Xth Sense: researching muscle sounds
for an experimental paradigm of musical performance

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Abstract

This paper seeks to outline methods underlying the development of the *Xth Sense* project, an ongoing research which investigates exploratory applications of biophysical sound design for musical performance and responsive milieux. Firstly, an aesthetical study of body sounds, namely muscle sounds is illustrated. I describe the development of an audio synthesis model for muscle sounds[1] which offered a deeper understanding of the body sound matter and provided the ground for further experimentations in signal processing and composition. Then follows a description of the development and design of the *Xth Sense,* a wearable hardware sensor device for capturing biological body sounds; this was implemented in the realization of *Music for Flesh I,* a first attempt at musical performance. Next, the array of principles underpinning the application of muscle sounds to a musical performance is illustrated. Drawing from such principles, I eventually describe the methods by which useful features were extracted from the muscle sounds, and the mapping techniques used to deploy these features as control data for real time sound processing.

Keywords

Biosensing technologies, biophysical control, muscle sounds.

1   Introduction

Biosensing musical technologies use biological signals of a human subject to control music. One of the earliest applications can be identified in Alvin Lucier's *Music for Solo Performer* (1965). Alpha waves generated when the performer enters a peculiar mind state are transduced into electrical signals used to vibrate percussion instruments. Over the past thirty years biosensing technologies have been comprehensively studied [3, 8, 13, 14, 15, 18, 22] and presently notable biophysical-only music performances[2] are being implemented at SARC[3] by a research group lead by the main contributor to the Bio Muse project[4] Ben Knapp (10).

Whereas *biological motion* and *movement and music* are arising topics of interest in neuroscience research [5, 12, 21], the biologic body is being studied by music researchers as a mean to control virtual instruments. Although such approach has informed gestural control of music, I argue that it overlooks the expressive capabilities of biological sounds produced by the body. They are inaudible but may retain a meaningful vocabulary of intimate interactions with the musicians' actions.

To what extent could biologic sounds be employed musically? In which ways could the performer's perceptual experience be affected? How could such experimental paradigm motivate an original perspective on musical performance?

2   Aesthetic principles

The long-term outcome of the research is the implementation of low cost, open source tools (software and hardware) capable of providing musicians, performers and dancers with a framework for biosensors-aided auditive design

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[1] A digital muscle sounds generator.

[2] Bio Muse Trio, GroundMe!.

[3] Queen's University, Sonic Art Research Center, Belfast, UK.

[4] A commercialized product exploiting electromyography and brainwaves analysis systems for musical applications.

(BAAD)[5] in a real time[6] environment; which framework will be re-distributable, customizable and easy to set up. However, given the substantial interdisciplinary quality of such project, its realization process needed to be fragmented into more specific and measurable steps.

The primary aim of the inquiry was to explore the musical and design capabilities of biological sounds of the body in a functional context – the production of *Music for Flesh I* a sonic solo performance for wearable biosensing device, which could demonstrate an experimental coupling between theatrical gesture and muscle sounds. In an attempt to inform the present state of augmented musical performance and embodied interaction, the characteristics of this pairing were identified in: the authenticity of the performer's somatic interaction, the natural responsiveness of the system and the expressive immediacy and transparency of the mapping of biological sound to the performer's kinetic behaviour. Such work required an interdisciplinary approach embracing biomedical computing studies, music technology and most importantly sound design. In fact, as I will demonstrate later in this text, the major research issue was not a technical implementation, but rather the definition of design paradigms by which the captured biological sounds could achieve a meaningful and detailed expressiveness.

3   Methods: understanding and capturing muscle sounds

The earliest approach to muscle sounds consisted of an analysis of the physical phenomena which makes muscle vibrate and sound. This study eventually developed in a sound synthesis model of muscle sounds. Although such model was not strictly related to the physical properties of muscle sounds, but rather to their aesthetic characteristics, it provided sonic samples which would satisfyingly resemble the original ones. Thereafter, the synthesised samples were used to explore design methodologies, while the sensor hardware implementation was still in progress.

