RAW: Exploring Control Structures for Muscle-based Interaction in Collective Improvisation

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ABSTRACT

This paper describes the ongoing process of developing *RAW*, a collaborative body–machine instrument that relies on 'sculpting' the sonification of raw EMG signals. The instrument is built around two Myo armbands located on the forearms of the performer. These are used to investigate muscle contraction, which is again used as the basis for the sonic interaction design. Using a practice-based approach, the aim is to explore the musical aesthetics of naturally occurring bioelectric signals. We are particularly interested in exploring the differences between processing at audio rate versus control rate, and how the level of detail in the signal—and the complexity of the mappings—influence the experience of control in the instrument. This is exemplified through reflections on four concerts in which *RAW* has been used in different types of collective improvisation.

Author Keywords

Improvisation, EMG, biosignals, sonification, mapping, ensemble, co-performance

CCS Concepts

•**Applied computing** → **Sound and music computing;** Performing arts; •**Human-centered computing** → *User centered design;*

1. INTRODUCTION

Over the last decades, we have seen a growing number of artist-researchers use the human body as part of their musical instrument. Rapid technological advancements now allow for capturing 'overt' information about human bodily processes (motion tracking), as well as measuring 'covert' processes (physiological measurements). As opposed to most traditional musical instruments, these new instruments are often 'touchless,' allowing for the creation of sonic interaction in the 'air' [13].

One challenge with playing such air instruments, is that the performance may bridge over to the aesthetics of theater acting and dance. We will leave that problem aside here, and focus on the types of air performance that is clearly situated within a context of music. Still there are several conceptual and practical challenges in how such instruments should be created. For example, how does one handle different spatiotemporal levels when not being restricted to a physical instrument? How does the design choices related to the spatiotemporal properties influence the perception of the performance? And, the question that is the main focus of this paper: how is it possible to create an 'air instrument' that can effectively be used in the context of group improvisation? From what we have seen, the majority of instruments developed for 'air performance' have focused on solo performance and/or a particular composition. But how is it possible to create a more open-ended instrument that can be used in collaborative musicking?

Figure 1: The second performance of *RAW* at the Web Audio Conference 2019 in Trondheim.

In this paper we report on the ongoing process of exploring improvisational concepts within the construction of *RAW*. Its building blocks range from the raw electromyographic (EMG) signals at audio rate, to the algorithmic approaches at control rate. Particular attention has been devoted to also interacting with other ensemble members via data interaction. After discussing the implementation, we present our subjective evaluation of using *RAW* in ecological conditions, and how that has informed the design and performance strategies.

2. BACKGROUND

2.1 Collective improvisation

In improvised music, freedom does not arise just from the notion of surprise and high complexity, but from doing so in appropriate and moderate ways [4]. Sawyer describes this as the "collaboratively emergent" nature of the group creativity, which enables something novel and coherent to occur [30]. Collective improvisation can therefore be seen as a case in which the creative agency is equally distributed among the ensemble members, which result in strict yet ever-changing constraints on an individual's creativity [15].

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2.2 Interaction dynamics

Borgo argues that the musical development of an improvising ensemble is unpredictable, and is based on the collective dynamics and decision-making of the group [4]. This can be thought of as similar to theories of nonlinear dynamical systems, in which complex neurobiological systems adapt and change their states through self-organization [7]. For example, imagine a double pendulum and how small changes in the initial angle, mass and speed conditions of the pendulum would influence the overall motion. This can be seen as similar to the interaction dynamics of 'forces' within an ensemble. Sawyer suggests that there is always an emergent intentionality in co-creation, based on a moment-to-moment contingency [30]. The result is that any action can be altered by the subsequent energy influxes from other agencies, be that of a performer, the audience, or a machine.

2.3 Mapping: control vs uncontrol

Mapping can be described as the conveying and perceiving of physical energy, and is in many ways at the core of an instrument [12, 39]. While many mappings may be seen as one-directional and deterministic, there are also mapping strategies that are based on exploring the boundary between control and 'uncontrol.' The latter can be seen as a type of mapping in which the performer has less direct influence over the instrument. In Snyder's *The Birl*, for example, the artificial neural network (ANN) that is responsible for the mapping, outputs a 'wrong' value whenever the input exceeds a certain threshold [34]. Similarly, Kiefer emphasizes unpredictability as a more expressive (un)control paradigm using nonlinear Echo State Networks (ESNs) [14]. Schacher and colleagues also aim at the breakpoints of the machine learning algorithms to inject a creative unpredictability in their instrument called *Double Vortex* [31]. Berdahl and colleagues focus on "razor-thin edge of chaos" sound synthesis techniques [2], while Mudd et al also explore the potential of nonlinear dynamical processes for the development of new creative digital technologies [22].

