioneers on the past, present, and future of non-rigid musical interfaces, to help form a research agenda and inspire future design and research efforts at NIME.

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2. BACKGROUND

In HCI, non-rigid interfaces are generally described as *"interfaces that use dynamic changes in a device's physical shape for input and output"* [1]. Depending on the research angle, previous HCI work emphasized either (1) the *output* characteristics of non-rigid interfaces, such as self-actuation [34], or (2) the *input* [3], for instance where deformable materials allow for novel interactions that are impossible with rigid materials, and/or disentangled from earlier HCI paradigms (e.g., shape-displays that can be "sculpted" for input [32]). As such, Boem and Troiano [3] distinguished between *deformable* and *shape-changing* interfaces, where the former are passive and can only shape change by means of user input (e.g., [38]), while the latter can autonomously shape change by means of self-actuation [34]; both interfaces fall under the umbrella term *non-rigid interfaces* [3]. Following [3], we define *non-rigid musical interfaces* in music as "musical interfaces that can be physically deformed [3] to generate and/or manipulate sounds, and that use shape change [34] to physically represent sounds (e.g., [16]) or dynamically respond to musicians performance".

While non-rigid interfaces are consolidating as a research area in HCI [1, 3], in the NIME fields they remain occasional, and with no comprehensive overview of existing examples. A comprehensive overview of non-rigid musical interfaces is needed to advance research in this area and unify the efforts of researchers and musicians that pioneered their exploration. As said earlier, previous HCI work [3, 34] has systematically reviewed non-rigid interfaces to help define the research area and identify grand challenges [1]. Following the same rationale, we summarize existing examples of non-rigid musical interfaces, to provide the reader with both (1) a structured overview of how NIME has appropriated non-rigid interfaces in previous work and (2) the necessary information to contextualize the survey presented in Section 3.

Before discussing previous NIME work with non-rigid interfaces, it is notable that no examples exist of non-rigid musical interfaces that use shape change for output. As such, self-actuation as investigated in HCI is foreign to NIME, and actuated shape-change has yet to be experimented with in musical interactions.

2.1 Non-Rigid Musical Interfaces

Non-rigid musical interfaces are made of malleable and deformable materials (e.g., rubber, fabric [3]), which musicians can squeeze [43, 4, 37, 41, 30], stretch [6, 45, 29], bend [23], and twist [13, 47], to control sounds and generate music performances. Previous work used only one type of non-rigid input to manipulate sounds, for instance like the *SonicBanana* [38], where a plastic tube loaded with flex sensors could be twisted to generate music, or combined different types of non-rigid inputs (e.g., twist + squeeze

+ bend, [2, 18]) for achieving multidimensional input [3].

Existing non-rigid musical interfaces display a variety of shapes, including traditional keyboard-like shapes [20, 45], as well as squeezable spheres like *The Music Ball* [17], squeezable cubes [19], and malleable tetrahedrons like *Sculpton* [2], which is made of springs covered in latex, and embedded with both light-reflective sensors and light-emitting diodes for deformation sensing. The *Ballagumi* [21] instead, is a musical pillow that displays a less "conventional" shape, which Boem and Troiano [3] define as *xenomorphic*. *SillyTone* [26] is shaped like a "rabbit" and its ears can be squeezed to generate sounds. *Clay Tone* [42] and *DIRTI* [36] are non-rigid musical interfaces through which musicians can directly model sounds by "sculpting" the surface of the interface; similarly, *MARSUI* [46] and *Soundflex* [39] allow musicians to sculpt sounds, but use silicone with metal wire embedded, instead of clay or sand, for creating shape-retaining musical interfaces. Other non-rigid musical interfaces used elastic fabric tensed on a rectangular [6, 45] or circular hard frame [29], to create flat surfaces that act like stretchable musical interfaces.

Besides experimenting with materials and shapes, previous work employed various approaches for sensing deformable inputs with non-rigid musical interfaces, which approaches Boem and Troiano [3] categorized as (1) *embedded* and (2) *external* sensing. Embedded sensing is most common. *The Sponge* [23, 24], for instance, is equipped with accelerometers and force sensing resistors, and deformable input is sensed directly on the surface via the embedded sensors. *FabricKeyboard* [45] is a flat MIDI keyboard made with embroidered conductive thread, which allows to control sounds with both touch and stretch input. Others, used a combination of inertial measurement units [13] or flex sensors [38] embedded in their non-rigid musical interfaces to sense twist, bend, squeeze, and stretch. External sensing is less common, as it uses more expensive sensors and may present portability issues (i.e., an entire camera and lighting setup). A common approach to external sensing is the use of image sensors, like charge-coupled devices (CCDs) or Kinect® cameras. For instance, *Silent Drum* [29] and *DIRTI* [36] use CCD sensors and computer vision to analyze the global deformation of their surface and monitor changes to model the user input. *ClayTone* [42] uses a CCD sensor to extract visual information (e.g., color, geometry) of clay being deformed by musicians, and processes that information in C++ to inform the mapping of input and output (I/O).

