Towards an Interactive Model-Based Sonification of Hand Gesture for Dance Performance

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ABSTRACT

This paper presents an ongoing research on hand gesture interactive sonification in dance performances. For this purpose, a conceptual framework and a multilayered mapping model issued from an experimental case study will be proposed. The goal of this research is twofold. On the one hand, we aim to determine action-based perceptual invariants that allow us to establish pertinent relations between gesture qualities and sound features. On the other hand, we are interested in analysing how an interactive model-based sonification can provide useful and effective feedback for dance practitioners. From this point of view, our research explicitly addresses the convergence between the scientific understandings provided by the field of movement sonification and the traditional know-how developed over the years within the digital instrument and interaction design communities. A key component of our study is the combination between physically-based sound synthesis and motion features analysis. This approach has proven effective in providing interesting insights for devising novel sonification models for artistic and scientific purposes, and for developing a collaborative platform involving the designer, the musician and the performer.

Author Keywords

Movement sonification, dance-music systems, physical modelling

CCS Concepts

•Applied computing → Sound and music computing; Performing arts; •Human-centered computing → Interaction design theory, concepts and paradigms;

1. INTRODUCTION

Our work lies at the crossroads of movement sonification, interactive dance music systems, interfaces for musical expression and physically-based sound synthesis. In the next sections, we briefly discuss how these fields consider motion, gesture and multimodality, highlighting complementarity and possible convergences.

1.1 Movement Sonification & Interactive Dance Music Systems

The field of movement sonification has become an established area of research involving a variety of scientific disciplines, such as psychoacoustics, neuroscience, medicine, human-computer interaction, biomechanics and musicology [16], providing different applications for sport training [17], movement rehabilitation [34] or product design [3]. Although the interest in sensorimotor learning with movement sonification has dramatically increased over the last ten years, the majority of neuroscience, medical and sport experiments still employ very basic interactive systems, often based on simple pitch or volume control of pure tones and electronic noises with little concern for sound design (for an extensive review, see [9]). During this time, artistic-based and artistic-oriented research has provided highly expressive applications, from real time software environments for the performing arts (e.g. InfoMus Lab's EyesWeb, Ircam's GestureFollower), to the tremendous variety of Digital Musical Instruments (DMI) [41] in the NIME community. Nonetheless, sensorimotor learning has been rarely studied explicitly in this context. Unsurprisingly, the term "movement sonification" has only recently been introduced in artistic-oriented research [10][30]. As has been noted by Bevilacqua et al.[2], although interactive dance/music systems and data-driven movement sonification both use movement interaction in order to generate sound content, their goals are generally different. While in the former, sound outcome is designed in order to produce an aesthetically meaningful interaction, in the latter, the sound feedback aims at providing an objective auditory representation of the movement. In the last few years, some attempts have been made in order to combine these two traditions. We will present them briefly in the next main section.

1.2 Sound and Motion Co-articulation

This paper presents a model-based sonification of hand gestures for dance performance, built upon practical experimentation with technologies. Our goal is to propose a conceptual framework and experimental methodology allowing system designers and performers to collaborate in order to combine aesthetically meaningful interactions and sensorimotor learning. As such, our work draws from research and practise-based knowledge in the fields of movement sonification as well as digital instrument and interaction design communities. Our primary hypothesis is that physical model parametrisation can provide a corporeal vocabulary that can be related to different motion sensing techniques and movement feature extraction, allowing for effective sonic feedback. Moreover, the somatic knowledge provided by the performer is taken into account during the design process [8]: his/her embodied experience and point of view orient the mapping and design process by providing a metaphorical level that relates to both sound generation (the virtual resonant body) and motion analysis (the performer's gesture features).

