This is an author copy. To cite this article:
Donnarumma, M. (2017). On Biophysical Music. In E. R. Miranda (Ed.), *Guide to Unconventional Computing for Music* (pp. 63–83). London: Springer.
https://doi.org/10.1007/978-3-319-49881-2_3

On Biophysical Music

Marco Donnarumma
Graduiertenschule, Berlin University of the Arts, Berlin, Germany
m@marcodonnarumma.com | http://marcodonnarumma.com

Abstract

Biophysical music is a rapidly emerging area of electronic music performance. It investigates the creation of unconventional computing interfaces to directly configure the physiology of human movement with musical systems, which often are improvisational and adaptive. It draws on a transdisciplinary approach that combines neuromuscular studies, phenomenology, real-time data analysis, performance practice and music composition. Biophysical music instruments use muscle biosignals to directly integrate aspects of a performer's physical gesture into the human-machine interaction and musical compositional strategies. This chapter will introduce the principles and challenges of biophysical music, detailing the use of physiological computing for musical performance, and in particular the musical applications of muscle-based interaction.

1. Introduction

There is an essential difference between traditional and electronic musical instruments.[1] The former are originally made to play music. The latter are engineering constructs originally made to compute any kind of data. Only through specialised modification they can be used to play music.[2] This implies that a player's physical engagement with a

---

[1] With the latter term I indicate instruments made of sensors, transducers, circuits and algorithms. This is an important distinction in the context of the argument I am weaving here. My use of the term electronic musical instrument does not include electronic instruments such as analogue synthesisers for instance, because they generally lack physiological or motion sensors and computational capabilities.

[2] A process that Sergi Jorda (2005) has aptly called 'digital lutherie', or the development of techniques and strategies for musical performance with computers.

traditional instrument is necessarily different than that with an electronic instrument. In the design of traditional musical instruments, the physical interaction of the performer's body and the instrument is a given. A player injects energy into the instrument, which in turn, responds by vibrating and so transmits energy back to the player's body in the form of physical vibrations and audible sounds (Hunt, 2000). It is a corporeal bond that calls upon the trained motor skills, perception and intuition of the player, the physical affordances and musical possibilities of the instrument, and the auditive and haptic feedback of sound (Leman, 2008). Hence the centrality of the corporeal bond between performer and instrument to the conception, practise and analysis of traditional musical performance (Berliner, 1994; Sudnow, 1978; Godoy, 2003).

In the design of standard computational interfaces, this is often not the case because their essential function is to compute input-output data flows. To them, the physical action of a user is a control input to be mapped to a variable output. Therefore, the capacity for physical interaction has to be explicitly embedded in an electronic musical instrument. This bears an important implication. In new music performance, the design and performance with standard computational interfaces is most often conceived on the basis of the degree of control that a performer has over the musical parameters of the instrument. As a result, the kind of physical engagement afforded by the interaction of performer and interface is often overlooked. This is evident in the fact that the (ongoing) debate on the nature of electronic musical instruments has been consistently approached from a control-based perspective (Moore, 1988; Wessel, 2002; Rokeby, 1985; Dobrian, 2006). A perspective that posits a focus on a prominently physical human-computer interaction is rarely adopted in this debate.

This chapter will characterise the performative and compositional principles of biophysical music (Donnarumma, 2015), a kind of electronic music performance based on a combination of physiological technology and markedly physical, gestural performance. The physical and physiological properties of the performers' bodies are interlaced with the material and computational qualities of the electronic interface, with varying degrees of mutual influence. Musical expression thus arises from an intimate and, often, not fully predictable negotiation of human bodies, interfaces and programmatic musical ideas.

This chapter is structured as follows. Physiological computing will be defined and its applications to musical performance will be described. This will lead to a discussion of the challenges posed by the representation of physical gesture and its expressive features, that is, the nuances of a player's motor skill which are crucial to musical expression. In order to delineate directions for future research, the chapter will look at the work which is presently being conducted in the field. The value of an interdisciplinary approach combining resources from neuromuscular studies (Tarata, 2009) with insights on electronic music instrument performance will be described. This will point to new feasible opportunities for the design of electronic music instruments, such as the capacity of an instrument to adapt and evolve according to the physical performance style of its player.

2. Physiological Computing

The term physiological computing is used in human-computer interaction, to describe the interaction with a computing system through physiological data (Fairclough, 2009). The interaction can vary in complexity: the input data can serve to monitor a user's physiological state, control a graphical interface, or provide information for an adaptive software. Physiological data is described by biosignals - biomedical signals which represent electrical potentials and mechanical mechanisms of the body. Because the amount of physiological mechanisms is large there exists an equally broad number of biosignals, which vary in nature and context (Kaniusas, 2012). Muscle activity can describe intention, dynamics and level of exertion of a physical gesture; brain activity can reveal attention level and emotional arousal; electrocardiography and respiration rate can describe stress levels or intensity of a physical activity.

In music performance with electronic instruments, the biosignals of a performer's body can be deployed to implement specific human-machine interactions. Biosignals can be applied to modulate sonic events, temporal structure, as well as the overall interaction with the instrument. Brain-computer musical interfaces (BCMI) use neuronal activity to control musical parameters (Lucier, 1976; Knapp, 1990) or drive generative musical processes (Rosenboom, 1990; Miranda, 2014). Muscle sensing musical interfaces use the muscle acoustic vibrations as live sound input and control data for adaptive systems (Donnarumma, 2011; Van Nort, 2015) and the muscle electrical potential to modulate and trigger musical processes (Tanaka, 1993; Nagashima, 1998). Here, I focus on muscle sensing interfaces, which function on the base of the performer's gestures and physical exertion during interaction with a musical system.[3] Muscle biosignals do not provide only gestural input, they can also describe the force and temporal profile of the gesture, the intention to execute a gesture, and the way that gesture is articulated (Caramiaux and Donnarumma, 2015). This information can be used to outline salient traits of a player's physical gesture and inform accordingly the human-machine interaction and compositional strategy which characterise an electronic music instrument.

---

[3] Throughout the remainder of this chapter the term 'gesture' is always intended as physical gesture.