Regarding I/O mapping, Boem and Troiano [3] identified two main mappings strategies with non-rigid interfaces (see [3], p. 892), namely *explicit* mapping, where input and output are physically consistent with each other (i.e., deforming a cube interface to deform a virtual cube [28]), and *implicit* mapping, where cross-modal correspondences between input and output are mostly established through metaphors; since non-rigid musical interfaces allow to manipulate sounds, which may not always be physically consistent with input, implicit mapping is popular among these non-rigid interfaces. For instance, Troiano et al. [40] found that musicians implicitly associate the action of squeezing with increasing loudness, or stretching for controlling the dry/wet signal of reverb and delay effects. However, no systematic investigation has been done to advance the understanding of cross-modal correspondences with non-rigid musical interfaces.

The majority of the non-rigid musical interfaces reviewed above were used in the context of live music performances (e.g., [24, 13, 43, 2, 38], but previous work showed also promise for their use in the context of music therapy [7, 12], as well as medical applications [21]. However, identifying fitting application areas for non-rigid musical interfaces remains an open challenge. For instance, the idea of "sculpting" sounds directly through a non-rigid interface that allows for multidimensional input may benefit sound design tasks (e.g., modeling the timbre of a sound); yet, to the extent of our knowledge, no previous work has attempted to use such interfaces for sound design and discuss the outcome. We attempt to answer the above and other emerging research questions by consulting experts and pioneers of non-rigid musical interfaces in a survey study, which we present next.

Table 1: The survey participants and their interfaces

Participant	Interface	Reference
P1	I1	The Spine [13]
P2	I2	PushPull [14]
P3	I3	IllumiWear [8]
P4	I4	Marsui[46]
P5	I5	SoundFlex [39]
P6	I6	Sonic Banana [38]
P7	I7	GGT [15] Ballagumi [21]
P8	I8a I8b	EchoFoam [18] NoiseBear [12]
P9	I9	Silly Tone Squish Factory [26]
P10	I10	Music Ball Project [17]
P11	I11	Squeezy [41]

3. EXPERT SURVEY

Inspired by earlier NIME work [25], we surveyed experts who previously researched about and designed non-rigid musical interfaces, and asked them about the past, present, and future of such interfaces. We contacted at least one author/designer for each interface reviewed in Section 2.1, and shared with them an online questionnaire using a protected Qualtrics[1] account. The questionnaire consisted of nine open-ended questions. Five questions asked the respondents to share details about the experience linked to the design and use of their non-rigid musical interfaces. These included design motivations and intended use, technical insight on materials and mapping, and the impact that the interfaces had on research and artistic expression. The initial five questions were intended as an opportunity for the respondents to share information about their work with non-rigid musical interfaces that may not be included in their scientific publications, for instance like technical issues/patches, anecdotes, and retrospects. Then, two questions asked the respondents to extend their insights on non-rigid musical interfaces beyond their own experience, and reflect more broadly on the impact of such emergent interfaces on NIME and its research. Then, other two questions invited respondents to share their insights on future research perspective and design of non-rigid musical interface. As said earlier, we found no existing examples of non-rigid musical interfaces using shape change for output. Hence, the last question inquired the respondents about the use of shape change within non-rigid musical interface design.

We collected answers from 11 participants (tagged as P1-11). Their average age was 38.5 (*SD* = 7.8). All respondents had an interdisciplinary background in music, engineering, digital art, and physics. Most respondents (i.e., 8) are musically trained and regularly perform live on instruments such as cello, piano, drums, saxophone, or on custom interfaces that they design. Except for P6, all respondents are conducting research on musical instruments and are active members of NIME community. Table 1 shows the list of non-rigid musical interfaces designed by the respondents. We reference their work as I1-11 and match the interface tag with the respondent tag (i.e., I1 was designed by P1, I2 by P2, and so forth). At `https://deformableui.com/nime2020/`, the reader can find a brief technical description and a picture of each interface listed in the table. Next, we present the results of our survey.