2.4 From biofeedback to biocontrol

Alvin Lucier's pioneering work, *Music for Solo Performer* (1964) for "enormously amplified brainwaves" [36], was the first musical piece to explore the complex and emergent behaviors of the human physiological system. Ironically, it relied on the performer's passive states, which may be thought of as a "biofeedback" paradigm [24]. Starting in the 1990s, we have seen a paradigm shift towards "biocontrol." This paradigm was first staged by Atau Tanaka's *Kagami*, featuring *The BioMuse* [19]. Later we have seen a further shift from control to a form of co-adaptation and configuration between the body and the system [38], such as in Tanaka's *Myogram* [37] and Donnarumma's *Ominous* [9]. While most of the experimentation has been done by solo performers, there are also a few examples of ensemble works using biosystems, including The Biomuse Trio [20] and Van Nort's collaborative sound-painting [23].

3. CONCEPTUAL DESIGN

Collective improvisation implies the exploration of relationships between players [1]. This may be based on balancing between "coherence" and "inventiveness" [29], or complexity vs comprehensibility, control vs uncontrol, and constancy vs unpredictability [3]. When setting out to develop *RAW*, one of our ideas was to rely on the EMG signals coming directly from the sensors. In their "uncooked" state, these signals are inherently noisy. They are also both controllable and uncontrollable at the same time. Since we are working with the raw sensor signals, we get a signal that is highly responsive, yet at the same time quite noisy.

There are two core ideas of *RAW*:

1. Explore the naturally occurring bioelectric signals at audio rate, and use these signals as the basis for the sound synthesis.
2. Build a set of control structures that range from being limited and constrained to highly open and surprising.

Together these two approaches allow for leveraging the full dynamics of the body motion at different spatiotemporal levels. It also makes it possible to exploit the stochastic and non-stationary characteristics of EMG signals [26], at an audible level. Conceptually, this is based on explorations of unconscious processing happening while playing [6]. This is also in line with the 'post-biocontrol' paradigm mentioned in 2.4, and will allow for using the system in relevant musical idea spaces of improvisation.

The development of *RAW* has been done using a practice-based approach and iterative design methodology. That is, once we had a working prototype, we started to use the instrument in live performances with different ensembles, each of which were evaluated and the feedback used to inform the continued development process.

4. IMPLEMENTATION

4.1 Hardware setup

The hardware setup of *Raw* includes:

- two Myo armbands placed on the forearms
- a laptop running a Python script for sensor data acquisition and a Max/MSP patch for sound sculpting
- a sound interface for audio I/O
- an iPad running the *Mira* app

The signal flow is sketched in Figure 2, and we will in the following go through each of the core components in detail.

4.2 EMG Data acquisition

EMG signals represent the electrical activity produced by muscles [26]. Each of the Myo armbands is equipped with 8 EMG sensors that are sampled at a rate of 200 Hz. Based on knowledge from hand-gesture recognition models [27], we decided to use the 4th and 8th Myo sensors. These correspond to the *extensor carpi radialis longus* and *flexor carpi radialis* muscles, respectively.

Since we have experienced a lot of problems in the past with Bluetooth-based devices, and particularly when using multiple devices at the same time, we decided to develop our own data acquisition solution.[1] This is a custom Python script based on Martin's *myo-to-osc* [21]. Here we implemented low-latency support for multiple Myo armbands, each connecting to the computer via separate Bluetooth Low Energy (BLE) adapters. This was important to overcome bandwidth limitations and data dropouts. The script can also be used to store data from the devices together with audio. This is useful to document and evaluate the latency and jitter of the data stream, and also for further analysis and model building. The script runs as multiple processes: data acquisition from the 1st and 2nd armbands, and audio recording using *PyAudio* [25], respectively.