Following this initial study, the scope of the research consisted of two interrelated strands. The first concerned the design and implementation of a wearable biosensing hardware device for musical performance; the second included the development of a tracking system for a performer's somatic behaviour by means of muscle sounds features extraction and data mapping methods.

The study of a synthesis model of muscle sounds is described in the next paragraph, whereas the research methods employed during the hardware and software design are discussed in the following paragraphs; however, being the focus of this paper on the research methodology, specific signal processing techniques and other technical information are not illustrated in detail, but they are fully referenced.

3.1   An audio synthesis model of muscle sounds

Muscles are formed by several layers of contractile filaments. Each of them can stretch and move past the other, vibrating at a very low frequency. However, audio recordings of muscle sounds show that their sonic response is not constant, instead it sounds more similar to a low and deep rumbling impulse. This might happen because each filament does not vibrate in unison with each other, but rather each one of them undergoes slightly different forces depending on its position and dimension, therefore filaments vibrate at different frequencies. Eventually each *partial* (defined here as the single frequency of a specific filament) is summed to the others living in the same muscle fibre, which in turn are summed to the muscle fibres living in the surrounding fascicle.

Such phenomena creates a subtle, complex audio spectra which can be synthesised using discrete summation formula (DSF). This technique allows the synthesis of harmonic and in-harmonic, band-limited or unlimited spectra, and can be controlled by an index [7], which seemed to fit the requirement of such acoustic experiment.

Being that the use of open source technologies is an integral part of the project, a Linux operating system was chosen as development environment. Muscle sound audio synthesis model was implemented using the open source framework known as Pure Data (Puckette 1996), a graphical programming language which offers a flexible and

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[5] BAAD is a novel term used by the author to indicate a specific sound design practice which relies on the use of biological signals. Although in this context is not possible to further elaborate on this practice, its essential principles are defined in paragraph 4.1.

[6] Real time refers here to a computing system in which there exists no perceivable delay between performer's actions and sonic response.

powerful architecture for real time sonic synthesis and processing. DSF was first used to generate the fundamental sidebands of the model; then the same formula was applied to a noise generator in order to add some light distortion to the model by means of complex spectra formed by small, slow noise bursts. Filter banks were applied to each spectra in order to emphasise specific harmonics, thus refining the design. Eventually the two layers were summed, passed through a further filter bank and a tanh function[7], which added a more natural characteristic to the resulting impulse. The model also included an automated random envelope generator used to constantly change the duration and intensity of individual impulses, thus better simulating a human muscle contraction.

Model was then embedded in a parent patch[8] in order to evaluate the suitability of diverse signal processing techniques. Although testing showed interesting results with most of the applied processes, single-sideband pitch shifting (SSB modulation) proved to be the most meaningful method; in fact, being the muscle resonance frequency so low to not be immediately perceivable to human ear, namely between 5Hz and 40/45Hz, it would result difficult to produce heterogeneous sonic material to be used in a musical performance. SSB modulation [4] disclosed a new viewpoint on the further use of muscle sounds, allowing me to shift the initial spectrum of muscle fibre sound to a higher frequency range[9]; such method enriched the musical pitch range of muscles, prompting the composition of a more elaborate score.

3.2 Xth Sense: first prototype sensor implementation

Before undertaking the development of the *Xth Sense* sensor hardware, few crucial criteria were defined:

- to develop a wearable, unobtrusive device, allowing a performer to freely move on stage;

- to implement an extremely sensitive hardware device which could efficiently capture in real time and with very low latency diverse muscle sounds;
- to make use of the most inexpensive hardware solutions, assuring a low implementation cost;
- to implement the most accessible and straightforward production methodology in order to foster the future re-distribution and openness of the hardware.

Study of the hardware sensor design began with a contextual review of biomedical engineering papers and publications focused on mechanical myography (MMG). The mechanical signal which can be observed from the surface of a muscle when it is contracted is called a MMG signal. At the onset of muscle contraction, significant changes in the muscle shape produce a large peak in the MMG. The oscillations of the muscles fibers at the resonance frequency of the muscle generate subsequent vibrations. The mechanomyogram is commonly known also as the phonomyogram, acoustic myogram, sound myogram or vibromyogram.