Our general mapping and design methodology can be described as a multilayered framework consisting of three hierarchical levels. The first two levels would provide invariants that should reflect objective proprieties of both sound and motion. Such a parallel classification allows highlighting existing meaningful resonances between acoustic and movement domains. From this point of view, the hierarchical sound-action taxonomy we propose provides a structured and objective classification that has proven useful in or-

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NIME'20, July 21-25, 2020, Royal Birmingham Conservatoire, Birmingham City University, Birmingham, United Kingdom.

der to implement the collaborative design process. In accordance with the sonification paradigm, such a systematic approach allows creating interactive sound feedback that can reflect objective properties of the movement, thereby conveying meaningful sensorimotor information to the user. The third level is the object of an ongoing development and questions the relation between specific features of a resonant body (e.g. roughness) and a peculiar movement quality. We believe that this level should be of a quasi-objective nature, developed in regards to specific choreographic repertoire or an idiomatic dance language.

2. RELATED WORK AND KEY THEORIES

Our work proposes a conceptual conjunction between movement sonification and physical modelling. Therefore, the next subsections introduce a brief state of the art of both fields, with an emphasis on real time interaction.

2.1 Interactive Movement Sonification in Dance Practice

Although the field of sonification represents a major area of research, at least since the 1990's [19], the term itself has only recently been adopted in performing arts and music technology research. In a seminal paper, Hunt and Hermann [16] argued how the "quality of interaction" can enhance perceptual skills in performing activities or in accomplishing simple sensorimotor tasks thereby providing a conceptual bridge between data sonification and interaction sound design. One of the earliest experiments in movement sonification for sensorimotor learning in performing arts was reported by Menicacci and Quinz [33]. In this study, the real time sonification of a physical quantity (i.e. performer's lower limb extension captured by flex sensors) is experimented in order to successfully support the dancer's postural reorientation. To our knowledge, the first studies that explicitly used the term "sonification" for sensorimotor learning in dance was carried out by Jensenius and Bjerkestrand [18]. The authors explore the sonification of professional dancers' micromovements (i.e movements that occur at the scale of milliseconds) with a Qualisys marker-based motion capture system. Other studies focus more particularly on how sound feedback can provide meaningful information during dance training. Grosshauser et al. [15] developed a wearable sensor-based system (including an IMU module, a goniometer and a pair of FSRs) in order to sonify classical ballet jump typologies (e.g. *Italian changement* and *Sauté*) in dance classes of different age and level. In terms of sonification, these two studies mainly use simple additive synthesis with pure tones (or white noise). Other remarkable applications have been developed for the learning of movement qualities in dance. Françoise et al. [11] report the results of an experimental workshop in which they propose an interactive sonification of effort categories issued from Laban Movement Analysis [20]. In a recent study Camurri et al. [5] describe the implementation of an EyesWeb algorithm based on dynamic symmetry analysis. The auditory feedback is conceived in order to provide a reward system for a student who tries to reproduce dynamic symmetry in a movement previously executed by a teacher. No particular attention has been paid to sound quality. In a following study [30], the authors explore the sonification of other mid-level features such as lightness and fragility, introducing an interesting model-based sonification in which a specific sound synthesis model is devised for each movement quality. In [10], Françoise et al. directly address kinesthetic awareness via interactive sonification, combining conceptual frameworks issued from somatic practices (e.g. Feldenkrais method, somaesthetics approach) and user-centered HCI. Participants (both skilled dancers and non-professionals) wore a pair of MYO armbands[1], placed on the lower legs, to sense neuromuscular activity of the calves and shins. Both sonification methods and user-centered strategies (e.g. adaptive system; neuromuscular sensing), combined with somatic approaches to experimentation, seem to provide a rich playground for accessing bodily awareness and especially the dynamic relation between proprioception and movement.

[1] https://support.getmyo.com/

2.2 Physical Modelling for Musical Creation

Sound synthesis by means of physical modelling has grown substantially over the past decades, both in academic and commercial applications, driven by the steady increase in computing power coupled with optimised simulation techniques. Nowadays, all major physical synthesis methods (waveguide, modal, finite difference schemes, mass-interaction models) can be computed in real time[2] and implemented into DMI sound production units, or more widely used as tools for multisensory creation [39]; below, we discuss various works regarding the articulation of the gesture-sound relationship in the context of physical modelling and virtual musical instruments.