3.1 Results

All survey responses can be accessed at `deformableui.com/nime2020/`. Upon survey completion, we performed thematic analysis on the responses based on *grounded theory* [11]. Af-

[1] `https://www.qualtrics.com/`

ter two rounds of analysis we reached consensus on the emergent themes that best summarize experiences and visions discussed by the participants. We organized the emergent themes in six categories that generalize the survey results beyond specific cases and provide structure to our discussion in Section 4.

3.1.1 Motivations

At the beginning of the survey we asked the participants to explain their motivations for designing and using non-rigid interfaces for music. Six participants (P1, P2, P4, P5, P8, P11) explained that their desire to *experiment new forms of control in music* was their main drive to design and build non-rigid musical interfaces. They explained that gestures like twist, stretch, bend, or squeeze could not be enabled by rigid materials, and hence started experimenting with non-rigid materials and different sensors' arrangements that would allow to identify such gestures. More specifically, P1 and P8 expressed their wish to *explore continuous and multidimensional input* (see [3], p. 887) in music through non-rigid materials - these have shown to be favorable for designing and implementing those types of input [40]. Differently P4 and P5 explained that their goal when building I4 and I5 was *"to study how sound cues (including musical cues such as harmonics dissonance) can be used to guide the user to forming certain shape"* (P5).

Six participants were motivated by their interest in exploring new design solutions that *challenge the aesthetics of existing controllers* (e.g., touch-screens, force-feedback devices), by augmenting every-day objects like plastic tubes (I6), toys (I9), or by experimenting with "unusual" shapes (I7), which Boem and Troiano describe as *organic* ([3], p. 888). P9 and P10, instead, said their motivation to design non-rigid musical interfaces was mainly to leverage the intuitiveness of interacting with non-rigid materials to create *"enjoyable and easy to use"* musical interfaces. Others (P4, P3, P1) were interested in designing musical instruments that can adapt to the shape of the human body and augment its movements by means of sonification (I1); for P1, the idea of using non-rigid materials emerged from the desire of turning a rigid interface (i.e., [22]) into a wearable interface for dancers and performers.

3.1.2 Applications

Most participants built non-rigid musical interfaces for application in *expressive and performative music activities*. Particularly, they were interested in creating control experiences that allow for new and intuitive ways of performing live music (P1, P2, P5, P10). In most cases, the designers of non-rigid musical interfaces were also the only users, except for P1, who built I1 and had dancers and performers use it in live performances. Others (P4, P5) used non-rigid musical interfaces applications in areas other than live music performances. For instance, I4 and I5 were designed for exploring how the sonification of physical objects that deform can be used as a cue to help users navigate through different functionalities in flexible smartphones (i.e., folding a smartphone engages the "smartwatch" mode). P7 mentioned that I7 was designed as a controller that can be used as a "musical pillow", which can also be interfaced with medical equipment (e.g., used from within functional magnetic resonance imaging machines), while P8 wanted to create interfaces that can be used by people with physical and cognitive disabilities in music therapy (I8b).

Besides their own work, we asked our participants to reflect on which musical applications may benefit from non-rigid interfaces in the broader context of NIME. Our participants highlighted that non-rigid materials can be leveraged to create deformable music controllers and instruments that increase musicians *"physical engagement"* through full-body input (I1, I3), and serendipitous discoveries (I8a). Our participants also mentioned applications for playful, visceral, and exploratory music experiences. According to participants P5, P9, and P10, non-rigid materials are potentially useful for creating interactive installations that appeal large audiences, and not only musicians, since non-rigid interfaces can *"excel to be manipulated with large actions"* (P9). Moreover, P5 suggested that non-rigid musical interfaces that can dynamically change affordances [35] and retain their shapes can give *"more possibilities for sound encouraged actions to emerge and could make the affordances of the interface to be more exploratory"*.

Notably, P6 and P7 drew an interesting parallel between the components of acoustic instruments and the characteristics of non-rigid interfaces. For instance, reeds, strings, whammy bars, and bendable saws are used to both modulate and produce sounds through material deformation. According to P6, such components "*often provide significant rolls in timbre and pitch expression of acoustic instruments and can be used to such expressive effects in electronic ones as well*". Therefore, non-rigid interfaces may also be used to augment rigid parts (see [3], p. 892) of acoustic instruments with non-rigid parts providing additional input. In that sense, P8 suggested considering a semi-malleable bow grip for the continuous modulation of the sound output of acoustic instruments (e.g., violin). Finally, P7 suggested that non-rigid controllers may be used to help people with disabilities and children to learn and experience music intuitively and easily (e.g., [7]).