Interestingly, MMG seems not to be a topic of interest in the study of gestural control of music and music technology; apparently many researchers in this fields focus their attention on electromyography (EMG), electroencephalography (EEG), or multidimensional control data which can be obtained through the use of wearable accelerometers, gyroscopes and other similar sensors. Notwithstanding the apparent lack of pertinent documentation in the studies of gestural control of music and music technologies, useful technical information regarding different MMG sensor designs were collected by reviewing the recent biomedical engineering literature.

In fact, MMG is currently the subject of several investigations in this field as alternative control data for low cost, open source prosthetics research and for general biomedical applications [1, 6, 9, 20]. Most notably the work of Jorge Silva[10] at Prism Lab was essential to further advance the research; his MASc thesis extensively documents the design of the CMASP, a coupled microphone-accelerometer sensor pair (figure 1) and represents

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[7] See TANH. Available at: http://idlastro.gsfc.nasa.gov/idl_html_help/TANH.html [Accessed January 12, 2011].

[8] In this context the term 'patch' refers to a Pure Data-based application.

[9] It was interesting to note that pitch-shifted muscles sounds quite closely resemble a plucked chord.

[10] See: http://jsilva.komodoopenlab.com/index.php/Main/Research#toc6

a comprehensive resource of information and technical insights on the use and analysis of MMG signals [19].

The device designed at Prism Lab is capable of capturing the audio signal of muscles sounds in real time. Muscle sonic resonance is transmitted to the skin, which in turn vibrates, exciting an air chamber. These vibrations are captured by an omnidirectional condenser microphone adequately shielded from noise and interferences by mean of a
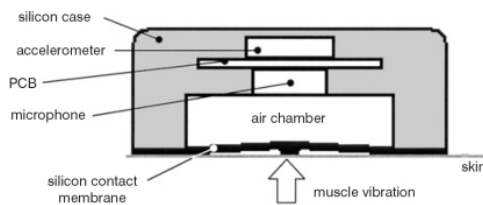
Figure 1. CMASP schematic

silicon case. A printed circuit board (PCB) is used to couple the microphone with an accelerometer in order to filter out vibrations caused by global motion of the arm, and precisely identify muscle signals. Microphone sensitivity ranges from 20Hz up to 16kHz, thus it is capable of capturing a relevant part of the spectrum of muscles resonances[11].

Although this design has been proved effectively functional through several academic reports, criteria of my investigation could have been satisfied with a less complex device. Supported by the research group at Dorkbot ALBA[12], I could develop a first, simpler MMG sensor: the circuit did not make use of a PCB and accelerometer, but deployed the same omnidirectional electret condenser microphone indicated by Silva (Panasonic WM-63PRT). This first prototype was successfully used to capture actual heart and forearm muscles sounds; earliest recordings and analysis of MMG signals were produced with the open source digital audio workstation Ardour2 and benchmark were set in order to evaluate the signal-to-noise ratio (SNR).

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[11] It is interesting to observe that the remaining part of muscles sounds spectra seems to sit below 20Hz, thus pertaining to the realm of infra-sounds. Such characteristic is not being explored at the moment only due to technical constraints, although it suggests appealing prospects for a further research.

[12] Electronics open research group based in Edinburgh. http://dorkbot.noodlefactory.co.uk/wiki

In spite of the positive results obtained with the first prototype, the microphone shielding required further trials. The importance of the shield was manifold; an optimal shield had to fit specific requirements: to bypass the 60Hz electrical interference which can be heard when alternating electric current distribute itself within the skin after a direct contact with the microphone metal case; to narrow the sensitive area of the microphone, filtering out external noises; to keep the microphone static, avoiding external air pressure that will affect the signal; to provide a suitable air chamber for the microphone, in order to amplify sonic vibrations of the muscles, and facilitating capture of deeper muscle contractions.