2.2.1 *Modularity and Interactivity*

A large portion of research regarding physically-based sound synthesis has focused on detailed reproduction of acoustical instruments, generally either employing specific interaction devices for specific instrumental paradigms (such as the bowed string implementation in [36]) or targeting for compliance with standard musical input devices (MIDI, etc.).

However, physical modelling techniques also present significant interests in terms of modularity [6] and flexibility. They allow for the interactive design and simulation of novel instruments with rich interaction possibilities [22], including using sensors, actuators and, more recently, mobile devices [29]. When considered under this light, physical modelling becomes a creative tool for crafting interactions with virtual objects that provide multisensory feedback. The coupled activities of creative physical modelling and interaction design at play in this framework are summarised by Gelineck et al. as follows [12]:

> *"[...] we must examine the exploratory qualities of the sound-synthesis model, the physicality of the interaction, and how the integration of the two can encourage exploration"*

2.2.2 *Gesture-sound relationship*

Physical modelling is also a fertile terrain for exploring the gesture-sound relationship at play in sonic and musical performance, especially through the use of force feedback technologies. Several works have studied gesture-sound coupling between a musician and a virtual physical instrument through a haptic device [26, 36], on the grounds that an entirely *energetically coherent*, *bidirectional* and *mapping-free* relationship between physical effort and virtual resonant body [25] allows for strong embodied cognition, similar to when playing a real musical instrument.

Many other works present a looser relationship, following a traditional DMI mapping between gestures and sound. It has however been argued that gestural mappings to physical model actions or parameters can be tricky to extrapolate and elaborate on [41]. To the best of our knowledge, and possibly because of this perceived difficulty, physical models are rarely employed for sonification purposes or in interactive dance-music systems, despite their inherent potential to foster meaningful relations from gestural qualities to physical sound production. We will discuss a proposed methodology allowing to structure hierarchical mappings from gestures to physical models in the following sections.

2.3 Embodied Approaches to Music Cognition and Interaction

From a theoretical point of view, our approach stems from the general framework of embodied cognition [35]. In particular, our design principles and empirical methodology are informed

[2] Depending on the complexity of the underlying model.

by phenomenological traditions [28], and more recent philosophical understandings concerning the enactive paradigm [38] and action/perception coupling [31]. Over the last years, such approaches have proven to be increasingly important not only for the theoretical understanding of human cognition and perception, but also for allowing researchers to go beyond a mere technological perspective in the design of interactive systems. Physical presence and holistic involvement seem to be main features in providing embodied and user-centred approaches to interaction [8]. Especially in sonic interaction design, the emergence of embodied approaches to music cognition and mediation technology provides novel important insights [21]. Embodied theories support the idea that there is no real separation between mental processes and corporeal activity, describing music cognition in terms of an « action-perception coupling system » [21]. According to this perspective, sound perception has a direct relevance for the sensorimotor system (in terms of both involuntary reactions and deliberate responses). Moreover, music-related gestures can be described as mediators between sound phenomena and music meaning formation [27].

Such theoretical assumptions are supported by empirical studies, demonstrating that both movements and verbal descriptions in response to music are strictly connected to the sound's morphological structure: according to motor-mimetic theory [7], highly significant features of music, such as melody, harmony, timbre, and rhythm are reflected in the movements of the perceivers [4, 32]. Sonic events and action trajectories can be thereby conceived in terms of «coarticulation» [14]. From this perspective music perception is not only action-oriented, but also ecologically situated and multimodal. Indeed, the perceiver doesn't need to perform computations in order to draw a link between sensations and actions; it is sufficient to find the appropriate signals in the environment and associate them with the correct motor response. Moreover, listening is a complex multimodal activity involving not only hearing but also visual cues, kinesthesia (sensation of motion), effort and haptic perceptions.