Music is created through physical effort, fine motor skill, heightened perception and intuition. In order for a musical instrument to be expressive, that is, to be capable of conveying meaning through sound, it has to afford for physical (Ryan, 1991) and visceral interaction (Moore, 1988), where visceral refers to a combination of conscious and unconscious thought. In the case of a piano, the player's gesture on the keyboard activates a mechanism which causes a string to be excited and produce sound. There is a direct link between the force exerted onto a key and the sound producing mechanism of the instrument. That direct link between performer and instrument enables a player to learn how to balance motor control and intuitive action in order to achieve a given musical result (Wessel, 2002). It is a multi-layered action-perception loop that relies on precise motor programs, or body schemata (Merleau-Ponty, 1962; Gallagher, 1986), to achieve a particular musically expressive result.

Musical works that use muscle sensing rely on the interplay between physiological and computational processes. The way in which that interplay is designed poses interesting challenges. How can we maintain consistency between a limb movement and its computational representation? What information does muscle sensing provide on the relation of perception and movement? Are there relations among muscle biosignals that can be quantified and how can those relations be used to endow an instrument with expressive features or influence its behaviour? The remainder of this chapter will broach these questions by providing: a detailed description of the muscle activation mechanism, an analysis of the resulting motor programs and their relation to perception and movement, as well as reflections on the ways in which unconventional computing techniques can be used to link expressive aspects of gesture to musical performance systems.

3. Describing Gesture through Muscle Sensing

Gestural performance involves a muscle activation mechanism and the related biosignals, the electromyogram, or EMG, and the mechanomyogram, or MMG. The characteristics of both biosignals are illustrated in Table 1. Grasping the process of muscle activation helps understand how these physiological components can be configured with the sound-generating devices of electronic instruments so to achieve convincing and novel gesture-sound coupling.

	EMG	MMG
Type	electrical	mechanical
Origin	neurons firing	muscle tissue vibration
Description of	muscle activation	muscle contraction force
Freq. range	0-500 Hz	0-45 Hz
Sensor	wet/dry electrodes	wideband microphones
Skin contact	yes	no
Sensitivity area	local	broad (due to propagation)

Table 1: Itemised characteristics of the EMG and MMG.

Human limb gesture is initiated by the activation of one or multiple muscle groups (Kaniusas, 2012). Of the two types of muscles found in the human body, smooth and striated, striated muscles are those subject to voluntary control and are attached to the skeletal structure by tendons. Voluntary muscle control is part of the somatic nervous system (SNS), a component of the peripheral nervous system which works in tight connection with synapses and muscles to govern voluntary muscle movement and perceptual stimuli integration. The SNS operates through two kinds of nerves, the afferent nerves, which handles the transport of signals from sensory receptors to the central nervous system (CNS) and the efferent nerves, which transport signals from the CNS to the muscles. In other words, the afferent nerves constitutes an interface to the worlds outside of one's own body. The efferent nerves handles the internal self-organisation of the body. It is through the efferent nerves that muscle activation takes place.

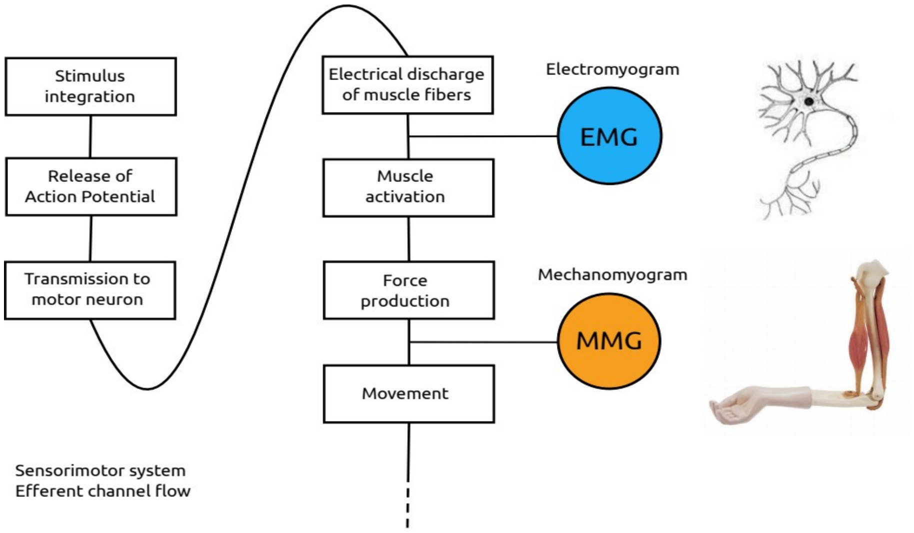

Illustration 1: Diagram of the efferent nerve information flow illustrating the muscle activation process. The blue and orange circles indicate respectively the EMG and MMG signals. The location of the circles illustrates the different stages of the activation process at which the signals are captured- assuming non-invasive recording methods using on-the-person stationary or ambulatory sensors (Silva et al., 2013).

At the onset of stimulus integration, the SNS sends an electrical voltage, known as action potential, to the motor neurons. When the action potential reaches the end plate of a neuron it is passed to the muscles by the neuromuscular synapse. The neuromuscular synapse is a junction that innervates the skeletal muscle cells and is able to send the electrical potential throughout a muscle so as to reach all the muscle fibres. A network of neuromuscular synapse and muscle fibres is known as a motor unit (MU). At this point, the motor unit action potential (MUAP) causes an all-or-none contraction of a muscle's fibres. All-or-none means that the MUAP can only trigger all of a muscle cells or none of them. A gradation in a muscle contraction is achieved by changing the number and frequency of MUAPs firing. By positioning surface electrodes on the skin above a muscle group, it is possible to register the MUAP as an electrical voltage. The resulting signal is known as the EMG (Merletti, 2004). This is the algebraic sum of all the motor unit action potentials (MUAPs) at a specific point in time. It is a stochastic signal because any number of MUAP pulses is triggered asynchronously.

While muscle contraction is the product of a bioelectrical effect, it results in a bioacoustic effect. When the muscle cells contract, they produce a mechanical vibration, a muscle twitch, which lasts about 10-100 ms. The mechanical vibration of the muscle cells causes a subsequent mechanical contraction of the whole muscle which, by means of its oscillation, can be picked up as an acoustic signal. Using a microphone on the skin above a muscle group it is possible to record an acoustic signal produced by the perturbation of the limb surface. This signal is known as MMG (Oster, 1980). While the EMG carries information on the neural trigger that activates the muscle, that is, it informs us of the deliberate intention of performing a gesture (Farina, 2014), the MMG carries information on the mechanical contraction of the muscle tissues, giving us access to the amount of physical effort that shapes the gesture (Beck, 2005). In this way, the two signals provide complementary information on muscle activity (Tarata, 2009) which can be used to gather insight on the expressive articulation of a gesture (see Illustration 1). The EMG (bioelectrical) and MMG (bioacoustic) can therefore be thought of as two complementary modes of biophysical music performance.