3.1.3 Uptakes

We asked our participants to talk about the current state of their non-rigid musical interfaces. Almost all participants answered that, although their interfaces still exists and may be functional (I1, I5, I7, I10), they are currently unused and did not undergo further development or design iterations. Only P2 reported that a few students are using copies of his non-rigid musical interface for artistic experimentation. We also asked participants to self-assess the impact of their work with non-rigid musical interfaces. Most participants saw their work as having most impact within academic and artistic research, through citations (P1, P3, P4, P5, P6), or through presentations, lectures and workshops (P1, P5, P6, P8). Others explained that their interfaces had sparked inspirations and interest in other musicians (P1, P7), as well as the industry (P5). However, none of the non-rigid musical interfaces designed and built by our participants were eventually commercialized, and no distribution or production plan has been made for that purpose.

3.1.4 Issues And Open Challenges

We asked our participants to describe the issues that they encountered while designing and building non-rigid musical interfaces. They described the crafting of their interfaces as highly challenging. P10 said that finding the right materials to build non-rigid musical interfaces poses many challenges, among which finding durable materials that are also pleasing to touch, and strategically place sensors not to obtrude musicians interaction; these challenges are also found in previous HCI work with non-rigid interfaces [3]. P9 described embedding sensors inside deformable materials as the most challenging task, while P8 needed to find appropriate "*techniques for embedding micro-controllers in non-rigid interfaces*". Three participants described the design of non-rigid musical interfaces as fragile and difficult to replicate (P7, P9, P10), thus emphasizing the need for finding robust and durable materials to build such interfaces ("*This project [I9] taught me a lot of hard lessons about robustness*" —P9). Participants also struggled with programming sensors. P8 mentioned "*massive non-linearities*" and "*slow hysteresis*" caused by the foam construction of I8a, while the "*resistive memory*" of the silicone that composed I9 forced P9 to cope with sensor values that kept changing over time. Along these lines, the use of "*advanced materials*" were deemed necessary by P2, P3, P4, P7, P8 and P9, including nanotechnologies, miniaturized components, and long-lasting batteries.

P11 describes overcoming such design challenges as an "*endeavour*", and suggests "*a well thought out mapping design strategy is needed to make [it] worthwhile*". However, another challenge described by participants was "*understanding*" the interfaces, as in how to properly design I/O mappings. P1 said that "*understanding the behaviour of the instrument for making mapping decisions can be particularly difficult with continuously-deformable interfaces*", while P2 said that they "*first had the working hardware artifact at hand*" before starting to reflect on I/O mappings. P8 reckoned that it was necessary to capitalize on "*techniques for using machine learning to interpret control signals from non-rigid interfaces*". The complex "*behavior*" of non-rigid interfaces was described as a hindrance to mastering control. P8 described I8a as "*a fun challenge to play, but also quite difficult*". P1 said that controlling continuous deformations makes it hard to develop "*idiosyncratic performance practices*". P11 described unwanted coupling effects between deformable and rigid input, which made music performances "*intricate*". P5 noted that "*as deformable interfaces can take innumerable distinct shapes, creating specific target configurations [to play with] can be a challenge*".

3.1.5 Future Vision

"We need to go beyond traditional square/hard/ technology-focused interfaces."—P10

As remarkably summed up by P10's quote, nearly all participants described non-rigid interaction as one of the future directions of novel musical expression (P3, P4, P5, P6), specifically thanks to its unusual and distinctive features (P7, P8, P9). Popularization was considered by many participants the crucial next step in the field; this includes the development of novel deformable non-rigid interfaces (P4, P5), as well as the improvement of existing ones (P3, P6). In two cases, popularization was referred to as the increase of the number of musicians having access to and playing non-rigid musical interfaces, leading to interesting takes on mastering and learning: P7 stated that "*getting [non-rigid] devices into the hands of end-users and out of the research labs would allow for the most interesting insights*", while P6 underlined the need to "*observe how others use these instruments, without instructing them, to see how they play them*". P4 was even more explicit about the importance of pedagogy, saying that exploring "*the learning process of deformable NIMEs*" is one of the essential steps for research on non-rigid musical interfaces to advance.

The participants' future vision of non-rigid musical interfaces was in some cases clearly influenced by the challenges they had to face while designing and using their interfaces (see Section 3.1.4). In particular, four participants expect an intensification of interdisciplinary efforts, spanning chemistry and material science (P8), sensing and nanotechnologies (P4), and more generally electronics (P10, P9); P9 further elaborated this comment, by hinting at future "*user friendly*" materials that may help artists appropriate non-rigid interaction, as much as Arduino did for micro-controllers.

