Real-time Sonification of muscle tension for piano players

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Abstract

This research focuses on the design of an Interactive Sonification (ISon) feedback system to inform piano players of high muscle tension. The system includes an Arduino board and EMG sensors as hardware, and Max and the Processing language as software. Experimental results demonstrate the feasibility of a system to self-monitor muscle tension in piano performance and in other real-time situations.

Table of Contents

Acknowledgements

I would like to thank my supervisor Prof. Andy Hunt for his great support, guidance and patience throughout this research.

Declaration

I declare that this thesis is a presentation of original work and I am the sole author. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References.

Chapter 1 Introduction & Hypothesis

1.1 Foreword

A world of sensors?

Wearable devices are being increasingly used in daily life. People are realising that life can be *smart*, and thus repetitive and necessary activities should be done more easily. This is where wearable equipment can really shine: Google Glass created a storm by proposing a smart new style of living; the Apple Watch blurs the boundaries between things sold in a boutique or in a high-tech shop. Myo, Oculus, and Leapmotion[1] are currently strange-sounding words that will very likely develop into indispensable elements in our world.

EEG and EMG[2] are no longer only recognized by medical experts. Using wearable and portable devices, some of which include such sensors, people can message each other, speak to each other, monitor their health status, access the world's information instantly, in fact almost anything with the little help of these small, smart and affordable gadgets. The number of sensors inside these devices is growing rapidly, leading to the conclusion that this is a new era; a world of sensors.

Interactive Sonification (ISon)

Interactive Sonification involves the use of sound to display data interactively. It is a timely discipline because displaying data with sound frees up the eyes, letting people deal with sudden small tasks without being disturbed by the need to look at any screens. It fits well with the abovementioned sensors. Sound is also very good at giving long-time as well as real-time information. You cannot look at your computer screen for 24 hours but you can definitely listen to music on a long bus journey while carrying out other mental activities, such as texting a friend. So, the combination of sensors and ISon technology is able to create a new world of possibilities, building

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[1] http://www.apple.com/uk/watch/; https://www.myo.com/; https://www.oculus.com/en-us/; https://www.leapmotion.com/

[2] Electroencephalography (EEG) http://www.nhs.uk/Conditions/EEG/Pages/Introduction.aspx
Electromyography (EMG) http://www.mayoclinic.org/tests-procedures/electroconvulsive-therapy/basics/definition/prc-20014183

applications never imagined before.

A new discipline

ISon itself is a relatively new area with great potential. Today's ultra-portable and increasingly affordable computing technology allows Interactive Sonification to be utilised by anyone. The pioneering concept of portraying data as sound is turning into a sophisticated discipline which links well to real-world applications and practices. Despite this, there are still many remaining issues that need research and development.

1.2 Motivation

In today's high-speed life, people tend not to do enough outdoor activity because of work pressure or lack of time, etc. With the rapid development of computers and the Internet, much work is based around sitting at a desk and operating computers. In spite of this, for their leisure time, people are also tending to spend yet more time playing on computers. This is causing major problems: during sustained working hours many people do not even get off their seats to take some exercise to refresh their body. Some people even do worse - they sit and work with a very awkward posture. By doing this over a long period of time, injury can often result. The most common serious injury is RSI (Repetitive Strain Injury)[3], which involves pain from muscles, nerves and tendons caused by repetitive actions or overuse. Also, when people are working they usually have stress that can cause RSI as well.

The harm of RSI is serious because:

- It can't be recovered from quickly;
- Sometimes RSI does not have obvious symptoms apart from pain; hence it is not easy to detect in the early stages.

The Health and Safety Executive (HSE) said that *"213,000 people in work had a musculoskeletal upper limb or neck disorder that was caused or made worse by work in 2007-08"*. Also, The Chartered Society of Physiotherapy (CSP) said *"RSI, which is*

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[3] http://www.medicalnewstoday.com/articles/176443.php

usually preventable, costs employers around £300m per year in lost working time, sick pay and administration". Nowadays RSI is considered a serious and common problem in companies.