4. Modes of Biophysical Music Performance

4.1. Bioacoustic

As the player performs physical gestures, microphone sensors worn on the player's limbs capture the muscle sound, or MMG, produced by the vibrations of the muscle tissue (Donnarumma, 2011). The MMG is then used as a direct audio input to be digitally sampled, mangled, stretched, fragmented and recomposed according to a set of features extracted from the same audio input (Donnarumma, 2012). The acoustic dynamics of the MMG follows closely the physical dynamics of the movement. MMG amplitude is proportional to the strength of the muscle contraction and MMG duration is equivalent to the duration of the contraction. For instance, a gentle and fast movement produces a MMG signal with low amplitude and short duration. The MMG does not capture movement in space, but rather the kinematic energy exerted to produce movement. Whereas limb orientation and position cannot be detected using the MMG, one can gather information on the way the gesture is articulated by looking at the MMG envelope and amplitude over time.

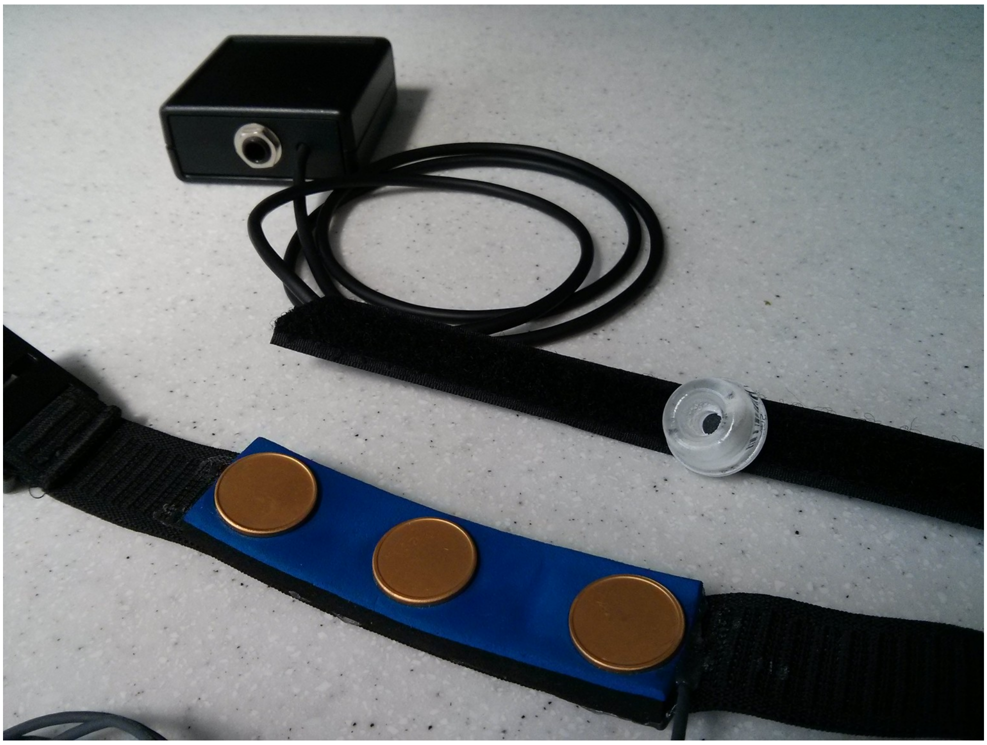

Illustration 2: The muscle-based musical instruments XTH Sense, above, and BioMuse, below. Theyboth use muscle sensing but rely on distinct modalities. The former uses a chip microphone tocapture the MMG, while the latter uses electrodes to capture the EMG signal.

The first electronic music instrument to make that use of muscle sounds was the XTH Sense (see Illustration 2) created in 2010 by the present author, and used ever since in an ongoing series of interactive music projects.[4] The XTH Sense uses the MMG in two ways: a) as a direct sound source to be live sampled and composed in real time; b) as control data to drive the sampling and compositional parameters. The XTH Sense provides the player with continuous control over sound processing and synthesis. The MMG is analysed to extract five features which are then mapped onto musical parameters using one-to-many or

---

[4] The XTH Sense is released as a free and open project (GPLV2 and CC licenses) to foster a grassroot approach to physiological computing for the arts. The instrument is used in interactive music projects by a growing community of musicians, composers and students worldwide. See http://xth.io.

one-to-one mappings. Because a muscle sound is produced only when a muscle contraction happens, actual physical effort is required in order to play biophysical music with a MMG-based interface. In this way, physical effort becomes an integral part of the artist's performance style.

4.2. Bioelectrical

Using medical grade wet-gel or dry electrodes attached to the skin, it is possible to capture electrical discharges from the neural activity and limb muscle tension of the performer. These electrical signals, the EMG, are then transmitted to a digital signal processing (DSP) algorithm that can output user-programmable control messages and MIDI events as a continuous data stream (Tanaka, 2012). This allows a performer to operate a computational interface or MIDI instrument not necessarily with evident physical gestures, but also by articulating muscular tension using almost imperceptible movements. The EMG does not report gross physical displacement, but the muscular exertion that may be performed to achieve movement. In this sense, the EMG does not capture movement or position, but the physical action that might (or might not) result in movement. The biosensor is not an external sensor reporting on the results of a gesture, but rather a sensor that reports on the internal state of the performer and her intention to make a gesture.

One of the earliest interfaces to make use of bioelectrical signals was the BioMuse (see Illustration 2) created by Benjamin Knapp and Hugh Lusted (Knapp, 1988) and used extensively by Tanaka (1993). Differently from the XTH Sense, the BioMuse does not itself produce a sound feedback, for the bioelectrical signal has to be converted into data or MIDI messages and then mapped onto a separate sound generator.[5] Discrete trigger events and continuous control data generated according to the muscular tension of a player's limbs are mapped to specific parameters of a digital synthesiser to achieve a nuanced control of sound synthesis parameters (Tanaka, 2012).