The analysis of the proposed future perspectives of non-rigid musical interfaces highlighted a neat division between participants, mainly revolving around the concept of expression. Around half of the participants framed forthcoming non-rigid interfaces as proper musical instruments, at least as expressive and precise as the instruments we currently use on stage and in studio. P5 discussed their use in performance and composition, P6 and P7 remarked the analogies with acoustics instruments, while P11 deemed deformable input ideal for instrumental control. Along these lines, when illustrating their interfaces, P3 and P2 discussed how non-rigid input can be used to sense from macro- to micro-gestures, and provide multi-modal feedback for expressive and dynamic playing.

In contrast with this vision, a second group of participants emphasized the trade-off between precision and expression that non-rigid input imposes on interaction. P8 described non-rigid interaction as "*sacrificing some precision for more expressive control*", P4 talked about "*expressive potential*" but need for "*more advanced sensing technologies*", while P10 used adjectives like "*different*" and "*joyful*" that are seldom used to describe musical instruments that allow for nuanced control and virtuosity. The same incompatibility with "*nuanced actions*" pushed P9 to consider non-rigid interfaces suitable for interactive installations rather than music performances and, likewise, P1 did not directly consider the use of non-rigid input in the design of musical instruments. Except for P1, the participants that connected non-rigid interaction to unpredictability and large scale actions are the same that experienced troubles with crafting their interfaces (Section 3.1.4), and that foster a stronger cross-contamination with research in new materials.

3.1.6 Shape Change

Five participants described the potential that shape change [34] may have in the context of novel musical interfaces. P8 and P4 hypothesized future scenarios in which shape and material properties of an interface can be adapted to specific musical tasks, while P5 emphasized how the "*contingent and dynamic nature of NIMEs could find more practice grounds*" with shape-changing interfaces. In contrast with the idea of shape adaptation, P9 and P1 talked of shape actuation as new means to provide haptic feedback; in particular, P1 saw this as a tremendous opportunity to increase "*the subtlety and nuance of interactions with the interface*".

The same idea was shared by P7, who framed shape change as a novel feedback modality ("*beyond vibro-tactile and force feedback*"), and envisioned non-rigid musical interfaces that "*vibrate along with its auditory output [that] get us toward programmable acoustic interfaces*". However, P7 also highlighted the extra challenges that shape-change adds to the design of non-rigid musical interfaces. How to design for shape change? What good mapping strategies exist or should be developed for shape-changing I/O? And how to master it? All these questions were shared among P7, P3, and P11. Further insight regarding the open problem of mastering a shape-changing musical interface was given by P6, who first praised shape change and the "*infinite space for exploring playing and sonic possibilities*" it generates; yet, he explained how difficult it would be to continuously develop playing techniques on a instrument that keeps changing its shape and functions, hence compromising "*the opportunity for virtuosity through practice*".

4. DISCUSSION

We reviewed existing non-rigid musical interfaces to define them as a research area of NIME. As such, we provided an overview of existing design practices for non-rigid musical interfaces which were not systematically approached before. Furthermore, we surveyed 11 experts to gather information about their practices, takes, and future perspectives on non-rigid musical interfaces, to help guide and inspire future research and design efforts. Next, we further discuss the results of our survey and consider possible directions for future work also referring to existing relevant literature.

4.1 Practices, Takes, and Future Perspective

Our participants had different motivations to design and build non-rigid musical interfaces, all of which expressed a desire to explore alternative and "unusual" ways of performing music, even compared to NIME standards. Such a desire for experimentation has also driven HCI to research about non-rigid interfaces, and both question and challenge earlier interaction paradigms [3, 1]. HCI has then moved past exploration through several user studies, practical applications (e.g., mobile interaction), and by formalizing grand challenges for non-rigid interfaces research [1]. This contrasts with the limited adoption that non-rigid interfaces show in music research. Except for [9, 14, 24], all the non-rigid musical interfaces discussed in this paper remain prototypical and were not further developed.

Our participants attributed such a difficulty in adoption and popularization of their interfaces to challenges in fabrication processes, maintenance, and the hardship of finding robust materials. Therefore, it was quite arduous for them to reproduce a design, improve it, as well as adapt it to the needs of other users. In other words, designers mainly built non-rigid musical interfaces with only one performer in mind, namely themselves (e.g., [38, 26, 41, 2, 45]). This emphasizes a general problem with adoption and popularization of new musical interfaces, which was previously discussed in NIME literature [25]. However, we have seen in recent years the emergence of consumer musical interfaces that feature (semi)non-rigid materials. Interfaces like *Skoog Music*[2], *ROLI Seaboard*[3], and *The Cell*[4], suggest that the latest advancements in material science may relax constraints linked to materials and crafting, and help foster the adoption and popularization of non-rigid musical interfaces.

