PRINCIPLES, CHALLENGES AND FUTURE DIRECTIONS OF PHYSIOLOGICAL COMPUTING FOR THE PHYSICAL PERFORMANCE OF DIGITAL MUSICAL INSTRUMENTS

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Abstract: **The design of and performance with sensor-based musical instruments poses specific opportunities and challenges in the translation of the performer's physical gestures into sound. The use of muscle biosignals allows directly integrating aspects of a performer's physical gesture into the human-machine interaction and compositional strategies which characterise a digital musical instrument (DMI). The highly personal musical techniques of a few instrument-builders and performers has the potential to evolve into more general musical performance practice, used by a range of artists, composers and students. In order to meet this challenge, there is a need to address the issue of usability of those musical techniques and to clearly specify the advantages that physiological computing offers.**

This paper describes the principles and challenges of physiological computing for musical performance with DMIs, focusing on muscle-based interaction. This approach is presented through the discussion of two musical interaction modalilties, biocontrol and biophysical. We report on three recent studies looking at multimodal muscle sensing and feature extraction to explain the potential of those methods to inform DMI design and performance. Opportunities for future research are delineated, including the implementation of gesture recognition and gesture variation following for the creation of adaptive DMIs.

1. INTRODUCTION

The term physiological computing is used in Human-Computer Interaction, to describe the interaction with a computing system through physiological data [1]. 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 - biological signals as electrical potentials and mechanical mechanism 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 [2]. Muscle tension can describe intention 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 the performance with digital musical instruments (DMIs), the biosignals of a performer's body can be deployed to implement specific human-machine interaction strategies. 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 [3, 4] or drive generative musical processes [5, 6]. Muscle sensing musical interfaces use the muscle electrical potential to modulate and trigger musical processes [7, 8], and the muscle acoustic vibrations as live sound input and control data [9].

Here we focus on muscle sensing interfaces, which function on the base of the performer's physical exertion during gestural interaction with a musical system. Throughout the remainder of this article the term "gesture" is always intended as physical gesture. Muscle biosignals do not provide only gestural input, they can also describe the intention to execute a gesture, the force and temporal profile of the gesture and the way that gesture is articulated [10]. That information can be used to specify (outline salient traits of) a player's physical gesture and inform accordingly the human-machine interaction and compositional strategy which characterise a DMI.

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 [11] and visceral interaction, where visceral refers to a combination of conscious and unconscious thought [12]. In the case of a piano, the player's physical gesture on the keyboard activates a mechanism which causes a string to be excited and produce sound. There exists 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 [13].

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? How can biosignals be meaningfully mapped onto musical parameters? Are there relations among muscle biosignals that can be quantified and how can those relations be used to endow an instrument with expressive features?

This paper will characterise the performative and compositional principles of physiological computing for the physical performance of DMIs. The advantages and downsides of muscle sensing as opposed to spatial and inertial sensing in physical 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 article will look at the work that is presently being conducted in the field. The value of an interdisciplinary approach that combines resources from neuromuscular studies [14] and machine learning [15] with insights on DMIs performance will be described. This will point to new feasible opportunities for the design of DMIs, such as the capacity of an instrument to adapt and evolve according to the physical performance style of its player.

2. MUSCLE-BASED INTERACTION

Limb movement involves muscle activation mechanisms. To produce a physical gesture, neurons fire electrical voltages transmitted through the body to cause muscle tension. The electromyogram (or EMG) is the electrical biosignal that results from neuron firing commanding muscle contraction. It can be captured in the form of an electrical voltage using electrodes (wet gel or dry), in surface contact with the skin [16]. When implemented in a DMI, the preferred sensors are generally dry surface electrodes as they don't require skin preparation. A muscle under tension contracts and changes shape, producing mechanical oscillations. The mechanomyogram (MMG) is the acoustic biosignal produced by these effects [17]. Muscle sound, as it can be known, is a low frequency vibration which can be captured acoustically using microphones [18]. In interactive music performance, chip microphones are the sensors of choice as they do not require skin contact and thus avoid noise in the signal which may arise from skin scratching.

The EMG and MMG provide complementary information on the

same limb gesture and can be thought of as two modalities, one that is biocontrol and the other, biophysical.

Biocontrol. During a performance, electrodes worn on the performer's limbs capture the EMG signal sent from the central nervous system to the muscle in order to activate it. This signal is used to track muscle tension to control computer-based sound [19].