4.3. Muscle sensing versus spatial sensing

Movements of a performer with an electronic music instrument are often observed using physical sensing, like spatial and inertial technologies (Medeiros, 2014). Spatial sensing involves capturing data relative to the movement of a human body in space. These methods include: motion capture systems, that track whole-body movement looking at the position of skeletal joints using visual references attached to the performer's body; infrasound sensors that measure the distance of the performer's body from a given point in a room or the distance between two limbs; and magnetometers that report the body's orientation in relation to the Earth's magnetic field. Inertial sensing also involves capturing data relative to translation in space, but rather than looking at displacement in space, it

---

[5] See http://www.biocontrol.com/producthistory.html.

looks at the rate of the displacement. This method uses accelerometers, which report on the increase in velocity across three dimensional axis, and gyroscopes, which report rotation rate. Muscle sensors offer a key advantage compared to spatial and inertial sensors in sensing the subtleness and nuance of limb gesture. They provide direct access to detailed information on the user's physical effort. Subtle movements or intense static contractions, which might not be captured by spatial or inertial sensing, are instead readily detected by muscle sensors, for they transduce energy (mechanical or electrical) directly from the muscles.

5. Principles

This section defines the principles of biophysical music performance by analysing the human sensorimotor system and how it influences and, in turn, is influenced by the use of instruments. Voluntary muscle activation in fact does not rely only on willing control. It is conditioned at a pre-conscious level by several kinds of stimuli, including interoceptive, exteroceptive and proprioceptive stimuli. Importantly, muscle activation is influenced in a similar way by visual and auditive stimuli. This is particularly relevant to biophysical music performance, for it helps understand how a player's bodily movement and muscle activity is not exclusively based on willing actions or programmatic ideas, but it is also affected by sound at a level the preempts voluntary action. Studies in neuroscience (Lotze, 2003), psychology (Cardinale, 2003), human-computer interaction (Caramiaux, 2012) and musical performance (Godoy, 2003) have shown that sound affects both the mechanism of muscle activation and the perception of one's own body. Importantly, sound is intended here as both audible vibrations, or air conducted sounds, and physical vibrations, or conducted sounds. These studies have suggested that there exist a strong audio-motor connectivity; in particular, Lotze and colleagues (2003) have shown that this association is not only related to action-perception loops, it also actively influences one's motor programs by freeing up resources of the motor system to increase the connectivity of limbs movement and auditory perception.[6]

5.1. Proprioception

Marcel Merleau-Ponty (1962) has explained that at the basis of human's use of instruments lies the mechanism of proprioception. Proprioception is a mechanism that allows the body to determine the position of its neighbouring parts and the strength of effort exerted to perform a physical gesture. Schmidt (1988) has described that this is made possible by the integration of information from a broad range of sensory receptors located in the muscles,

---

[6] This relation goes as far as to alter the perception of one's body based on the timbre of an auditive stimulus, as Tajadura et al. (2015) have recently demonstrated.

joints, and the inner ear.[7] A development of the proprioceptive sense is fundamental to musical performance: on one hand, proprioception enables the learning and training of new physical skills which require prompt response to unpredictable conditions (Keogh, 1985); on the other, it is critical to closed-loop motor control (Latash, 2008), which is the selection and adjustment of a physical action according to a perceptual stimulus, a basic process of musical performance. A further analysis of the proprioceptive sense can help us detail the relation of perception and movement in musical performance.

Merleau-Ponty (1962) describes that perception is not followed by movement, but rather they combine into a system. Perception and movement function together, constituting a delicate balance between intention and performance, between the movement as intended and how it actually occurs.[8] Merleau-Ponty points to the fact that proprioception, and the related closed-loop motor control mechanisms, are both conscious and pre-conscious. An example of a conscious proprioceptive mechanism is the case where one touches the tip of the nose with the eyes closed. In this case, one does not learn the position of the nose through sight, but it is the sense of proprioception that provides this information. On the other hand, pre-conscious proprioception is demonstrated by the righting reflex. This is a reflex, an involuntary reaction, that the human body produces to correct the body orientation when falling or tripping. For instance, when one falls asleep while sitting on a train, the head repeatedly tends to fall on one side and the body autonomously moves the neck muscles to position the head correctly. The fact that proprioception is both conscious and pre-conscious is important for it shows that "the body and consciousness are not mutually limiting, they can only be parallel," as Merleau-Ponty (1962: 124) argues. It is a question of understanding physiology, perception, cognition and action as elements that interact continuously with each other. For Fuller (2005: 63), it is from their "sustained interactions" that one's expression emerges. This implies that physiology, perception, cognition and action are not hierarchically organised, rather, they operate by affecting each other.

5.2. Body Schemata

To further understand the superposition of conscious and pre-conscious factors determining human movement and use of instrument, it is worthwhile looking at Shaun Gallagher's work on body schemata (Gallagher, 1986). Body Schemata are motor control

---

[7] Technically, a sensory receptor is the ending of a sensory nerve. It transduces internal or external stimuli in an electrical impulses for the central nervous system. The muscle sensory receptors are called muscle spindles, and they sense the changes in the muscle length, for instance.

[8] For a radical take on this problematic see the work of phenomenologist Maxine Johnstone (1999) on the primacy of movement, where she argues that, in short, feeling is the embodiment of movement and that it is movement to yield one's subjectivity. I do not make use of her work here as I want to focus the discussion on movement in relation to the use of instruments, as opposed to an analysis of movement in itself, which would require a different kind of analytical framework than the one I set up in this chapter.

programs that govern posture, movement and the use of instruments. Body schemata, Gallagher (2001) explains, are pre-conscious in that they operate below "the level of self-referential intentionality". When moving or maintaining a posture, the human body automatically performs a body schema and so allows one to move without consciously focusing on the state of the body and the position of limbs. One does not need to be consciously aware of the position of the feet while running up a familiar staircase. A body schema, according to Gallagher (2001), should not be confused with a reflex. Whereas a reflex is an automatism which one can hardly influence, a body schema enables movements that "can be precisely shaped by the intentional experience or goal-directed behaviour of the subject". When one reaches for a glass of water with the intention to drink from it, as Gallagher illustrates, the hand "shapes itself" in an a way that allows one to accurately grab the glass. One does not shape the hand posture in advance. Body schemata thus are not a cognitive operation, yet they can contribute to, or undermine, intentional activities.