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[1] `https://github.com/chaosprint/dual-myo-recorder`

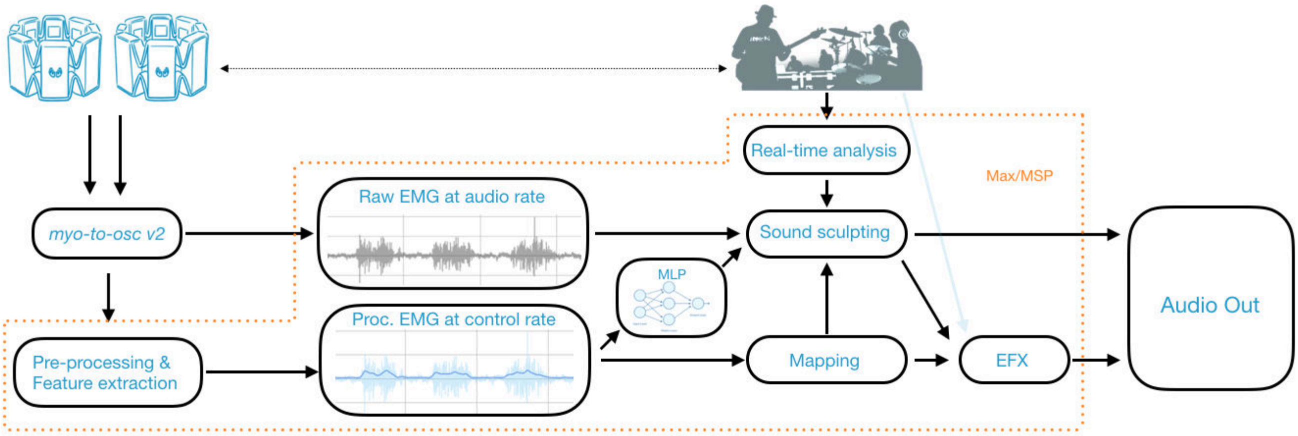

Figure 2: Simplified signal flow diagram for the performance of *RAW*.

4.3 Sound sculpting

The sound generating part of *RAW* relies on 'sculpting' raw EMG signals at audio rate. The incoming raw signals (2 channels per arm) are first normalized, and then written recurrently into buffers every 50 samples (250ms). This is below the constraint of a 300-ms acceptable delay [10], and provides four dynamic wavetables that are continuously updated. Then, the wavetables are brought to an audible range and their frequency spectra are controlled by time-scaled sawtooth signals. Finally, the buffers are 'sculpted' using direct audification of the raw EMG signals via processed control signals mapped to low-level MSP operators.

The second sound module uses a database of recorded percussive sounds of 1–5-s duration. As opposed to the sustained signal quality of the sonified muscle signals, this module provides a pointillistic way of wave-shaping. In addition, we also use the aforementioned wavetable strategy for external audio input reserved for other ensemble members. This allows for both sound sculpting and live processing throughout the performance.

4.4 Control signals

The signal coming from an EMG sensor is fairly complex, due to its stochastic and noisy nature. This is interesting at audio rate, but poses more challenges when used to create meaningful control signals. The first part of the signal chain is based on a fourth-order Butterworth filter with bandpass at 20–200 Hz. Second, we apply feature extractors to reduce the dimension of the discrete signals into a better representation. Here we take the root mean square (RMS) of the signal to represent the overall energy trend.

RMS works well for extracting larger-scale events from the EMG signal. However, one might consider alternative features for a better responsiveness to agility in motion. For that purpose, we relied on nonlinear Bayesian filtering (using the *pipo.bayesfilter* Max external object) as it provides significant advantages for the amplitude estimation of 'sudden changes' [11], as opposed to estimators such as the RMS that trims 'bumpy' information for a better trend.

As we do not use a physical interface, triggering sonic events in a more time-sensitive manner can become a challenging task. To tackle this issue, a relevant strategy is to detect the onsets, or, in other words, to determine the period of muscle activation based on the amplitude of the EMG signal. Among a range of methods, we relied on the Teager-Kaiser Energy (TKE) operation [17] for the muscle onset detection. We included TKE extractor in the Python script to process the signals in time domain as y(n) $= x^2(n) - x(n-1)x(n+1)$.