The first electronic musical instrument based on EMG was the *BioMuse* (Fig. 1), documented for the first time by Knapp and Lusted in 1988 [20] and used extensively in public performances by the second author. The original *BioMuse* was conceived as an alternative MIDI controller – a non-keyboard based way to control synthesizers. In this sense, it stretched, but nonetheless conformed to the event-parameter paradigm of MIDI[1]. Musical events are initiated as notes, with associated expressive parameters accompanying the initial event trigger – typically in the form of velocity captured on the keyboard, mapped onto a range of synthesis parameters. Subsequent shaping of sound would take place as continuous data streams would modulate sustained sound synthesis.

This event-based control paradigm presented a challenge for the musical use of EMG as a continuous flow of rich, complex data. The *BioMuse* performed envelope following, from which note events could be generated by amplitude threshold triggers. Various strategies were developed to use the multiple EMG channels in conjunction with one another to generate series of events whose sustaining sounds were shaped by subsequent muscle gesture. The richness of expressivity then came out of how naturally and how fast events could be generated and in what ways continuous control could directly modulate sound synthesis.

Later, with the arrival of MSP and real-time signal processing in the Max graphical programming environment, these notions were implemented free of commercial synthesizer manufacturer constraints. Sound sources could now arbitrarily be wavetable oscillators or samples, and could be looped or granulated. This fed different forms of frequency shifting, harmonizing, resonant filters and ring modulation, before an output stage that included waveshaping and amplitude modulation. These were all controlled through dynamically changing mappings based on strategies established in the field of New Instruments for Musical Expression (NIME) over time. These include "one-to-many" mapping, where a single sensor input is mapped to multiple synthesis parameters, or "many-to-one" where multiple sensor inputs might be combined to control a single synthesis parameter [21].

Figure 1: The muscle-based musical instruments BioMuse, below, and Xth Sense, above. They both use muscle sensing but rely on distinct modalities. The former uses electrodes to capture the EMG signal for biocontrol, and the latter uses a chip microphone to capture the MMG for biophysical music.

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[1]Musical Instrument Digital Interface. This is a technical standard for data communication across different devices and software

Biophysical. Biophysical music performance builds upon the methods of biocontrol to offer a related, yet distinct interaction strategy. Here, as the player performs physical gestures, microphone sensors worn on the player's limbs capture the muscle sound produced by the vibrations of the muscle tissue [9]. The muscle sound 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 [22]. Since a muscle sound is produced only when a muscle contraction happens, actual physical effort is required in order to play biophysical music. In this way, physical effort becomes an integral part of the performance style of each artist.

The first DMI to make that use of muscle sounds was the *Xth Sense* (Fig. 1), created in 2010 by the first author, and used ever since in an ongoing series of interactive music projects[2]. 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 one-to-one mappings.

The signal analysis and processing is designed to seamlessly enhance the inherent interaction which links the player's movement and the MMG signal. A basic characteristic of the MMG is that the strength of the muscle contraction is proportional to the perceived loudness of the amplified MMG. For instance, a sudden and strong flexion/extension of the limb produces a loud sound with a sharp attack and a very short release. The *Xth Sense* uses an ad hoc mapping technique which extends that relationship between exerted force and resulting sound by adding multiple dimension to it. The dynamics of each MMG signal is used as a continuous event to manipulate the qualities of a musical piece. In order to ensure a fair amount of complexity and richness, an array of eight simultaneous mapping dimensions is available to the player, and the player can use up to twenty distinct arrays in a single piece.

The temporal structure of the piece can be fixed or dynamic. In the former case, the user creates keypoints in time using a graphical timeline. When a keypoint is reached, the instrument changes its configuration by loading the new set of mappings and audio processing chains. In the latter case, a machine learning algorithm learns offline four physiological states of the performer's body. During live performance, the instrument configuration changes automatically only when the performer's body enters one of those states. This method favours an improvised performance style that can vary from one performance to another, while the instrument retains the basic gesture-to-sound relationship predetermined by the performer.