Merleau-Ponty (1962) exemplifies the working of body schemata observing the case of a blind man's stick. The stick is not an external object to the man who carries it. Rather, the stick is to the blind man a physical extension of touch. This happens because the stick becomes an additional source of information on the position of the limbs, and thus, with continuous training, it is integrated in the body schemata; it is converted into a sensitive part of the body that complements the proprioceptive sense. To add more to his view, Merleau-Ponty looks at instrumental players, specifically at organists. When rehearsing for a performance with an organ that a player has not used before, the organist, according to Merleau-Ponty, does not commit to memory the objective position of pedals, pulls and stops. Rather, she incorporates the way in which given articulations of pedals, pulls and stops let her achieve given musical or emotional values. Her gestures draw "affective vectors" (Ponty, 1962: 146) mediating the expressiveness of the organ through her body. The organist does not perform in an objective space, but rather in an affective one.

5.3. Shared Control

To look at the physiology of human movement allows for an understanding of how a performer's movement is generated rather than how it happens in space. The generation of movement happens through the configuration of the performer's voluntary motor control, her physiological constraints, the body schemata, the presence or absence of sound, and the object, or lack thereof, against which muscular force is exerted. As these elements influence one another in a process of continuous negotiation, movement is manifested in space. The qualities of movement as it becomes apparent (size, velocity and abruptness) are a result of that negotiation and thus are partly conscious and partly pre-conscious (Gallagher, 1986). In other words, a physical gesture might not occur as initially intended by the performer.

The analysis of muscle biosignals provides thus an entry point to both the intentional and unintentional aspects of the articulation of physical gesture. From this standpoint, the understanding of the physiological basis of movement is key to the development of performance strategies that do not rely exclusively on the control of the performer over the instrument, but open up musical performance with electronic instrument to unintentional factors involved in the articulation of a physical gesture. In musical performance, body schemata drive the way the performer physically interacts with the instrument in accord to the musical or emotional significance that given parts of the instrument allow for. By using bioacoustic or bioelectrical muscle sensing techniques it is possible to map particular features of a body schema to targeted sounds synthesis parameters or software behaviours. This creates a positive feedback loop between performer and instrument, a loop that is not based exclusively on intentionality but also on the immediacy of the physical interaction between player and instrument and the new musical ideas it may yield.

For instance, the temporal structure of a musical piece can be fixed or dynamic. In the former case, the player creates key points in time using a graphical timeline. When a key point is reached, the instrument changes its configuration by loading the new set of mappings and audio processing chains. In the latter case, described in detail in (Donnarumma, 2014), a machine learning algorithm can learn offline different muscle states of the performer's body. Then, during live performance, the instrument configuration can autonomously change when the performer's body enters one of those states. This method enables an improvised performance style that varies from one performance to another, while the instrument retains a set of basic gesture-sound relationship predetermined by the performer.

6. Challenges

When performing electronic music with computational interfaces, the digitisation of a performer's movement represents physical gestures to be linked to sound synthesis. Questions on how sensor data can represent the performer's physical movement and the expression it could convey are aesthetic and technical challenges that lie at the core of the design of electronic music instruments. In Joel Ryan's words, "[e]ach link between performer and computer has to be invented before anything can be played" (Ryan, 1991). Indeed, the abstraction of a computer system has to be confronted with the physicality of musical performance for interaction to be designed. The digitisation of a performer's movement is the first link that needs to be established between a performer and a computer; and the way in which such a link is created determines the subtleness and playfulness of interaction with the instrument. While muscle biosignals can provide detailed information on the articulation of a physical gesture, that information may be too noisy or not exploitable in a way that is immediately evident to the audience. Meanwhile, the capability to detect exertion and effort independently from gross physical movement makes biosignals a unique and rich source of information for musical interaction. One way to decode the complexity and specificity of biosignals is the use of advanced information analysis methods such as pattern recognition and machine learning. Also, interesting combinations can result from the use of muscle biosignals in conjunction with complementary physical sensors.

6.1. Multimodality

Multimodal interaction uses mutiple sensor types (or input channels) in an integrated manner so as to increase information and bandwidth of interaction (Dumas, 2009). The combination of complementary modalities provides information to better understand aspects of the user input that cannot be deduced from a single input modality. These modalities might include, for example, voice input to complement pen-based input (Oviatt, 2003). One of the early examples of interactive musical instrument performance is the pioneering work of Waisvisz with The Hands, one of the first gestural controllers, which he created in 1984 with the help of the team at STEIM.[9] Waisvisz's set of hand-held remote controllers capture data from accelerometers, buttons, mercury orientation switches and ultrasound distance sensors (Dykstra-Erickson, 2005). The use of multiple sensors on one instrument points to complementary modes of interaction with an instrument (Camurri, 2007). However, electronic music instruments have for the most part not been developed or studied explicitly from a multimodal perspective, which would be a useful approach (Medeiros, 2014).

Techniques for multimodal interaction to distinguish similar muscular gestures in different points in space have been explored by Tanaka (2002) and the present author, in collaboration with Tanaka and Dr. Baptiste Caramiaux. In an EMG-based instrument, also produced at STEIM, Tanaka supplemented four channels of EMG with 3D accelerometers embedded in two gloves to detect wrist flexion and tilt. Recently the XTH Sense and the BioMuse instruments were combined for a gesture-sound mapping experiment, described in Section 7. Recent Research. The biomedical literature shows that the use of a multimodal system where EMG and MMG analyses are combined is a useful resource (Tarata, 2009). The EMG and MMG signals are produced at different moments of the same physical gesture, hence they provide diverse, yet complementary information. Through multimodal muscle signal analysis it is possible to detect both intention and amount of kinetic activity. That information can be used to enrich the design of gesture-sound relationships of an electronic music instrument.

---

[9] Studio for Electro-Instrumental Music. See http://steim.org. The team included Johan den Biggelaar, Wim Rijnsburger, Hans Venmans, Peter Cost, Tom Demeijer, Bert Bongers and Frank Balde.

6.2. Characterisation

Another challenge of biophysical music performance involves the extraction of salient features from biosensor data, a range of methods known as feature extraction (Guyon, 2006). By using mathematical or statistical functions, the raw muscle biosignals can be processed and features extracted - such as overall muscular tension, abruptness of the contractions, and damping, the rate at which a muscle recovers its initial shape following a contraction. These features can provide a higher-level representation of muscle activity that can be used to diversify the gesture-sound palette afforded by a computational interface. Although, in the field of electronic music instrument design and performance, muscle biosignal feature extraction has not been formalised yet, useful resources can be borrowed from the biomedical literature, namely from the area of pattern recognition for prostheses control, where muscle biosignals are the standard control inputs. The description of muscle biosignals features and the methods for their extraction will not be discussed here as they are beyond the scope of this paper. The work by Hofmann (2013) includes a comprehensive review of EMG features and signal processing, and the work by Islam (2013) offers an equally exhaustive review for the MMG.