4.5 Attractor states

In *RAW* we program the compositional 'motives' based on *attractors*. This is inspired by the fields of dynamical systems, in which an attractor represents a set of points in space that evolve using differential equations. These equations draw identifiable trajectories in the *phase space* [18], illustrating broad outlines of complex behavior.

Our implementation is based on a Support Vector Machine (SVM) classifier that recognizes the pinch grips of the performer. These are then drawn as a new set of points on the orbit that is mapped to sound synthesis parameters. The non-periodic and unstable behavior of these attractors trigger seemingly random spectro-temporal events. Yet, the trajectories accumulate to a final shape that looks 'attracted' to the compositional motif, such as in using a pre-written chord progression.

In addition to the SVM classifier, we employ various random processes in the mapping structure, based on Brownian noise. Random values are preferred for the exponential base of scaling curves, as well as for wave-shaping and amplitude modulation. This is to create a more uncertainty than what is typically achieved with linear mapping structures.

4.6 Machine learning

The system uses supervised Multi-Layer Perceptron (MLP) algorithms for regression, using the *ml.** library for Max [5]. Each artificial neural network (ANN) is set up with three hidden layers, relying on bipolar sigmoid activation functions to map the 8-dimensional EMG data to a 2D-point on an XY plane. The ANNs are trained on a dataset consisting of hand waving and a detour on the plane. In other words, the start (x=0, y=0) and endpoints (x=127, y=0) are constant, while the trajectory is nonlinear. This can be thought of as a 'gamified' strategy. Imagine having a 'ball' (point) on each hand, sharing the same plane, in which the goal is to make the two balls intersect to successfully trigger and/or adjust the events. The performer is then required to have a clear imagery of the plane to have complete control on the generation of events. In most cases the performer will make 'mistakes,' willingly or unwillingly, which will lead to unexpected events.

4.7 Ensemble interaction

An important feature of *RAW* is the implementation of strategies that allow for direct interaction with an ensemble.

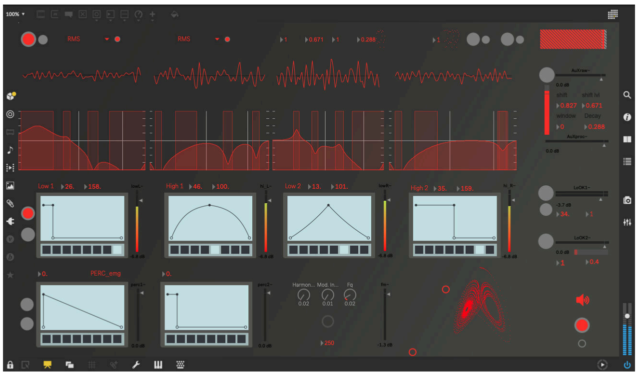

Figure 3: The graphical user interface (GUI) of *RAW*, designed in Max/MSP.

One of the ways to achieve this is through a real-time audio analysis module that is programmed to interact with any kind of audio input. This module is implemented using a chain consisting of: an envelope follower based on a median filter; a tempo tracker using the btrack~ object [35]; an onset detector using the spectral flux for controlling temporal events, such as stutter, tremolo and delay; and *pipo~* plugins from the Ircam MuBu library [32] for spectral analysis.

4.8 Outboard

The last part of the sound signal flow in *RAW* is a small set of effects. This includes: a simple reverberator based on the Schroeder model [33]; delay lines based on comb filtering effect (*comb~*); and state-variable filters (*svf~*) that are driven by the time-scaled output of the interaction modules.

5. PERFORMANCES

RAW has been used in four public performances to date,[2] each with a different ensemble. We will in the following discuss how the different performances have shaped the performance strategies and the development of the instrument.

5.1 Ensemble 1: Trio with live coding, voice & body resonators

The premier performance of *RAW* took place in a cultural center in Oslo, Norway. The ensemble featured Tejaswinee Kelkar, performing with kitchen utensils actuated through her voice, and Qichao Lan using a live coding environment, Quaver Series ([16]), designed by himself. The 20-minute set was structured as short solo acts of each musician, followed by a collective improvisation.

The *RAW* solo started with a short interlude with the vocalist. The voice was fed into the instrument and processed using modest time-stretching, controlled by the performer's upper arm abduction and wrist flexion/extension. Here we observed how the (spoken) voice influenced the body motion of the performer in a particular way, which was largely based on sustained motion with occasional impulses. The muscle tension was generally low, and its fluctuations were slightly perceivable. This interplay set an example for how a combination of creative interactions and emerging constraints enable an experience of *flow* [8].