Within this context, music perception can be described as a multimodal, situated and motion-related experience. What is important for our study is that sound perception is strictly related to action and to sensorimotor learning (i.e. «action-perception coupling»), while sound feedback itself is conceived as an action-related phenomenon capable of eliciting gestural affordances. Systematic applications of this paradigm have been experimented in the fields of music performance [40], movement pedagogy [1], movement analysis [13] and healthcare/well-being [24].

3. A HIERARCHICAL MULTILAYERED MAPPING MODEL

We now introduce the analytical aspects and methodology of our proposed model-based interactive sonification, combining both computational classification methods [5] and artistic-based approaches to interaction design and mapping [42]. A core feature of our model is the hierarchical structure that we conceived in order to provide a substantial sound-motion correlation. From a methodological point of view, we adopted an empirical procedure to roughly design a preliminary classification. In the first phase, the first author created a repertoire of short videos exploring different kinds of motion parameters that can be extracted by raw sensors' data and computed motion descriptors. Various motion sensing technologies (9 DoF IMU, EMG and Computer Vision techniques) have been used to this purpose. The second author designed a similar taxonomy by listing different types of physical model parameters and by recording audio examples. In the second phase, we compared our classifications and defined a unique hierarchical structure for both taxonomies. Classifications were conceived by adopting the following general criteria: 1. Degree of computation (e.g. a motion/stillness feature occupies a higher level than simple accelerometer raw inclination); 2. Richness of the transformation (e.g. a pitch tone variation is considered less rich and complex than a change in timbre caused by the coupled dynamics of several virtual resonating structures); 3. The metaphorical and/or multimodal evocativeness of the feature (e.g. "roughness" suggests a rich sensorial image that can applied to both sound texture and movement quality). It should be noted that [5] use the expression "amodal feature" in order to describe some mid-level features that provide meaningful characterisation for both sonic and movement domains. Nonetheless, we suggest that the term "multimodal" should be preferred because it highlights the way in which a certain quality resonates in several sensory fields.

3.1 Motion Features

Motion features classification takes inspiration from several taxonomies proposed over the years by InfoMus Lab team [5]. Similarly to their work, we adopted a hierarchical framework for the purpose of classifying previously stored motion features according to the computing process complexity. Unlike the approach by InfoMus, we explicitly avoided a temporal scale classification as a main criterion. Since our goal is to provide real time interaction models there is no reason to include larger time scale features, nominally "Communication of expressive qualities". Nonetheless, a phenomenological description of the temporal domain (e.g. continuous, event, etc.) is introduced in order to depict the temporal quality of each feature (both motion and sound). It should be noted that we don't use the term "motion feature" in its ordinary technical meaning, i.e. a computed quantity extracted from movement analysis. In our classification, the raw data from motion sensors are considered as "motion features" since, in terms of sonification, they provide meaningful information about movement. Therefore, our classification is based on three hierarchical layers.

The first one – *low-level features* – includes physical signals issued from sensors and equivalent parameters stemming from basic computations (e.g. pitch inclination issued from accelerometer and gyroscope sensor fusion). The second one – *mid-level features* – covers structured movement descriptors (e.g. Quantity of Motion, Force, Intensity, etc.) and some dynamic gestural features (Spin, GestureMotion, Repetitiveness, etc.). The third one – *high-level features* – includes movement qualities. As mentioned above, this level should be adapted according to a specific choreographic idiom or, at least, to a well-defined dance style repertoire. From this perspective, the features included in this level have to be defined as quasi-objective, if not explicitly subjective.