Before implementing those resources in the design of biosignal musical instruments an important distinction between the contexts of musical performance and prostheses control must be considered. The biomedical experiments with muscle feature extraction are conducted in a laboratory context where all conditions are highly regulated. Every aspects of such studies is directed thoroughly by the experimenters, including the participants' movement, which often times is limited to isometric contractions - a contraction where the limb is static. In a real world scenario the situation is different. The performance conditions, including room temperature, magnetic interferences and the like, cannot be controlled and the movement of a performer is highly dynamic. This points to the need for a careful selection of a set of features which maintain their content meaningful in the specific condition of a performance with electronic music instruments.

7. Recent Research

The issues of physiological multimodal sensing and feature extraction for the analysis of expressive gestural interaction with musical systems have been recently investigated by the author in collaboration with Caramiaux and Tanaka. In particular, the author, in collaboration with Caramiaux, has created a performance system for bimodal muscle sensing and live sonification, which is used in a performance entitled *Corpus Nil*.[10] This section provides an overview of this recent research and describes the insight it provided.

---

[10] See https://marcodonnarumma.com/works/corpus-nil. The piece was premiered at ZKM, Zentrum fuer Kunst und Medientechnologie Karlsruhe, on February 6th, 2016.

For the sake of economy, the full details of the experiments are not included in this chapter; the interested reader is invited to refer to the related publications, most notably the comprehensive research process and subsequent musical applications discussed in (Donnarumma, 2016).

7.1. Gesture Analysis with Physiological, Spatial and Inertial Data

In the first study, we analysed the physical gesture vocabulary of a performance piece by the first author which has been performed a number of times over the years (Donnarumma, 2013). The physical gesture of the performer were recorded using MMG sensing, which was already part of the piece, and spatial (motion tracking) and inertial (accelerometer) sensing, which were added specifically for the experiment. We were interested in how the different sensing modalities detect different aspects of gesture and how those modalities relate to one another as well as to the musical output. The analysis of the recorded data showed that:

- Physiological and spatial modalities provide complementary information that are related to the gesture musical output.
- Only the physiological modality can sense the preparatory activity leading to the actual gesture.
- The modulation of signals across different modalities indicate variations of gesture aspects, such as power and speed, which relate to variations in loudness and richness of the musical output.

These findings showed that musical variations in the output of a muscle-based electronic music instrument are dependent on quantifiable variations in the physical aspects of a gesture.

7.2. Bimodal sonification of EMG and MMG

The second study focused on physiological sensing and used EMG and MMG in a bimodal configuration. The biosignals were used as a combined input to an interactive sonification system (Donnarumma, 2013). Here we looked at the ability of non-experts to activate and articulate the biosignals separately with the aid of sound feedback. We were interested in investigating how it is possible to transmit performance skill with a muscle-based instrument to non-experts. The participants were asked to execute physical gestures designed by drawing upon complementary aspects of the EMG and MMG, as reported in the biomedical literature (Jobe, 1983; Madeleine, 2001; Day 2002; Silva, 2004). The biosignals produced during the execution of the gesture were sonified in real time, providing a feedback to the participants. This helped them identify which biosignals were activated through the different articulations of their gesture. By looking at the recorded biosignals we understood the physical dynamics through which participants were able to control the parameters of the sonification system. Our findings showed that:

- Non-experts are able to voluntary vary parameters of the sonification of the EMG and MMG following a short training.
- The variations of gesture articulation produce variations in the biosignals activity.
- Specific muscular articulations lead to specific musical results.

This indicated that, by refining the control over the limbs motor unit with the aid of biosignals sonification, a non-expert player is capable of engaging in musically interesting ways with a muscle-based electronic music instrument.

7.3. Understanding Gesture Expressivity through Bimodal Muscle Sensing

Building upon the insight of the previous studies, we designed a new experiment to look at the articulation of muscular power during human-computer gestural interaction (Caramiaux and Donnarumma, 2015). We designed a vocabulary of six gestures (on a surface and in free-space) and asked participants to perform those gestures several times varying power, size and speed during each trial. A questionnaire was provided to the participants in order to look at their understanding of the notion of power. EMG and MMG signals were recorded and three features for each biosignal - signal amplitude, zero-crossing and spectral centroid - were extracted and quantitatively evaluated. The questionnaire showed that for the participants power was an ambiguous notion; according to the type of gesture and the context of interaction, they used it to indicate subtly different notions such as physical strain, pressure or kinematic energy. The participants also noted that variations on power were conditioned by variations in speed or size of the gesture.[11] A quantitative analysis of the recorded biosignals helped objectively test the findings provided by the questionnaire. By looking at the biosignal features we showed that:

- Participants are able to voluntarily vary muscle tension and that variation can be detected through physiological sensing.
- Exertion through pressure is better indicated by the EMG amplitude, whereas

---

[11] As the basic definition of power found in physics implies, power and speed are intrinsically linked, and this of course applies to limb movement as well, as emerged in our experiment.

intensity of a dynamic gesture is better detected through the MMG zero-crossing.

- Bimodal muscle sensing allows to observe how the modulation of power is affected by the modulation of speed, and vice versa, speed is affected by power.

These findings showed that specific expressive nuances of a physical gesture such as strain and dynamic tension, can be well described by looking at muscle sensing data. This capability of physiological sensing can be applied to the design of gesture-sound mappings where musical features, such as timbre, are driven by real time analysis of the player's physical effort, an approach that is difficult to achieve with physical or spatial sensors.

The experiments described above offer an interesting overall view on the use of physiological computing for the design of and performance with electronic music instruments. Physiological sensing provides useful information on gesture which spatial and inertial sensors cannot detect. Specifically, bimodal muscle sensing allows the detection and quantification of those aspects of limb movement which make a gesture expressive, such as static exertion and dynamic tension; these aspects cannot be detected with spatial sensing. The extraction of biosignals features, such as signal amplitude, zero crossing and spectral centroid, provides a unique insight on gesture articulation, which can be used to inform the design of musical interaction with computational interfaces.