Musical performance is most common among the use and applications for non-rigid musical interfaces, as evidenced by our results. Surprisingly, however, none of the participants has mentioned developing specific musical compositions (in contrast with [24, 43]) or choosing particular sounds to play with their interfaces. In that respect, Troiano et al. [40] found that non-rigid musical interfaces were deemed by musicians as both generic and specific; during their performance study, the authors observed that musicians would try different sounds when experimenting with the mapping of non-rigid gestures to musical parameters (see [40], pp. 381–382), but once they found the desired combinations they would consolidate I/O relations and focus on musical practice; this suggests that non-rigid musical interfaces can develop into strong specificness [44] if used over prolonged time. The lack of musical "standards" and specificity found among our participants may be explained by their primary focus in designing the non-rigid musical interfaces, rather than focusing on music composition and practice. By contrast, the musicians involved in the performance study of Troiano et al. were provided with ready-made non-rigid musical interfaces, and were then free to concentrate on exploring musical solutions and composition; however, their experience with performing music using non-rigid interfaces was rather brief (i.e., 10 minutes). To further validate the insights from [40], we need longitudinal studies, studies out-of-the lab [40], and studies in-the-wild [5] that observe how users learn to play with and master non-rigid musical interfaces over time, and relieved from the burden of design.

Besides musical performance, our participants designed non-rigid musical interfaces for diverse applications, including music therapy [7] and sonification [39, 46]. As such, differently from other musical interfaces, non-rigid interfaces and non-rigid input can be leveraged for designing interactions that do not only encompass music performances, but can also fit musical interactions more broadly. For instance, previous work [40] reported that musicians using non-rigid musical interfaces had the impression of "having the sound in the hand" and felt like "sculpting sounds" during their interactions. These insights suggest that such interfaces can benefit applications in sound design that disentangle from WIMP (i.e., window, icon, menu, and pointer) paradigms. This enhances "true" physical modelling of sounds, a concept that has been previously explored in virtual reality applications [27], but not yet with non-rigid musical interfaces.

4.2 What's Next for Non-Rigid NIMEs?

As evidenced in Section 3.1.4, one of the most pressing issues for designers of non-rigid musical interfaces is the need to find robust sensors, materials, and design standards that help move beyond prototypes and enhance reproducibility. According to our participants, the solution lies in establishing collaborations with material scientists and chemists, and leverage HCI work that investigates smart materials and nanotechnologies [33].

Our participants (P1, P8) indicated multidimensional input as an area of interest within the design of non-rigid musical interface. However, at present, our knowledge of how musicians leverage multidimensional non-rigid input for music is limited, and we need studies that systematically explore such novel input method. For instance, research questions like "What is the maximum number of deformations that musicians can comfortably and effectively control simultaneously?", "How do musicians perceive individual non-rigid input dimensions when they blur into one another?", and "Which musical tasks are a good fit for multidimensional non-rigid input, and why?" remain unanswered. We suggest that future NIME efforts investigating multidimensional non-rigid input align with what previously suggested in HCI work [3], namely to leverage psychophysics method [10] for systematically investigating users' perceptions of and the capacity to handle multidimensional non-rigid input. Similar to earlier work investigating expressive touch on interactive tabletops [31], a psychophysics approach to investigate multidimensional non-rigid input may also contribute a systematic understanding of the precision-vs-expression trade-off in non-rigid musical interfaces (see Section 3.1.5).

Boem and Troiano [3] pointed out how mapping remains substantially under-explored in non-rigid HCI and highlighted the need for further investigating I/O cross-modal correspondences with non-rigid interfaces. They suggested that HCI may do well looking at existing work on mapping in digital music instruments (DMIs) to advance this area. It is not coincidental, in fact, that existing work with non-rigid interfaces that has more carefully considered I/O relations, and proposed technical solutions for mapping, were mainly research in the musical domain [18, 12, 39, 23, 24, 2]. Given the above, and the long tradition that NIME and DMIs have on systematically investigating mapping and cross-modal correspondences, we argue that not only research on non-rigid musical interfaces, but also research on non-rigid HCI will benefit from NIME investigations in this particular area.