3. PRINCIPLES

Proprioception. Proprioception is the awareness of limb position and strength of a physical gesture. This awareness of one's own body arises from sensation at receptors in muscles, joints, the inner ear, amongst others [23]. A sensory receptor is the ending of a sensory nerve. It records an internal or external stimulus, and transduces it in an electrical impulse that is transmitted to the central nervous system. The muscle sensory receptors are called muscle spindles, and they mechanically record the changes in the muscle length. Proprioception is critical to closed-loop motor control [24], which is the selection and adjustment of a physical action according to a stimulus, a fundamental aspect of musical performance. A sense of self carries with it, according to Merleau-Ponty, a tension between conscious and unconscious, between "intention and performance" [25]. It seems appropriate that a development of the proprioceptive sense is critical to musical performance [23]. In the case of musical performance with muscle-sensing DMIs, a heightened sense of proprioception is critical for it

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[2]This instrument is released as a free and open project 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.

relates to motor learning.

Proprioception does not only relay real-time information to the brain, but it also enables the learning and training of new bodily skills that require prompt response to unpredictable conditions [26].

Figure 2: An empty-handed gesture executed during the performance of a contemporary music piece for biophysical music. The lack of an external object to manipulate makes the performer internalise physical effort through restraint strategies.

This is shown for instance in the case of a guitarist, who, by training his motor skills on a specific guitar, becomes able not only to improvise on any other guitar, but also to play in unexpected combinations with other instrumentalists. Merleau-Ponty outlines the link between musicians' training and learning of new motor skills and their bodily effort when he explains that playing habits constitute "knowledge in the hands" which is achieved "only when bodily effort is made and cannot be formulated in detachment from that effort" [25].

Effort and restraint. Muscle tension requires physical exertion. At the same time, free space gesture presents an interesting contradiction in the lack of an object of exertion. As there is no physical object on which to exert effort, the performer of a muscle sensing musical interface makes gesture in a void without tactile or haptic feedback (Fig. 2). We propose two solutions to this situation: first, the internalization of effort through restraint, and second, the creation of haptic feedback through the physicalization of sound output. The physicalization of sound is the projection of audio of specific frequencies at amplitudes sufficient to create sympathetic resonance with parts of the body other than the ear and creates a kind of haptic feedback loop through acoustical space of the effort engaged in musical gesture [27]. On a traditional instrument, restraint on the exertion applied on an instruments needs to be exercised in order to keep the performance within the physical bounds of the instrument. Restraint in the maximum effort needs to be exercised to avoid breaking the guitar string when bending it, or bottoming out or cracking the clarinet reed when blowing. At the opposite extreme, a minimum exertion needs to be performed in order to produce sound. Restraint is needed in sensor systems such as accelerometers to prevent "overshoot". Poupyrev shows that haptic feedback which renders accelerometer-based interaction more physical improves performance of simple tasks, such as tilting to scroll in a list [28]. When playing with a muscle-sensing musical interface, strategies of restraint allow the execution of fluid movement with little muscle tension and the efficient realization of high biosignals levels without awkward exertion.

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 as a mediation among the performer's voluntary motor control, the physiological constraints of the performer's body and its autonomic processes. The qualities of movement as it becomes apparent in space (size, velocity and abruptness) are a result of that mediation and, in this sense, are partly conscious and partly unconscious. In other words, a physical gesture might not occur as initially intended by the performer. The analysis of physiological data from a performer's body gives access to that information because

it describes the way in which a given movement is articulated rather than the way in which it takes place in space. 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 opens up musical performance with DMIs to unconscious thought and intuition.

4. Physiological versus physical sensing

Movements of a performer on a DMI are often observed using physical sensing, like spatial and inertial technologies [29]. 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 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 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.

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 nor position, but the corporeal action that might (but 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 his intention to make a gesture. The MMG is an acoustic signal resulting from the physical dynamics of muscle tension. This means that 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 the contraction duration. 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 that produces that movement. Whereas limb orientation and position cannot be detected using the MMG, by looking at the biosignal envelope and amplitude over time one can gather information on the way the gesture is articulated.

Muscle sensors offer a key advantage compared to spatial and inertial sensors in sensing the subtleness and nuance of limb gesture. Physiological sensing provides direct access to information on the user's physical effort. Subtle movements or intense static contractions which might not be captured by spatial or inertial sensing are detected since physiological sensors transduce energy (mechanical or electrical) directly from the muscles.