Meanwhile, RSI does not only happen to office workers. There is another category of people who have a particularly high likelihood of this problem - pianists. Piano players practice for a long time each and every day, sitting on a chair often in a non-relaxed posture. Their body can be stressed; their fingers may also suffer from high tension when playing a technically difficult piece of music; also their mental condition can involve excessive concentration and tension when expressing their intensive emotions. A few professional pianists have been noted as having a problem with RSI and some of them even abandoned their career because of it, including many dedicated pianists such as Leon Fleisher, who once stopped playing for an entire 15 years because of having RSI problems (Lim, 2014).

Therefore, the prevention of RSI among office workers and pianists is considerably important. A good potential solution would be to monitor their actions, detect the wrong motions or positions, and then give them an auditory alarm in order to remind them. Due to the method of their work, visual feedback for them is not realistic; people find it difficult to concentrate on their visual-based work whilst constantly remembering to check other visual indicators at the same time. Hence, auditory feedback can be very useful here: people are not required to "actively" monitor the visual feedback, but to listen out for an audio alarm "passively".

With this above concept, we may design an auditory feedback system that keeps reminding people about wrong posture when carrying out difficult tasks.

The research in this PhD focuses on using Interactive Sonification to build a system that has the potential of reducing long-term injury for seated keyboard users.

1.3 Hypothesis

This research has two hypotheses: one general and one more specific.

The initial hypothesis (Hypothesis 1) of this research is:

> *"By using Sonification feedback it is possible to inform keyboard users, (e.g. piano players or office typists) of activity which could otherwise cause long-term injury."*

This PhD research aims to provide audio feedback based on human actions/movement when difficult tasks are being carried out. Particularly, there are four areas of focus, which this research is interested in:

- pianists
- office typists
- Phone users / gamers (who use thumb intensively)
- Badminton players (easy to get injuries on multiple muscles)

In the early stages, this research investigated how sound could be used to monitor tension, and thus via feedback to release it. It is easy to imagine that the advantages of using sound as feedback are attractive: an auditory signal indicates problems or tension immediately and directly; people concentrate on jobs they are doing without being constantly disturbed by looking at some visual feedback, for instance.

RSI injuries can come from a sustained high muscle tension over a long period of time[4]. Therefore EMG biofeedback (Chapter 3) was used to monitor the muscle tension and allow the data to be stored on a computer. A good way to transfer the data into sound is to map the data corresponding to inappropriate muscle tension into an alerting (or alarm) sound which people will notice and correct their posture. Hence this data will be transformed into sound by DSP (Digital Signal Processing) carried out in the *Max* programming language.

However, after some initial study, it became clear that a full test of this hypothesis would be almost impossible to carry out because the experiments on piano players