First, the microphone was insulated by mean of a polyurethane shield, but due to the strong malleability of this material, its initial shape tended to flex easily. Eventually, the sensor was insulated in a common silicon case that satisfied the requirements and further enhanced the SNR. Once the early prototype had reached a good degree of efficiency and reliability, the circuit was embedded in a portable plastic box (3.15 x 1.57 x 0.67) along with an audio output (¼ mono chassis jack socket) and a cell holder for a 3V coin lithium battery.
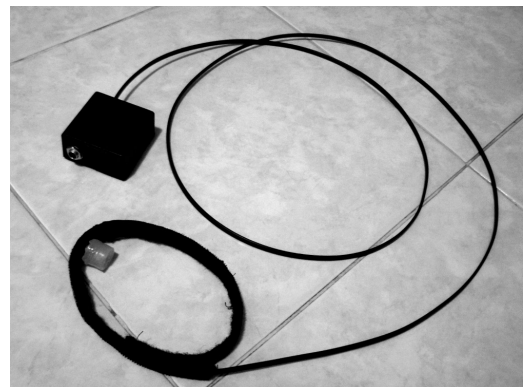
Figure 2. *Xth Sense* wearable MMG sensor prototype

Shielded microphone was embedded in a Velcro bracelet and needed wiring cables were connected to the circuit box (figure 2).

4   Performance testing: mapping and design definitions

At this stage of the project the understanding and creation of mapping and design paradigms for muscles sounds was the major goal. The main

principles and some technical implementations are illustrated in the next paragraphs.

4.1   Sound performance and design principles

Major aim of the design of the MMG audio signals was to avoid a perception of the sound being dissociated from the performer's gesture. The dissociation I point at does not only refer to the visual feedback of performer's actions being disjointed from the sonic experience, but it also, and most importantly, concerns a metaphorical level affecting the listener's interpretation of the sounds generated by the performer's somatic behavior [2]. In this project the use of muscle sounds had to be clearly motivated in order to inform classical approaches to gestural control of music. Therefore, chosen sound processing and data mapping techniques were evaluated according to their capability of enhancing the metaphorical interpretation of performer's physiological and spatial behaviour.

In this perspective, the essential principles of BAAD in a performing environment were defined as follow:

- to make use of biological sounds as major sonic source and control data;
- to exclude the direct interaction of the performer with a computer and to conceal the latter from the view of the public;
- to demonstrate a distinct, natural and non-linear interaction between kinetic energy and sonic outcome which could be instinctively controlled by the performer;
- to provide a rich, specific and unconventional vocabulary of gesture/sound definitions which can be unambiguously interpreted by the audience;
- to allow the performer to flexibly execute the composition, or even improvise a new one with the same sonic vocabulary;
- to make both performer and public perceive the former's body as a musical instrument and its kinetic energy as an exclusive sound generating force.

4.2   MMG features extraction

Since the project dealt with sound data, a pitch tracking system would have possibly been a straightforward solution for an automated evaluation and recognition of gestures, however muscle sounds resonance frequency is not affected by any external agent and its pitch seems not to change significantly with different movements [17]. Whereas muscles sounds are mostly short, discrete events with no meaningful pitch change information, the most interesting and unique aspect of their acoustic composition is their extremely rich and fast dynamic; therefore, extraction of useful data can be achieved by RMS amplitude analysis and tracking, contractions onset and gesture pattern recognition. In fact, each human muscle exerts a different amount of kinetic energy when contracting and a computing system can be trained in order to measure and recognize different levels of force, i.e. different gestures. Feature extraction enabled the performer to calibrate software parameters according to the different intensity of the contractions of each finger or the wrist and provided 8 variables: 6 discrete events, 1 continuous moving event and 1 continuous exponential event. First, sensor was subjected to a series of movements and contractions with different intensity to identify a sensitivity range; this was measured between 57.79 dB (weakest contraction) and 89.04 dB (strongest contraction). The force threshold of each finger discrete contraction was set by normalizing and measuring the individual maximum force exertion level; although some minor issues arisen from the resemblance between the force amplitude exerted by the minimus (little finger) and the thumb still need to be solved, this method allowed the determination of 6 independent binary trigger control messages (fingers and wrist contractions).