3.2 Physical Sound-Action Features

The models developed for our work use the mass-interaction physical modelling paradigm, a discretisation of point-based mechanics in which virtual physical objects are designed by building networks of connected masses, springs and other (linear or non-linear) interaction elements. This approach offers a high level of modularity and flexibility in the design of both the instrument (arbitrary physical topologies, access to all parameters) and physical interactions (such as bowing, striking, etc.), while remaining computationally efficient for real time synthesis in popular environments such as Max/MSP.

As a consequence of this flexibility and low-level control, any given mass-interaction model may possess tens or even hundreds of physical parameters, excitation mechanisms and inputs/outputs. While designing the instrument itself generally requires explicit knowledge and control over these parameters, addressing them explicitly during performance or while designing mapping strategies can certainly be quite daunting.

Consequently, we propose a methodology in which generic categories of virtual actions that may be performed upon a physical model are structured into hierarchical levels, drawing inspiration from the "physical functions" described by Tache in his studies of a mass-interaction model organology [37]. These "sound-actions" (for lack of a better term) such as *excite*, *intensity* or *roughness*, provide a set of generic features heavily based on gestural and phys-

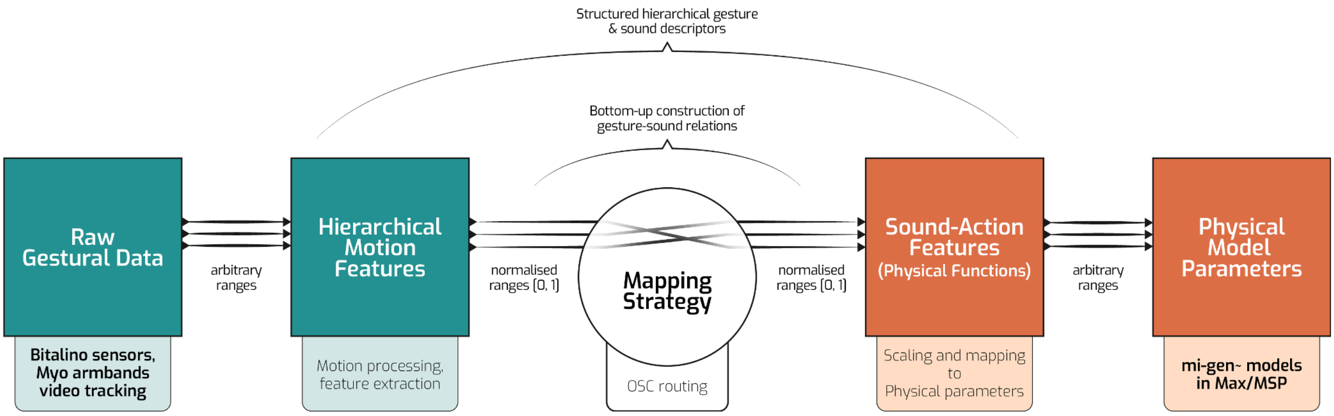

Figure 1: Hierarchical multilayered mapping model from gesture to physically-based sound.

Table 1: Sound-action examples and implementation in the bowed string physical model. Functions used in the case study mapping are highlighted in orange.

Sound-Actions	Implemented Actions
Low Level Features	
Pitch	Move a virtual finger along the bowed string
Inertia	Change the inertia (mass) of the string
Resonance	Change the damping of the string
Mid Level Features	
Excite	Move the virtual bow across the string
Intensity	Control pressure of the bow on the string
Move Exciter	Change the bow/string excitation point
Move Listener	Change listening point on the string
High Level Features	
Roughness	Modulate a non-linear collision between the string and a fixed obstacle near the bridge
Coupling	Modulate coupling with the resonant mesh

ical metaphors, serving as guidelines for creating physical models with interaction design in mind. They allow structuring and transferring of mapping strategies onto any physical model, so long as it implements these features into concrete actions and modifications performed on the virtual physical object.