5. Challenges

In the performance with DMIs, the digitisation of a performer's movement represent 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 are at the core of the design of DMIs. In Ryan's words, "[e]ach link between performer and computer has to be invented before anything can be played" [11]. 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 between a performer and a computer that needs to be established, and the way by 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 be exploitable in a way that is immediately evident to the audience in the way that physical and spatial interaction could be. Meanwhile, the independence of exertion and effort from gross physical movement makes biosignals a unique and potentially rich source of information for musical interaction. This also makes them

idiosyncratic and less useful as a general purpose control signal. One way to decode the complexity and specificity of biosignals include the use of advanced information analysis methods such as pattern recognition and machine learning. Also, interesting combinations could result from the use of muscle biosignals in conjunction with complementary physical sensors.

Multimodality. Multimodal interaction uses multiple sensor types (or input channels) in an integrated manner so as to increase information and bandwidth of interaction [30]. 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 [31].

One of the early examples of interactive musical instrument performance is the pioneering work of Waisvisz with *The Hands* which he created in 1984. Waisvisz's set of hand-held remote controller capture data from accelerometers, buttons, mercury orientation switches, and ultrasound distance sensors [32]. The use of multiple sensors on one instrument points to complementary modes of interaction with an instrument [33]. That being said, DMI have for the most part not been developed or studied explicitly from a multimodal perspective, which would be a useful approach. [29].

We have explored techniques for multimodal interaction to distinguish similar muscular gestures in different points in space [34]. In an EMG-based instrument produced at STEIM[3], we supplemented four channels of EMG with 3D accelerometers embedded in two gloves to detect wrist flexion and tilt (Fig. 3), and recently the *Xth Sense* and the *Bioflex* instruments were combined for a gesture-sound mapping experiment, described in Section 6. The biomedical literature shows that the use of a multimodal system where EMG and MMG analysis is combined is a useful resource [14]. 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 (see Section 2). That information can be used to enrich the design of gesture-sound relationships of a DMI.
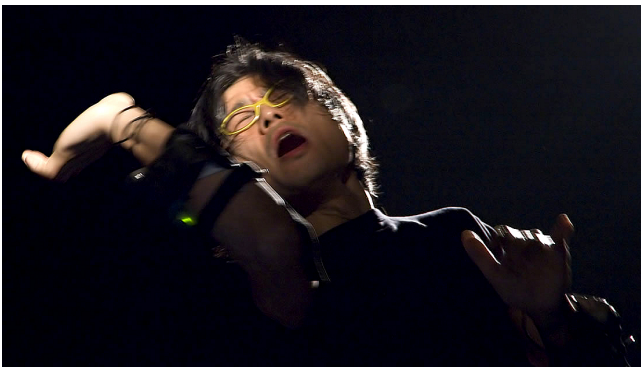
Figure 3: A multimodal version of the BioFlex instrument developed at STEIM. The instruments was embedded with four channels of EMG and 3D accelerometers. This allowed for detection of wrist flexion and tilt movements.

Characterisation. Another challenge of physiological computing for musical performance involves the extraction of salient features from sensor data, a range of methods known as feature extraction [35]. By using mathematical or statistical functions, the raw biosignals can be processed and features extracted. These can provide a higher-level representation of muscle activity. Although, in the field of DMI 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 of [36] includes a comprehensive review of EMG features and signal processing, and the work of [18] 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 shall 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 instead 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 DMIs.

6. RECENT RESEARCH AND FUTURE PROSPECTS

We have recently investigated the issues of physiological multi-modal sensing and feature extraction for the analysis of expressive gestural interaction with musical systems. In this section, we provide an overview of those studies and describe the insights they provided. The details of the studies do not fit the scope of this article, the interested reader is invited to refer to the related publications. In the first study, we investigated the use of physiological, spatial and inertial sensing in two different multimodal configurations. The goal was to examine the expressive aspects of physical gestures as performed by experienced players and non-experts. In the second study, we used a physiological-only bimodal setup to look at the power of expressive gestures, where power is intended as pressure, physical strain or kinetic energy resulting from motion.

The first study was divided in two parts. In the first part, 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 [37]. 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 and to the musical output. The analysis of the recorded data showed that a) physiological and spatial modalities provide complementary information that are related to the gesture musical output; b) only the physiological modality can sense the preparatory activity leading to the actual gesture; c) 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. Those findings showed that musical variations in the output of a muscle-based DMI are dependent on quantifiable variations in the physical aspects of a gesture.