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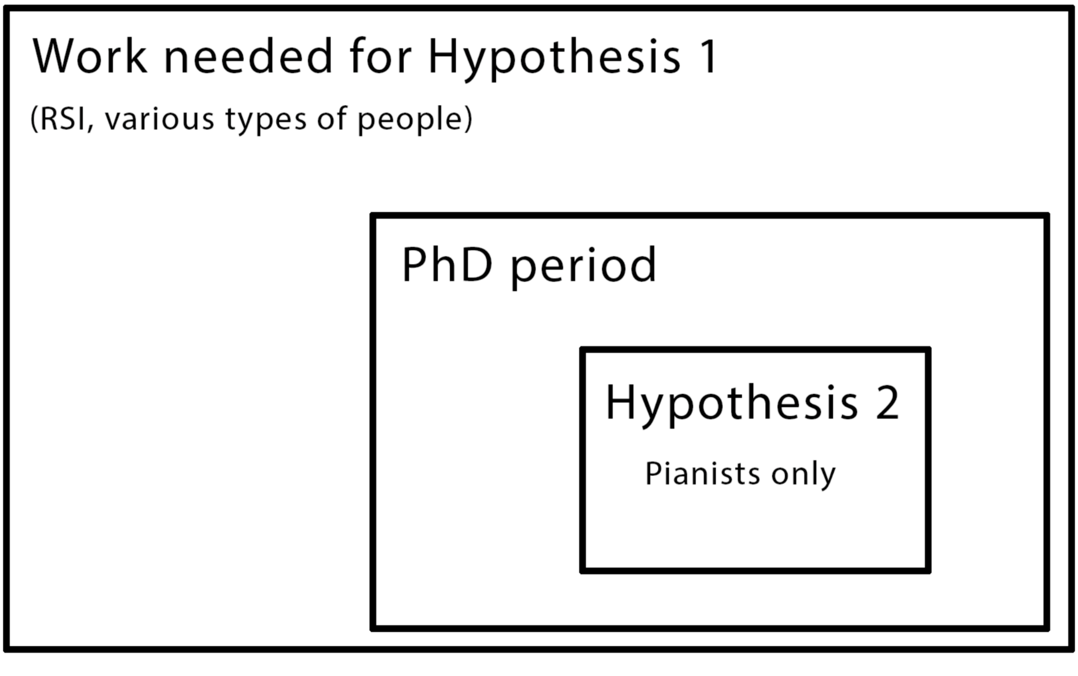
[4] http://www.medic8.com/healthguide/sports-medicine/repetitive-strain-injuries.html

would need to have prolonged sessions (a few hours) as well as long period tracking (a few months to years). Also during multiple initial tests on QWERTY keyboard users, only very little bad effect (discomfort) could be seen from purely typing activity, no matter how fast they typed or for how long. Most of badminton players who were asked for doing experiment with device wired on their body express discomfort and refuse to carry on the experiment. These observations gave the insight that the initial hypothesis was too wide to be investigated within a PhD time frame. The new focus was purely on piano players, and this led to the development of Hypothesis 2, which is the main hypothesis for this work:

> *"By using Sonification feedback it is possible to inform piano players of muscle tension in real-time, which will allow them to reduce tension"*

The relationship between Hypothesis 1 & 2 can be explained as:



1.4 Thesis Structure

This thesis includes the following chapters:

Chapter 2 & 3 *Interactive Sonification*, *Piano Related Injuries & Biofeedback* give a review of related key topics to this thesis, including auditory display, sonification, RSI, piano technique related injuries (PRMD) and so on.
Chapter 4 *Research Methodology* summarises the thoughts after considering the literature. From what had been found, a plan for making a new contribution is presented.
Chapter 5 *Practical Development* describes the technical design and construction required for the experiments. It contains documentation of the hardware and software developed during the procedure.
Chapter 6 *Experiments & Analysis* is the core part of this thesis. Many subjects were involved in a range of tests, and these have yielded useful results and insight. In the "analysis" section, the results are discussed, and the hypothesis is evaluated.
Chapter 7 *Conclusion & Future work* summarises and explains the key findings of this research, and highlights the potential developments of the developed technology and procedures.

Chapter 2 Auditory Display and Interactive Sonification

2.1 Introduction

This chapter describes the term “Auditory Display” and a subclass of this topic - “Interactive Sonification” in detail. By looking at the field covered by these two terms, the advantages and disadvantages of displaying data as sound are listed and explained and the methods of sonification classified. Finally, several real-world evaluations of Interactive Sonification are analysed to illustrate the strong need for auditory displays in real-time interactive systems.

2.2 Auditory Display

In a conventional human-computer interaction (HCI) system, the information is converted to a form which humans readily accept by means of a visual display. However, the field of Auditory Display introduces sound as feedback in HCI systems, and can – in certain situations – become the main method of transmitting information to allow the user even better understanding. This section looks at the different ways of translating data (variables in terms of quality and quantity) into an alternative perceptually-friendly medium for human users.