8. Conclusions and Future Prospects

This chapter elaborated on the principles and challenges of biophysical music, providing an analysis of its technical and performative components. It offered experimental and technical insights on how to extend the use of physiological technology for expressive musical interaction. By combining muscle sensing techniques with electronic music instrument design, one can create computational instruments that sense expressive features of a player's physical effort; such as the differences between the amount of planned effort and the effort actually exerted, the changes in the abruptness of physical gestures and the transients between exerted effort and muscle relaxation. Mapping these nuances of physical effort to the sound production units of a musical instrument affords an interaction with sound that is physical and leaves room for intuition. Drawing on these principles, artists and researchers can create experiments and performances where a player and an electronic music instrument are tightly configured. On one hand, the physiological signals of the performer's body are fed to the instrument in the form of sounds and electrical signals, informing its operational program. On the other, the instrument's responses are fed back to the performer in the form of sound, informing her performance.

Creating electronic music instruments that rely on multimodal muscle sensing and biosignals feature extraction is important. Not only it enables to create real world scenarios where to test the usability and the expressive capability of such novel musical systems. It also offers the opportunity to experience and study in detail novel ways of interacting with computational machines. Muscle sensing also affords an investigation of the notion of physical effort in musical performance. Combined muscle sensors and feature extraction methods could be used to analyse how instrumental players' physical effort varies from one performance to the other, or across performances of different scores. Another interesting opportunity is the use of machine learning methods to implement a computational model of muscle-based variations that would allow an instrument to recognize and adapt to the way a performer articulates different aspects of a gesture. The instrument could create personalised gesture-to-sound mappings that the player would then explore, evolve, manipulate, and even 'break', simply through physical engagement. This is an exciting prospect for it shows the potential to undo the notion of a performer's absolute control over the instrument by endowing the instrument with a certain degree of agency. An approach that can yield new ways of performing and conceiving live electronic music.

Acknowledgements

The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. FP7-283771.

References

Beck, T. W., Housh, T. J., Cramer, J. T., Weir, J. P., Johnson, G. O., Coburn, J. W., et al. (2005). Mechanomyographic amplitude and frequency responses during dynamic muscle actions: A comprehensive review. *Biomedical Engineering Online,4*, 67.

Berliner, P. F. (1994).*Thinking in Jazz: The infinite art of improvisation*. Chicago, IL: The University of Chicago Press.

Camurri, A., & Coletta, P. (2007). A Platform for Real-Time Multimodal Processing (pp. 11–13). In *4th Sound and Music Computing Conference, Lefkada*, July 2007.

Caramiaux, B. (2012). *Studies on the relationship between gesture and sound in musical performance*. Ph.D. thesis, University of Paris VI, Paris.

Caramiaux, B., Donnarumma, M., & Tanaka. A. (2015). Understanding gesture expressivity through muscle sensing. *ACM Transactions on Computer-Human Interactions, 21*(6), 31.

Cardinale, M., & Bosco, C. (2003). the use of vibration as an exercise intervention. *Exercise and Sport Sciences Reviews,31*(1), 3–7.

Day, S. (2002). *Important factors in surface EMG measurement*. Technical report, Bortec Biomedical Ltd., Calgary.

Dobrian, C., & Koppelman, D. (2006). The 'E' in NIME: Musical expression with new computer interfaces (pp. 277–282). In *International Conference on New Interfaces for Musical Expression, Paris*. IRCAM—Centre Pompidou.

Donnarumma, M. (2012). Incarnated sound in music for flesh II. Defining gesture in biologically informed musical performance. *Leonardo Electronic Almanac,18*(3), 164–175.

Donnarumma, M. (2014). Ominous: Playfulness and emergence in a performance for biophysical music. *Body, Space & Technology*.

Donnarumma, M. (2015). Biophysical music sound and video anthology. *Computer Music Journal,39*(4), 132–138.

Donnarumma, M. (2016). *Configuring corporeality: Performing bodies, vibrations and new musical instruments*. Ph.D. thesis, Goldsmiths, University of London.

Donnarumma, M., Caramiaux, B., & Tanaka, A. (2013a). Body and space: Combining modalities for musical expression. In *Work in Progress for the Conference on Tangible, Embedded and Embodied Interaction, Barcelona*. UPF–MTG.

Donnarumma, M., Caramiaux, B., & Tanaka, A. (2013b). Muscular interactions combining EMG and MMG sensing for musical practice. In *Proceedings of the International Conference on New Interfaces for Musical Expression, Seoul*. KAIST.

Dumas, B., Lalanne, D., & Oviatt, S. (2009). Multimodal interfaces: A survey of principles, models and frameworks. *Human Machine Interaction*, 3–26.

Dykstra-Erickson, E., & Arnowitz, J. (2005). Michel Waisvisz: The man and the hands. *Interactions,12*(5), 63–67.

Fairclough, S. H. (2009). Fundamentals of physiological computing. *Interacting with Computers,21*(1), 133–145.

Farina, D., Jiang, N., Rehbaum, H., Holobar, A., Graimann, B., Dietl, H., et al. (2014). The extraction of neural information from the surface EMG for the control of upper-limb prostheses: Emerging avenues and challenges. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 4320*(C).

Fuller, M. (2005). *Media ecologies: Materialist energies in art and technoculture*. Cambridge, MA: MIT Press.

Gallagher, S. (1986). Body image and body schema: A conceptual clarification. *The Journal of Mind and Behavior,7*(4), 541–554.

Gallagher, S. (2001). Dimensions of embodiment: Body image and body schema in medical contexts. In S. Kay Toombs (Ed.), *Phenomenology and medicine*(pp. 147–175). Dordrecht: Kluwer Academic Publishers.

Godøy, R. (2003). Motor-mimetic music cognition. *Leonardo,36*(4), 317–319.

Guyon, I., & Elisseeff, A. (2006). An introduction to feature extraction. *Feature Extraction Studies in Fuzziness and Soft Computing,207*, 1–25.

Hofmann, D. (2013). *Myoelectric Signal processing for prosthesis control*. Ph.D. thesis, Gottingen Universität.

Hunt, A. (2000). Mapping strategies for musical performance. In M. M. Wanderley & M. Battier (Eds.), *Trends in gestural control of music* (pp. 231–258). Paris: IRCAM.

Islam, M. A., Sundaraj, K., Ahmad, R., Ahamed, N. U., & Ali, M. A. (2013). Mechanomyography Sensor development, related signal processing, and applications: A systematic review. *IEEE Sensors Journal,13*(7), 2499–2516.

Jobe, F. W., Tibone, J. E., Perry, J., & Moynes, D. (1983). An EMG analysis of the shoulder in throwing and pitching. A preliminary report. *The American Journal of Sports Medicine,11*(1), 3–5.