3.3 Interaction Design

Both motion and action-sound features are classified within a multi-layered framework that allows us to intuitively conceive the mapping process. Furthermore, the hierarchical structure of the framework is intended to highlight perceptual idiosyncrasies between the physical model parameters and the motion sensing descriptors. From this perspective, our design process develops as a proper «coarticulation» [14] between action and sound.

4. PRACTICAL CASE STUDY

For this practical experimentation, we worked with Loredana Tarnovschi, a young professional dancer and choreographer, and also a music practitioner (mainly percussion). Her multidisciplinary experience within these fields was considered crucial for the formulation of effective insights about the relation between the sound feedback and the movement execution and creation. In the following sections, we describe the technology and methodology adopted during our collaboration, one that strongly integrates the point of view of the performer. The experimentation we describe in the present case study was carried out during a four-day residency in November 2019 at the Maison de la Création et de l'Innovation's Somatic Lab in Grenoble-Alpes University.

4.1 Motion Sensing Technologies

The technical setup for the residency was based on two different commercial devices: a Myo armband (that provides data generated by the performers' neuromuscular activity via EMG electrodes) and a Bitalino R-IoT unit (that embeds a 9-DoF IMU-Marg system, i.e. triaxial accelerometer, gyroscope and magnetometer). The Bitalino was worn on the back of the performer's right hand and the Myo on her right forearm. This solution allowed measuring both isotonic and isometric activity of the performer's hand gestures. The incoming raw data was processed in Max/MSP, using (among other things) customised algorithms based on Ircam's Mubu library.

The initial motion features were modified and refined during the residency according to their effectiveness in producing an interesting outcome in terms of sensorimotor learning and instrumental expressive control, resulting the following four mid-level features being retained: *Motion*, *Intensity*, *Hand Force* and *Arm Force*.

4.2 Bowed String Physical Model

The virtual model used in the presented case study and shown in Figure 2 was designed using mi-gen~ [23], a Max/MSP toolbox for designing modular mass-interaction physical models, which are then compiled into gen~ DSP code, allowing for efficient real-time performance and control. It is composed of a string, coupled to a resonating mesh. The string can be bowed using a gestural input by controlling the "bow mass" velocity, pressure on the string, as well as the bow position along the string (as continuous interpolated control). Modulation of the string/mesh coupling springs yields an increase in pitch and rough inharmonic tones when the two mechanical structures are intertwined. The generic physical functions and concrete implementations in the bowed string model are summarised in Table 1.

4.3 Bottom-up Strategy and User Experience Approach

The four day residency allowed for step by step collaborative prototyping of a sonification model via discussions, practical experimentation phases and systematic feedback from the performer regarding the quality of the interaction and the sound outcome (e.g. the effectiveness of the auditory feedback compared to her corporeal engagement in executing gestures), thus informing our design approach. Empirical testing was articulated in two parts. The first part aimed at evaluating the effectiveness of the sound interaction from a sensorimotor learning point of view, by initially asking the performer to improvise movement by focusing her attention on the way in which the sound was able (or not) to convey an effective and meaningful audio representation of the executed movement. In this phase our research question was: "can the sound outcome

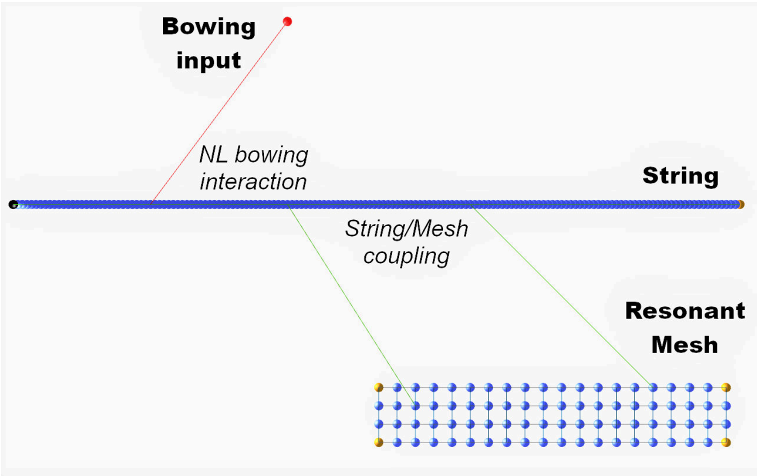

Figure 2: Left: performer executing hand gestures, equipped with Bitalino sensors and Myo armband for gestural input. Right: mass-interaction bowed string physical model used for real time sonification.