Since the establishment of the International Conference on Auditory Display (ICAD) in 1992, the field of Auditory Display has been evolving rapidly. In recent years it has been classed alongside visualisation, and is becoming a more widely accepted method of data display. Implementations of auditory displays are used in many fields including chaos theory, biomedicine, data mining, seismology, interfaces for disabled people and so on. It is also one of the most complex areas to study because in order to carry out a successful implementation, several disciplines must be comprehended and mastered, such as Physics, Acoustics, Psychoacoustics, computer science, etc. (Hermann et al., 2011).

Kramer listed the advantages and disadvantages in his pioneering article "Auditory Display: Sonification, Audification, and Auditory Interfaces" (Kramer, 1993). The most important and relevant advantages are listed below:

1) No visual contact is needed. Firstly it is clear that for people with impaired sight, this is a good solution for interactions between them and the system. Secondly, in unsatisfactory environments such as low light, visual data can be difficult to read or perceive, which makes the system no longer purposeful. Lastly, since human activities often involve the use of eyes, an interactive system that demands visual attention may distract the concentration, which can damage the effectiveness of the feedback system and even be dangerous.

2) Humans perceive sound more quickly than visual content. If the sound changes due to the data changing, especially if changing rapidly, this can be perceived immediately. For visual feedback, it usually takes more time for a response; "lag" is a good description to express the difference of response time between visual and sound perception.

3) Audio is suitable for conveying alarms, because sound itself can be very alerting. When an auditory alarm system is built carefully, the sound rises quickly when the appropriate factors are all satisfied. A good alarm has suitable frequencies, which are usually loud enough in order to be heard in noisy environments. The term "alarm" can also be used to help the user to perceive irregularities in the data. For example, imagine an audio stream representing the average temperature of every day in a year. When the temperature swiftly becomes 20 degrees lower in a single day, the listener can be made aware of that change even if they are not paying full attention to the sound all the time. This is one of the biggest advantages compared to visual feedback systems.

4) Human ears can accurately perceive tempo. If there are two different rhythms (not too similar), humans can distinguish them without difficulty. This means that sound can be used for analysing data in time sequence. If there are more than one

piece of information, it is possible to combine them with different rhythms allowing all information to be rendered into a single stream of sound but with the various pieces of information individually recognisable.
There are also disadvantages or difficulties which must be kept in mind when producing a system using auditory display. These are:

1) Musical displays can interfere with musical performance. The most crucial issue (and the most related to this research) is that in the situation of tracking the movements of music performance, if the auditory display uses musical relationships itself (for example the use of chords or harmonic lines), it may influence or disturb the performer. When this happens, the Auditory Display system is not stable because the actions as well as the mind of the music performer are influenced by the feedback, resulting in an unusual and unwanted interaction between the system and user.

2) If the sound is annoying it can cause fatigue. Equally, if the sound is too pleasing it may draw too much attention, thus distracting users from their original actions.

3) Sound cannot be printed like a graph. This means that if the result requires sound with a long duration to represent the data, a process of sustained listening to the entire audio must be undertaken in order to get the whole picture of the result and finish the analysis.

4) The direct relationship of the system input and output cannot be shown in a single audio stream, unlike a visual graph, which is able to do so with a simple X-Y plot.

5) If the audio goes outside the range of human hearing (20Hz-20KHz; also with age and hearing loss the hearing range can be reduced) important data might be inaudible.

Although disadvantages of Auditory Displays exist, they can be avoided by using certain methods. For instance, a very well designed system considers how to deal with the data where the corresponding sound is outside the hearing range. Sometimes, Auditory Display and visual feedback are often used *together* to merge the advantages of both, usually resulting in a better quality of analysis. Furthermore, along with the recent rapid development of portable HCI devices/applications, Auditory Displays free up the eye-display communication (which has been essential in the past), unlocking unlimited possibilities as a strong non-visual support tool.