In Section 3.1.6 participants anticipated that self-actuation and shape change may be used for creating dynamic, adaptive, and responsive musical interfaces. This concept has been explored by MIT in their work TRANSFORM [16], where a hybrid musical/shape-changing display would change its physical shape to represent different sound waves (e.g., saw-tooth, sine wave). We encourage NIME to further experiment with a physical "embodiment" of sounds through shape change, for enhancing multi-sensory interactions beyond visual displays, and create reactive musical interfaces that establish dynamic "dialogues" with musicians via non-rigid I/O.

5. CONCLUSION

Non-rigid interfaces introduce new forms of controlling input and receiving output that may fundamentally reshape existing interactive paradigms. In this paper, we have explored challenges and open questions brought by non-rigid interfaces to musical interactions and proposed that future work engage in cross-disciplinary research efforts between HCI and NIME to advance the area. Our work will benefit designers and researchers that wish to contribute to NIME, as well as non-rigid interfaces at-large, by further exploring non-rigid musical interfaces and their prospective potential in enhancing new forms of musical expressions.

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7. REFERENCES

[1] J. Alexander, A. Roudaut, J. Steimle, K. Hornbæk, M. Bruns Alonso, S. Follmer, and T. Merritt. Grand challenges in shape-changing interface research. In *Proc. CHI*, 2018.

[2] A. Boem. Sculpton: A malleable tangible interface for sound sculpting. In *Proc. ICMC+SMC*, 2014.

[3] A. Boem and G. M. Troiano. Non-rigid HCI: A review of deformable interfaces and input. In *Proc. ACM DIS*, 2019.

[2] `https://skoogmusic.com/`

[3] `https://roli.com/products/seaboard`

[4] `http://cmg.tokyo/`

[4] B. Bongers and Y. Harris. A structured instrument design approach: The video-organ. In *Proc. NIME*, 2002.

[5] M. Callon and V. Rabeharisoa. Research "in the wild" and the shaping of new social identities. *Technology in society*, 25(2):193–204, 2003.

[6] A. Chang and H. Ishii. 2007. Zstretch: A Stretchy Fabric Music Controller. In *In Proc. NIME*, 2007.

[7] F. L. Cibrian, O. Peña, D. Ortega, and M. Tentori. Bendablesound: An elastic multisensory surface using touch-based interactions to assist children with severe autism during music therapy. *Int. Journal of Human-Computer Studies*, 107:22 – 37, 2017.

[8] J. U. Davis. Illumiwear: A fiber-optic etextile for multimedia interactions. In M. Queiroz and A. X. Sedó, editors, *Proc. NIME*, 2019.

[9] J. U. Davis and N. Hanover. Illumiwear: A fiber-optic etextile for multimedia interactions. 2019.

[10] G. A. Gescheider. *Psychophysics : The Fundamentals*. Psychology Press, USA, June 2013.

[11] B. Glaser and A. Strauss. *The Discovery of Grounded Theory: Strategies for Qualitative Research*. Routledge, USA, 2000.

[12] M. Grierson and C. Kiefer. Noisebear: A malleable wireless controller designed in participation with disabled children. In *Proc. NIME*, 2013.

[13] I. Hattwick, J. Malloch, and M. Wanderley. Forming shapes to bodies: Design for manufacturing in the prosthetic instruments. In *Proc. NIME*, 2014.

[14] A. Hinrichsen, S.-I. Hardjowirogo, D. H. M. Lopes, and T. Bovermann. Pushpull. reflections on building a musical instrument prototype. In *Proc. ICLI*, 2014.

[15] T. J. Hollinger, Avrum and M. M. Wanderley. An embedded hardware platform for fungible interfaces. In *Proc. of the ICMC*, pages 56–59, 2010.

[16] H. Ishii, D. Leithinger, S. Follmer, A. Zoran, P. Schoessler, and J. Counts. Transform: Embodiment of "radical atoms" at milano design week. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*, CHI EA '15, page 687–694, New York, NY, USA, 2015. Association for Computing Machinery.

[17] A. R. Jensenius and A. Voldsund. The music ball project: Concept, design, development, performance. In *Proc. NIME*, 2012.

[18] C. Kiefer. A malleable interface for sonic exploration. In *Proc. NIME*, 2010.

[19] Y. Kinoshita, M. Nishio, S. Shiraga, and K. Go. Investigation of pleasantness in the manipulation of deformable interfaces for musical expression. In *Proc. Int. Conf. on Kansei Engineering Emotion Research*, 2018.

[20] R. Lamb and A. Robertson. Seaboard: A new piano keyboard-related interface combining discrete and continuous control. In *NIME*, pages 503–506, 2011.

[21] J. Malloch, S. Sinclair, A. Hollinger, and M. M. Wanderley. *Input Devices and Music Interaction*. Springer Berlin Heidelberg, 2011.