Jordà, S. (2005). *Digital Lutherie: Crafting musical computers for new musics' performance and improvisation*. Ph.D. thesis, Unversitat Pompeu Fabra.

Kaniusas, E. (2012). *Biomedical signals and sensors I. Linking physiological phenomena and biosignals*. Biological and Medical Physics, Biomedical Engineering. Berlin: Springer.

Keogh, J., & Sugden, D. (1985). *Movement skill development*. New York, NY: Macmillan Publishing Co.

Knapp, R. B., & Lusted, H. S. (1988). A real-time digital signal processing system for bioelectric control of music (pp. 2556–2557). In *Acoustics, Speech, and Signal Processing (ICASSP-88).*

Knapp, R. B., & Lusted, H. S. (1990). A bioelectric controller for computer music applications. *Computer Music Journal,14*(1), 42–47.

Latash, M. (2008). *Neurophysiological basis of movement, 2nd*(editio ed.). Champaign, IL: Human Kinetics.

Leman, M. (2008). *Embodied music cognition and mediation technology*. Cambridge, MA: MIT Press.

Lotze, M., Scheler, G., Tan, H.-R., Braun, C., & Birbaumer, N. (2003). The musician's brain: Functional imaging of amateurs and professionals during performance and imagery. *NeuroImage, 20*(3), 1817–1829.

Lucier, A. (1976). Statement on: Music for solo performer. In D. Rosenboom (Ed.), *Biofeedback and the Arts: Results of early experiments* (pp. 60–61). Vancouver, BC, Canada: Aesthetic Research Centre of Canada, A.R.C.

Madeleine, P., Bajaj, P., Søgaard, K., & Arendt-Nielsen, L. (2001). Mechanomyography and electromyography force relationships during concentric, isometric and eccentric contractions. *Journal of Electromyography and Kinesiology,11*(2), 113–121.

Medeiros, C., & Wanderley, M. (2014). A comprehensive review of sensors and instrumentation methods in devices for musical expression. *Sensors, 14*(8), 13556–13591.

Merleau-Ponty, M. (1962). *Phenomenology of perception*. Ebbw Vale: Routledge.

Merletti, R., & Parker, P. A. (2004). *Electromyography: Physiology, engineering, and non-invasive applications*. Hoboken, NJ: Wiley.

Miranda, E. R., & Castet, J. (Eds.). (2014). *Guide to brain-computer music interfacing*. Berlin: Springer.

Moore, R. F. (1988). The dysfunction of MIDI. *Computer Music Journal,12*(1), 19–28.

Nagashima, Y. (1998). Biosensorfusion: New interfaces for interactive multimedia art (number 1, pp. 8–11). In *Proceedings of the International Computer Music Conference*.

Oster, G., & Jaffe, J. S. (1980). Low frequency sounds from sustained contraction of human skeletal muscle. *Biophysical Journal,30*(1), 119–127.

Oviatt, S., Coulston, R., Tomko, S., Xiao, B., Lunsford, R., Wesson, M., et al. (2003). Toward a theory of organized multimodal integration patterns during human-computer interaction (p. 44). In *Proceedings of the International Conference on Multimodal Interfaces*.

Rokeby, D. (1985). Dreams of an instrument maker. In *Musicworks 20: Sound constructions*. Toronto: The Music Gallery.

Rosenboom, D. (1990). *Extended musical interface with the human nervous system*, number 1. Leonardo.

Ryan, J. (1991). Some remarks on musical instrument design at STEIM. *Contemporary Music Review,6*(1), 3–17.

Schmidt, R. A., & Lee, T. (1988). *Motor control and learning*(5th ed.). Champaign, IL: Human Kinetics.

Sheets-Johnston, M. (1999). *The primacy of movement*(2nd ed.). Amsterdam: John Benjamins Publishing Company.

Silva, H., Carreiras, C., Lourenco, A., & Fred, A. (2013). Off-the-person electrocardiography (pp. 99–106). In *Proceedings of the International Congress on Cardiovascular Technologies*.

Silva, J., Heim, W., & Chau, T. (2004). MMG-based classification of muscle activity for prosthesis control (Vol. 2, pp. 968–71). In *International Conference of the IEEE Engineering in Medicine and Biology Society*.

Sudnow, D. (1978). *Ways of the hand: The organization of improvised conduct*. Cambridge, MA: Harvard University Press.

Tajadura-Jiménez, A., Fairhurst, M. T., Marquardt, N., & Bianchi-berthouze, N. (2015). As light as your footsteps: Altering walking sounds to change perceived body weight, emotional state and gait (pp. 2943–2952). In *Proceedings of the ACM Conference on Human Factors in Computing Systems, Seoul*. ACM.

Tanaka, A. (1993). Musical technical issues in using interactive instrument technology with application to the BioMuse (pp. 124–126). In *Proceedings of the International Computer Music Conference*.

Tanaka, A. (2012). The use of electromyogram signals (EMG) in musical performance: A personal survey of two decades of practice. *eContact! Biotechnological Performance Practice / Pratiques de performance biotechnologique*, 14.2.

Tanaka, A., & Knapp, R. B. (2002). Multimodal interaction in music using the electromyogram and relative position sensing (pp. 1–6). In *Proceedings of the 2002 Conference on New Interfaces for Musical Expression*.

Tarata, M. (2009). The electromyogram and mechanomyogram in monitoring neuromuscular fatigue: Techniques, results, potential use within the dynamic effort (pp.

67–77). In *MEASUREMENT, Proceedings of the 7th International Conference, Smolenice.*

Van Nort, D. (2015). [radical] signals from life: From muscle sensing to embodied machine listening/learning within a large-scale performance piece. In *Proceedings of the International Conference on Movement and Computing (MoCo), Montreal, QC, Canada.*

Wessel, D., & Wright, M. (2002). Problems and prospects for intimate musical control of computers. *Computer Music Journal,26*(3), 11–22.

Author details

Marco Donnarumma is a performance artist and scholar. He received a Ph.D. from Goldsmiths, University of London in 2016 and is currently a Research Fellow at Berlin University of the Arts (2016-2018). Here, he leads a practice-based 2-year research project combining performance art, body theory and embodied robotics. His performances and artworks toured over sixty countries and are regularly presented at leading art events. His current research looks at the links between ritual performance, autonomous computation and body politics through the lens of abjection and intimacy. He has published across the fields of performance studies, aesthetics, human-computer interaction and unconventional computing.