2.3 Interactive Sonification

"Sonification" is a subclass of Auditory Display. Research into sonification began to take shape in the 1990s, when Kramer et al made the early definition of sonification as: *"the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation"* (Kramer et al., 1999). This states that sound is used for transferring imperceptible relations of data into perceptible acoustic signals. It is a "bridge" between data sets and the mind of the listening human. In general, sonification is the use of sound to render data. Hermann's more recent definition states: *"Sonification is the data-dependent generation of sound, if the transformation is systematic, objective and reproducible, so that it can be used as scientific method"(Hermann, 2008)*. Sonification must satisfy the demands below:

- It must be clear that the changes in the sound are caused by the data.
- The relations or the objective contents are mirrored by the sound.
- Normally sonification uses synthesized sounds in response to data, and thus does not typically involve real-world acoustics. However on some occasions real-world sounds and interactions can be seen as sonification. A very good example was given by Hermann: using a spoon to hit a bottle filled with water once per minute can be considered as sonification because the amount of rainfall measured by the fill level is represented by pitch of the sound.
- The process of the data/sound change must be repeatable; if the same data and interactions are given, the output sound must be recognisably the same.

Interactive Sonification (often abbreviated to ISon) is the use of sonification in a real-time interactive feedback loop with human users. For the use to be classed as "interactive", the study of Human Computer Interaction (HCI) is needed. HCI is "*a discipline concerned with the design, evaluation and implementation of interactive* *computing systems for human use and with the study of major phenomena surrounding them*" (Hewett et al., 1992). The role of HCI studies is to enhance the interactions between humans and computers so that computer users can use them more easily. At the practical level, it is mainly concerned with designing new interfaces, where interaction occurs between a human and a computer. Usability takes the highest priority during the design procedure.

Interactive Sonification can be defined as "*the discipline of data exploration by interactively manipulating the data's transformation into sound*" (Hunt, 2011). It allows (and actively encourages) users to make actions while hearing the sound feedback. This can create new data (or new 'views' of the data), which in turn encourage the user to manipulate the computer to give new feedback. When this procedure loops, Interactive Sonification is delivered. Figure 2.1 shows the relationship between the data and its transformation controlled by the user in ISon systems:

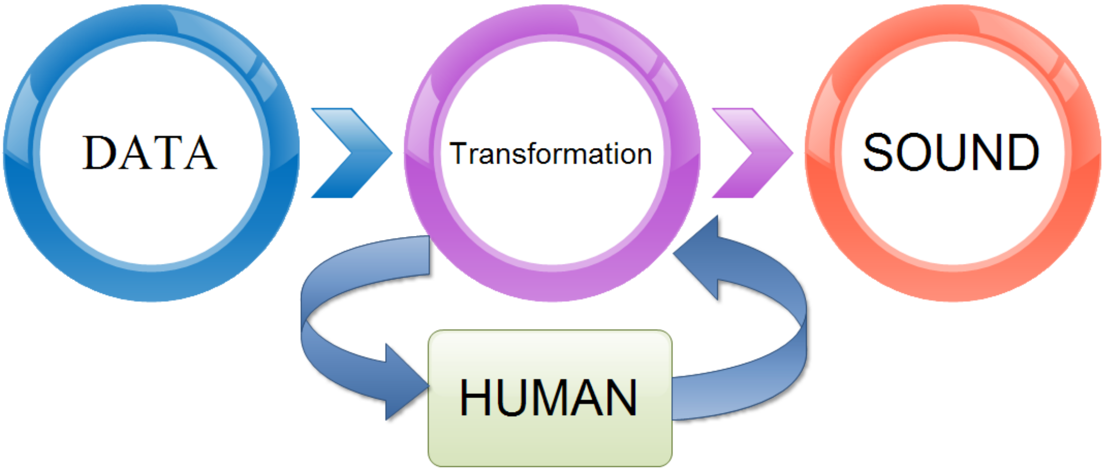


Figure 2.1: Basic Principle of ISon (Based on Hunt, 2011)