[22] J. Malloch and M. M. Wanderley. The t-stick : From musical interface to musical instrument. In *Proc. of NIME*, 2007.

[23] M. Marier. The sponge a flexible interface. In *Proc. NIME*, 2010.

[24] M. Marier. Designing mappings for the sponge: Towards spongistic music. In *Proc. NIME*, 2014.

[25] F. Morreale, A. McPherson, M. Wanderley, et al. Nime identity from the performer's perspective. 2018.

[26] G. C. Morris, S. Leitman, and M. Kassianidou. Sillytone squish factory. In *Proceedings of the International Conference on New Interfaces for Musical Expression*, pages 201–202, Hamamatsu, Japan, 2004.

[27] A. Mulder and S. Fels. Sound sculpting: Manipulating sound through virtual sculpting. In *Proc. of the 1998 Western Computer Graphics Symposium*, pages 15–23, 1998.

[28] T. Murakami and N. Nakajima. Do-it: deformable object as input tool for 3-d geometric operation. *Computer-Aided Design*, 32(1):5 – 16, 2000.

[29] J. Oliver and M. Jenkins. The silent drum controller: A new percussive gestural interface. In *Proc. ICMC*, 2008.

[30] D. Overholt. The matrix : A novel controller for musical expression. In *Proc. NIME*, 2001.

[31] E. W. Pedersen and K. Hornbæk. Expressive touch: studying tapping force on tabletops. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 421–430, 2014.

[32] B. Piper, C. Ratti, and H. Ishii. Illuminating clay: A 3-d tangible interface for landscape analysis. In *Proc. CHI*, 2002.

[33] I. P. S. Qamar, R. Groh, D. Holman, and A. Roudaut. Hci meets material science: A literature review of morphing materials for the design of shape-changing interfaces. In *Proc. CHI*, 2018.

[34] M. K. Rasmussen, E. W. Pedersen, M. G. Petersen, and K. Hornbæk. Shape-changing interfaces: A review of the design space and open research questions. In *Proc. CHI*, 2012.

[35] M. K. Rasmussen, G. M. Troiano, M. G. Petersen, J. G. Simonsen, and K. Hornbæk. Sketching Shape-changing Interfaces: Exploring Vocabulary, Metaphors Use, and Affordances. In *Proc. CHI*, 2016.

[36] M. Savary, D. Schwarz, and D. Pellerin. Dirti —dirty tangible interfaces. In *In Proc NIME*, 2012.

[37] H. Sawada, N. Onoe, and S. Hashimoto. Sounds in hands: A sound modifier using datagloves and twiddle interface. In *Proc. ICMC*, 1997.

[38] E. Singer. Sonic banana: A novel bend-sensor-based midi controller. In *Proc. NIME*, 2003.

[39] K. Tahiroğlu, T. Svedström, V. Wikström, S. Overstall, J. Kildal, and T. Ahmaniemi. SoundFLEX: Designing Audio to Guide Interactions with Shape-Retaining Deformable Interfaces. In *Proc. of ICMI*, 2014.

[40] G. M. Troiano, E. W. Pedersen, and K. Hornbæk. Deformable Interfaces for Performing Music. In *Proc. CHI*, 2015.

[41] J. Wang, N. d'Alessandro, S. S. Fels, and B. Pritchard. Squeezy : Extending a multi-touch screen with force sensing objects for controlling articulatory synthesis. In *Proc. NIME*, pages 531–532, Oslo, Norway, 2011.

[42] E. Watanabe, Y. Hanzawa, and M. Inakage. Clay Tone: A Music System Using Clay for User Interaction. In *SIGGRAPH*, 2007.

[43] G. Weinberg. Playpens, fireflies and squeezables: New musical instruments for bridging the thoughtful and the joyful. *Leonardo Music Journal*, 12:43–51, 2002.

[44] S. A. Wensveen, J. P. Djajadiningrat, and C. Overbeeke. Interaction frogger: a design framework to couple action and function through feedback and feedforward. In *Proc. ACM DIS*, 2004.

[45] I. Wicaksono and J. Paradiso. Fabrickeyboard: Multimodal textile sensate media as an expressive and deformable musical interface. In *Proc. NIME*, 2017.

[46] V. Wikström, S. Overstall, K. Tahiroğlu, J. Kildal, and T. Ahmaniemi. Marsui: Malleable audio-reactive shape-retaining user interface. In *Proc. CHI*, 2013.

[47] M. Zadel, P. Kosek, and M. M. Wanderley. A pliable, inertial interface. Technical Report, 2003.