The second part of that 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 [38]. 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 [39, 40, 41, 42]. The biosignals produced during the execution of the gesture were sonified in real time, providing a feedback to the participants. This helped them identifying 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 i) non-experts are able to voluntary vary parameters of the sonification of the

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EMG and MMG following a short training; ii) the variations of gesture articulation produce variations in the biosignals activity; iii) 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 player – even if non-expert, is capable of engaging in musically interesting ways with a muscle-based DMI.

Building upon the insights of the first study, we designed a new experiment to look at the articulation of power during human-computer gestural interaction [10]. 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 power is an ambiguous notion which can be used to indicate physical strain, pressure or kinematic energy according to the type of gesture and the context of interaction. The participants also noted that variations on power were conditioned by variations in speed or size of the gesture. A quantitative analysis of the recorded biosignals helped objectively testing the findings provided by the questionnaire. By looking at the biosignal features we showed that 1) participants are able to vary muscle tension and that variation can be detected through physiological sensing (Fig. 4); 2) exertion through pressure is better indicated by the EMG signal amplitude, whereas intensity of a dynamic gesture is better detected through the MMG features; 3) gesture power and speed are interdependent, i.e., 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.

Those experiments offer an interesting overall view on the use of physiological computing for the design of and performance with DMIs. Physiological sensing provides useful information on gesture which are not provided by spatial and inertial sensing technologies. Specifically, bimodal muscle sensing allows detecting and quantifying certain aspects of limb movement which make a gesture expressive, such as static exertion and dynamic tension, which cannot be detected with spatial sensing. The extraction of biosignals features such as signal amplitude, zero crossing and spectral centroid provides an entry point to such low level insights on the gesture articulation, which can be used to inform the design of musical interaction with DMIs.

Creating DMIs that rely on multimodal muscle sensing and biosignals feature extraction would enable real world scenarios where to test the usability and the expressive capability of such musical systems. Muscle sensing also offers the possibility to investigate in detail 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 modeling of muscle-based variations that would allow a DMI to recognize and adapt to the way a performer articulates different aspects of a gesture. The DMI could create personalised gesture-to-sound mapping 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 a DMI with a certain degree of agency. An approach that could yield new ways of performing and conceiving live electronic music.
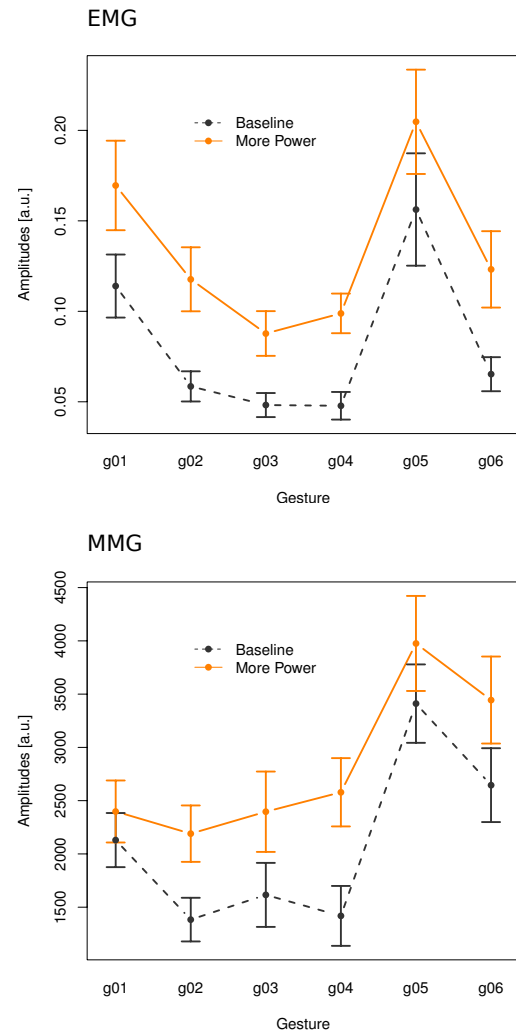
Figure 4: Amplitudes for both EMG (top) and MMG (bottom) averaged across participants and six gesture trials. Two conditions are considered: baseline and more power. Both signals show increase in amplitude when participants are asked to performance a gesture with "more power".

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