In 2004, Hermann and Hunt emphasised the importance of using Human Computer Interaction (HCI) technology in sonification methods to explore datasets while they are being transformed into sound (Hermann and Hunt, 2004). Human senses are used continuously for interacting with the physical environment, and clearly visual perception has always been an important task for the human brain. However, when a dataset is mirrored by exploratory interaction (continuously controlling its transformation into sound), new insights are gained into the macro and micro-structure of the data. This is a huge advantage over regular visual presentation because those structures are not necessarily obvious in visual rendering (Hermann and

Hunt, 2004). They also reviewed the history of interfaces regarding their quality, then suggested that for abstract data, high-quality and directly controlled interfaces should be used for examination.

Since sonification is still a very young research field, many terms like “sonification”, “Auditory Display”, and “audification” have only relatively recently been given precise and widely agreed definitions. Therefore Hermann introduced a new definition for sonification, such that “*a technique that uses data as input, and generates sound signals (eventually in response to optional additional excitation or triggering) may be called sonification*” (Hermann, 2008). There are four strict conditions for this:

- Properties in the input data must be objective,
- Systematic transformation must occur, which means the way that the data is changed into sound has a precise definition,
- Same data and interactions cause identical results,
- The system can be used with different data and also with the same data repetitively.

Figure 2.2 below exhibits the structure and conditions:

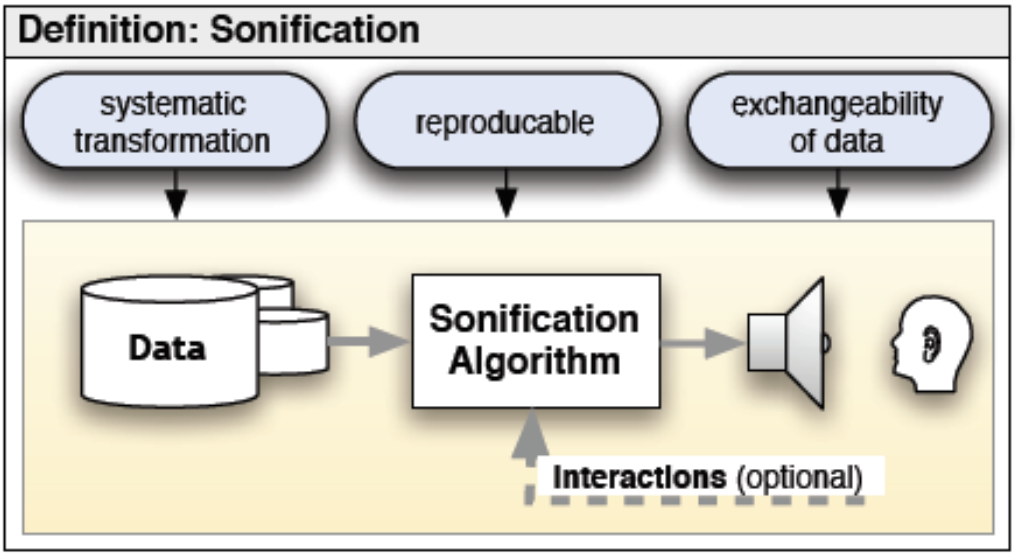


Figure 2.2: Sonification structure (taken from Hermann, 2008)

A sonification system with interaction using HCI provides an extra important benefit as the user can manipulate the data based on their perception of the sonification process. Therefore, a repetitive / loop system is built since the sonification is done interactively.

2.4 Sonification Techniques

In the early years of research into this subject, Auditory Displays were divided into 5 categories, (Walker and Kramer, 2004):

1) Alerts, notifications, warnings
2) Auditory icons
3) Earcons
4) Audification
5) Sonification.