Secondly, by measuring the continuous amplitude average of the overall contractions, it was possible to extract the running maximum amplitude of performer's gestures; in order to correct the jitter of this data, which otherwise could not have been usefully deployed, value was extracted every 2 seconds, then interpolated with the prior one to generate a continuous event and eventually normalized to MIDI range. Lastly, a basic equation of single exponential smoothing (SES) was applied to the moving global RMS amplitude in order to forecast a less sensitive continuous control value [16].

4.3 Mapping kinetic energy to control data

A first mapping model deployed the 6 triggers previously described as control messages. These were used to enable the performer to control the real time SSB modulation algorhythm by choosing a specific frequency among six different preset frequencies; the performer could select which target frequency to apply according to the contracted finger; therefore, the voluntary contraction of a specific finger would enable the performer to "play" a certain note.

A one-to-many mapping model, instead, used the continuous values obtained through the RMS analysis to control several processing parameters within five digital signal processing (DSP) chains simultaneously. Being that this paper does not offer enough room to fully describe the whole DSP system which was eventually implemented, I will concentrate on one example chain which can provide a relevant insight on the chosen mapping methodology; namely, this DSP chain included a SSB modulation algorhythm, a lofi distortion module, a stereo reverb, and a band-pass filter.

The SSB algorhythm was employed to increase the original pitch of the raw muscle sounds by 20Hz, thus making it more easily audible. Following an aesthetical choice, the amount of distorsion over the source audio signal was subtle and static, thus adding a light granulation to the body of the sound; therefore, the moving global RMS amplitude was mapped to the reverb decay time and to the moving frequency and Quality factor[13] (Q) of the band-pass filter.

The most interesting performance feature of such mapping model consisted of the possibility to control a multi-layered processing of the MMG audio signal by exerting different amounts of kinetic energy. Stronger and wider gestures would generate sharp, higher resonating frequencies coupled with a very short reverb time, whereas weaker and more confined gestures would produce gentle, lower resonances with longer reverb time.

Such direct interaction among the perceived force and spatiality of the gesture and the moving form and color of the sonic outcome happened with very low latency, and seemed to suggest promising further applications in a more complex DSP system.

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[13] Narrowness of the filter.

The *Xth Sense* framework was tested live during a first public performance of *Music for Flesh I* (figure 3) at the University of Edinburgh (December 2010). Although the system was still in development, it proved reliable and efficient. Audience feedback was positive, and apparently what most appealed some listeners was an authentic, neat and natural responsiveness of the system along with a suggestive and unconventional coupling of sound and gestures.

Figure 3. *Music for Flesh I* first public performance, 2010

5 Conclusions

Results reported in this paper appear to disclose promising prospects of an experimental paradigm for musical performance based on MMG. The development of the *Xth Sense* and the composition and public performance of *Music for Flesh I* can possibly demonstrate an uncharted potential of biological sounds of the human body, specifically muscle sounds, in a musical performance.

Notwithstanding the seeming rarity of interest of the relevant academic community towards the study and the use of these sounds, the experiment described here shows that muscle sounds could retain a relevant potential for an exploration of meaningful and unconventional sound-gesture metaphors. Besides, if compared to EMG and EEG sensing devices, the use of MMG sensors could depict a new prospect for a simpler implementation of unobtrusive and low-cost biosensing technologies for biophysical generation and control of music.

Whereas the development of the sensor hardware device did not present complex issues,

several improvements to the tracking and mapping techniques can lead to a further enhancement of the expressive vocabulary of sound-gestures. In an attempt to enrich the performer's musical control over a longer period of time, hereafter priority will be given to the extraction of other useful features, to the development of a gesture pattern recognition system and to the implementation of polyphony, using two sensors simultaneously.

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