produce a meaningful perpetual resonance of the movement, and if so, can the sound outcome inform corporeal knowledge by highlighting relevant aspects of movement?" The second part consisted in examining the expressive potential of the interaction in artistic terms, by inviting the performer to improvise in a more performative, and expressive way, thereby exploring the whole palette of acoustic modulations, addressing the question: "can the interaction provide a satisfactory outcome in terms of control, adaptability and variation? Is the sound outcome sufficiently rich and varied so as to enable a musical interplay?"

Gesture-to-sound mappings were elaborated with a bottom-up strategy, starting with simple, low-level interactions that could be elaborated upon once validated by both the performer and the researchers. Excitation of the resonant body was associated with simple hand motion in space, jointly evaluating which movement features could be meaningfully translated into sound generation parameters. This iterative process resulted in the following motion features and mapping strategy:

- **Motion** : a logarithmic ramp generated by combining the continuous value of the spin (i.e the amount of velocity when a change in movement direction occurs) and the global intensity of the gesture (e.g. computed from acceleration). A motion/stillness threshold was implemented to filter micro-movements. Coupled to the *Excite* sound-action (i.e continuous bowing on the string).
- **Intensity** : the average of the compressed logarithmic intensity computed from gyroscope velocity. Linked to the *Intensity* sound-action feature (i.e. bowing pressure).
- **Hand Force** : computed by a statistical analysis of the eight-channel EMG data, focusing on the muscular groups involved in outward hand motion. Coupled to the *MoveExciter* sound-action, displacing the bow's position along the string (e.g near the middle, close to the bridge, etc.).
- **Arm Force** : overall muscular activity (also computed via the EMG data). Linked to the *Coupling* sound-action, resulting in effort provided by muscular contraction yielding inharmonic and rough tones, especially in their extreme range.

The elaboration of features/mappings as well as free exploration phases by the performer were documented and recorded[3].

[3]Complementary material and video demonstration : www.mi-creative.eu/post_SonificationHandGesturesDancePerformance

5. DISCUSSION & FUTURE WORK

Our work supports the theory that engagement through movement practice and kinesthetic awareness plays an essential part in designing movement interaction [10]. Moreover, the technical setup allows for on-the-fly interaction and gestural feature prototyping during sessions by programming and re-programming gesture-sound relationships in real time, exploring different mapping variations and sonic outcomes. This approach has proven effective in developing a collaborative platform involving the designer, the musician and the performer. We consider that this conceptual framework could provide interesting insights for developing novel sonification models for artistic and scientific purposes.

Qualitative contributions from movement / dance scholars would be a significant addition to the work presented in this paper, allowing for deeper somatic knowledge to complement the performer's know-how. This complementary point of view could also help in providing a better articulation for experimentation (allowing for a more qualitative analysis of the different exploration phases).

An exciting future perspective would be to question the qualitative aspect of the movement, and not only its formal characteristics. To this end, a next step would be to consider machine learning techniques in order to record, classify and analyse different qualities of movement, defined as high-level features, and associate them with different virtual models. Such a research perspective may provide new insights on sound and motion intertwining, thereby helping to move beyond designing technical systems.

6. ACKNOWLEDGEMENTS

This work has been carried out with support and funding from the Performance Laboratory *Gestures and Frequencies* Project (Idex), the French Ministry of Culture, CNRS, Grenoble INP and Universite Grenoble Alpes.

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