Similarly, as a subset of Auditory Display, Sonification itself can be further classified into 5 types based on the recent book “The Sonification Handbook” (Hermann et al., 2011), as follows:

I. Audification

The simplest technique: play the data directly as a sound waveform (Kramer, 1993). Note that the data has to be waveform-like, and needs to be time-compressed and scaled to make an audible waveform. If the original data form is almost ready to be played - this is the most direct technique. However, audification is usually not an ideal method due to several reasons: the data stream may be too short to be played / it might be very noisy / the data source might not be similar to a waveform.

II. Auditory Icons

An Auditory Icon was defined as *“a sound that provides information about an event that represents desired data”*. This means using non-speech sounds to perform as corresponding events to significant changes in the data (Gaver, 1986). To understand this, a very common example is the use of short sound effects when events are triggered in a computer operating system (e.g. in Microsoft Windows). For example, when a page is being turned in an electronic book, a sound can be played as if two pieces of paper are rubbing against each other in real-life. By hearing this sound, users subconsciously realise what is happening, or the illusion of ‘turning a page’ is made to feel more real by the superimposition of sonic feedback on top of the visual animation.

Auditory Icons traditionally assist graphical interfaces as well as many pioneering interfaces (e.g. wearable devices). With the rapid development of ubiquitous (or pervasive) computing, this method will perform a widely used role to support those new interfaces by giving multisensory feedback.

III. Earcons

An Earcon is also a portrayal of an event. But unlike an Auditory Icon, it does not have a direct acoustic correlate with the event. This is a good thing where it is difficult to find a sound having a close correspondence to the event. For example, in Microsoft Windows the sound effect of telling the user that there is an error during operation is the sound of “musical bang”; and the famous system start-up music is widely recognised by people, yet is not sonically representing a machine starting up.

Earcons are easy to make, with many guidelines (Brewster et al., 1995) for creating them. One possible method is making natural sounds from the surrounding environment (Blattner, 1989). They are also easy to learn, and there are many ways to give users training (Hermann et al., 2011). It is a popular technique when composing an adequate auditory display.

IV. Parameter Mapping Sonification

Parameter Mapping Sonification (also written as PMSon) “involves the association of information with auditory parameters for the purpose of data display” (Hermann et al., 2011), which is excellent for displaying multivariate data. When mapping a data parameter to a sound parameter, in many cases a data trend is represented, which is especially good for statistics, such as using sound to show the trend of stock-market share prices or weather-based parameters such as temperature.

There are three categories of PMSon mapping method:

‘1 to 1’ mapping

This is the simplest and most direct method. If one sound parameter is linked to only one data stream, it is a “1 to 1 mapping” (Fig. 2.3). The sound is used as an analogue of the data. For instance, if mapping temperature to the frequency of sound, the trend of temperature will be given by the audible pitch trajectory.

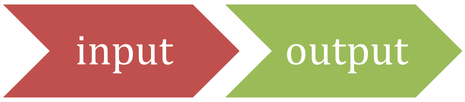


Figure 2.3: 1 to 1 mapping

'1 to many' mapping (also known as divergent mapping)

This means that several synthesis parameters are driven by a single data parameter (Fig. 2.4). It is often used when there are some key values across the entire range which can indicate qualitative change. For example, suppose we have a continuous number order from 1-10, however when the value is between 3.4 and 7.9 this indicates a special case. If mapping this order into sound, two different sound notifications need to be designed apart from the normal scale corresponding to the value of the order.

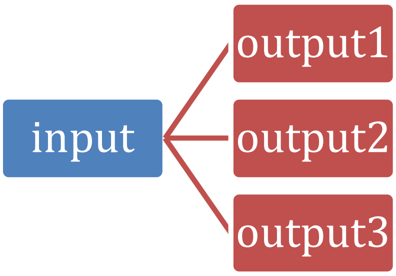


Figure 2.4: 1 to many mapping

'Many to 1' mapping (also known as convergent mapping)

If there are several sources of input data but only one output is needed, the mapping can be considered as 'many to 1' (Fig. 2.5). Many-to-one mappings are commonly found when researching into musical interfaces since sound parameters are usually controlled by multiple human inputs (for instance the pitch of a violin depends on finger position, bow pressure and vibrato modulation).