The collaborative improvisation part evolved into the use of rhythmic structures. Here we observed two distinct layers: a set of pulse-based rhythms, and a set of discontinuous dynamic (accelerating vs decelerating) rhythms with intermittent textures. Drawing on Grisey's continuum of rhythm (as elaborated in [28]), each of these rhythmic structures represented two extremes: 'Order' (predictability) on one end, and 'disorder' (unpredictability) on the other. Finally, the higher complexity of rhythmic structures steered *RAW* towards a higher rhythmic complexity as well, quite different from its smooth and sustained trend in the solo section.

5.2 Ensemble 2: Quintet with live coding, shared electric guitar & laptop, voice & laptop

This performance (Figure 1) was part of the Web Audio Conference 2019 (WAC) in Trondheim, Norway. It also featured live coder Steven Yi, together with Ariane Stolfi on live processed voice, and Luis Arandas and Michel Buffa who shared a guitar and a laptop. In live coding, the musician writes code on the computer to generate sounds. The striking aspect of this performance style is that it heavily relies on the machine clock rather than human bodily rhythms. So in a collaborative performance, the human performers naturally tend to align with how the live coder structures the (machine) time.

The first salient feature of this collaborative performance was the gentle pulses coming from a performer on a Csound-based live coding environment. While the live-coded sound shapes were more 'vertical,' the rest of the ensemble played more sustained sonic patterns. The first half of the performance demonstrated a mellow and ambient musical structure, along with short-lived dynamic articulations.

Borgo speaks about two types of transitions in free improvisation: small-scale transitions that occur dynamically between different parties within the ensemble, and larger-scale transitions that happen through complete synchrony and flow [4]. In this performance we observed one larger-scale transition between the two halves of the performance. There was also a dynamic interplay happening between *RAW* and the voice, while the guitar maintained the ambient layer along with live coded pulses. It was interesting to observe, once again, a naturally occurring musical coupling between processed voice and a muscle-based instrument, which should be further investigated. Finally, in this performance *RAW* relied on control structures of low complexity, which showcased the potential of using gentle, sustained, body motion in muscle-based performance.

5.3 Ensemble 3: Duo with gestural controller

This duo performance was part of a special event for gestural interaction, which took place in a nightclub in Istanbul, Turkey (Figure 4). The ensemble featured *RAW* together with *Armonic*, a gestural control system based on inertial measurement units (IMUs) and capacitive sensors. *Armonic* specializes in a gestural live sampling technique, with a particular focus on precision and control. Görkem Arıkan, the inventor of *Armonic*, draws an analogy between his performance style and 'puppetry:' controlling "sounds through 'invisible' ropes prolonging from [his] hands."

This was a quite different performance, in that both performers played on 'air instruments.' Thus, even though both of the instruments were untraditional, they shared some similar affordances. This, combined with the coziness of a small club stage, allowed both performers to develop an interpersonal language beyond their normal strategies for action–sound mappings. This was experienced as being similar to how dancers often do contact improvisation (CI), in which the emphasis is put on inter-corporeal experimentation, curiosity, and self-surprise [15].

This relatively short (10′) performance demonstrated rapidly changing idea spaces, and several larger-scale transitions. The overall trend of rhythmic structures alternated between the two extremes of the before-mentioned Grisey's continuum (from *smooth* to *random*), which also resulted in an

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[2] Videos available at `http://bit.ly/raw_videos`

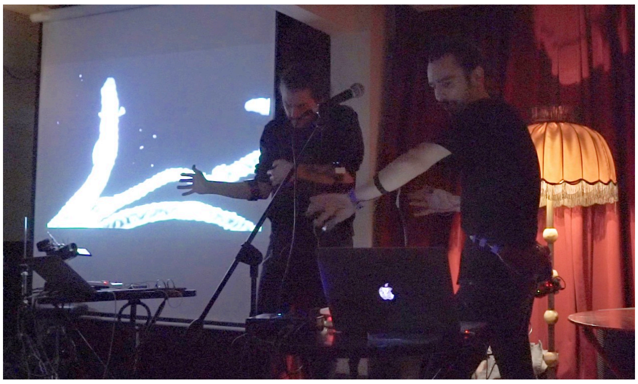

Figure 4: Duo performance by Çağrı Erdem and Görkem Arıkan in Istanbul 2019. The improvised performance featured two 'air instruments': *RAW* and *Armonic* (Photo: Mehmet Ömur)

energy trend that varied almost idiosyncratically. In the case of *RAW*, this led to a dynamic interplay based on an extensive use of control structures of high complexity, particularly the ANN-based 'gamified' strategy.

5.4 Ensemble 4: Duo with drums

This duo performance featured *RAW* together with drummer Onur Başkurt, and took place in a jazz club in Istanbul, Turkey, as part of a larger event that hosted several improvisation ensembles. The drummer used a small drum set, and it was not equipped with microphones, except for an overhead ribbon microphone that was used to capture audio for *RAW*.

The performance was based on a rough sketch of playing three sections in A-B-A′ form. The A section was focused on exploring the full dynamic potential of a muscle-based instrument. *RAW* relied on sound-sculpting the muscle signals, using both extremes of the dynamic range actively. This first part of the performance was completely led by muscle contraction effort processed at audio rate. The drummer tried to carefully follow the dynamic fluctuations, using accelerating and decelerating rhythms. This echoed how Grisey indicates the intrinsic relationship between tension and discontinuous rhythmical dynamics.

The B section opened with a short drum solo interlude. *RAW* eventually joined in with chopped-up (iterative) samples. In this section, we observed how muscles are intrinsic to small-scale body motion that is hardly perceivable.

The A′ section was mostly a recap of A, with an additional closing as it was the end of the performance. All in all, *RAW*'s strict control over the dynamic shape, combined with unexpected timbral outcomes, led to an interesting combination of controllability and surprise.

6. CONCLUSIONS

The central ideas of *RAW* were to explore the raw EMG signals at audio rate, and to build a set of control-level mapping structures. Already from the first prototype and performance, this worked quite well. Subsequent performances were important for further exploration, evaluation, and modification of the system.

One important finding from the development, is that there is a huge difference in the mean amplitude of muscle signals at rest versus during performance. Such changes in psychophysiological conditions are important to bear in mind when developing a muscle-based instrument, and are not possible to test without carrying out real-world performances.

Another finding is that of the importance of a certain level of causality between action and sound. This became particularly evident in Ensemble 3, in which both performers played with 'air instruments.' Here both performers used full-range sound spectra distributed through the same sound system. This caused problems of masking and lack of spatialization.

All in all, we find *RAW* to be a well-functioning instrument, and it has proved to be stable in real-world performance contexts. Still there are numerous things to improve in future iterations:

- Action–Sound Causality: Even though a 'blind' exploration of (musical) gestures may be exciting at first, performing with different ensembles ascertained the necessity of a certain level of causality between action and sound, hence the possibility of repeatable playing technique. Since we are working at a level of muscle-control, future developments will include explorations of fine motor patterns. Through this we aim to improve the mapping structures and interactive affordances of the instrument.
- Interaction: Unpredictable processes work well in small-scale transitions, since these moments allow for 'debate' between performers. Moreover, such processes showed that simple mappings can be engaging and serendipitous. However, a whole-group synchrony is crucial for transitions of larger musical idea spaces. This is where traditional instruments allow for a superior responsiveness and causality than most 'air instrument' designs. To this end, we will focus on better machine listening and real-time interaction strategies.
- Rhythm tracking: Performing with a drum set in Ensemble 4 revealed the necessity for implementing a better non-periodic rhythm-tracking, and developing 'riff-based' playing techniques.
- Spatiotemporality: Each of the co-performing instruments have had unique spatiotemporal characteristics, which combined with the spatial range, metabolism and biomechanics of the human body, have led to many interesting audiovisual moments. In live coding, for example, you sit, and write and rewrite text. When playing a drum set, you also sit, surrounded by several physical objects of different sizes, shapes and materials. A muscle-based 'air instrument' is not bound to the same type of physical space, but this still leads to many questions about how space should be used, how time should be structured, and how to interact audiovisually with the other performer(s).

These conceptual and practical challenges will be addressed in our future developments of muscle-based performance.

7. ACKNOWLEDGMENTS

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