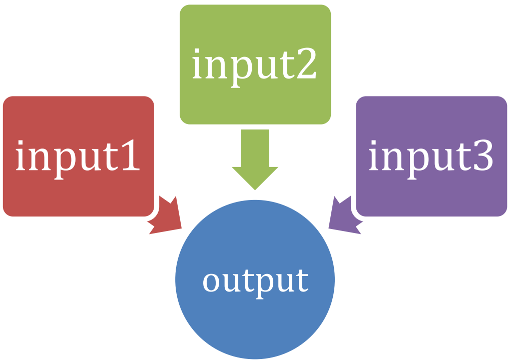


Figure 2.5: many to 1 mapping

Parameter Mapping Sonification is effective in a wide range of applications. Users are able to perceive multivariate data with only one sound, as the sound is comprised of multiple elements: pitch, timbre, etc.; or a valuable piece of information (with many attributes) can be identified by the user due to the same reason.

V. Model-Based Sonification (MBS)

As the name of this method implies, Model-Based Sonification generates a physical model – based on the data. This model works as a medium for the user to interact with and gives sonic responses depending on the user input. MBS was introduced by Hermann and Ritter in "*Listen to your Data: Model-Based Sonification for Data Analysis*" (Hermann and Ritter, 1999). In MBS, sounds are derived from the data, which follow the physical laws applied to the model, rather than converting raw data streams into sound as can be seen in parameter mapping. It can be helpful to think of the following analogy: In PMSon the data is like 'score' which plays an instrument (the sonification algorithm), whereas in MBS the data itself forms the instrument, to be played interactively by the user. MBS is used in variety of applications: musical gesture analysis, data exploration, augmenting human computer interaction, process monitoring and so on. It is particularly useful where there is no obvious time-ordering to the data. In such cases parameter mapping struggles to form the data into a fixed sequence to be played in time, but MBS uses the data complexity to aid the formation of a complex model.

Out of the five techniques of Sonification described above, there is no single optimum method; all methods can work well in their special application areas. Audification and Parameter Mapping are best for time-indexed data; Auditory Icons and Earcons work well for simple/short notifications and alarms; Model-Based Sonification shines through when the data sets are complex. These methods, as a group, show the versatility of Interactive Sonification being one of the most powerful new tools available for researchers wishing to analyse data.

2.5 Applications of Interactive Sonification to Movement Capture

In this section some real-world examples of ISon are reviewed, demonstrating the capability of applying it to achieve effective analysis work for multiple purposes.

(1) Quantifying the effectiveness of interaction
Hunt and Pauletto created and evaluated a system for interacting with an algorithm for the sonification of several data streams. They concluded "*the addition of a relatively high level of interaction to a sonification display improves the efficiency of the analysis of the sonified data*" (Pauletto and Hunt, 2007). The overall auditory analysis experience can be improved by the addition of human interaction. This opens up a whole new field of analysis where movement itself can be monitored and portrayed as sound, allowing eyes-free feedback for real-time human activity.

(2) EMG Sonification
EMG can also be used as a source for the auditory display of data to allow the monitoring of a variety of muscle conditions. Hunt & Pauletto indicated the two advantages of a real-time auditory display for EMG: *"it frees the eyes of the analyst, or the physiotherapist, and it can be heard by the patient too who can then try to match with his/her movement the target sound of a healthy person."* (Pauletto and Hunt, 2006). The second point is really important: patients usually do not understand what the medical examination or physiotherapy procedure is exactly doing on their body; it is as if the doctor is operating 'unidirectionally'. However if patients could hear the sound and map this to the changes of their activity, and the feelings in their body, they might be more interested and willing to cooperate with the therapist, hence enhancing the effect of the medical intervention. Some significant examples are introduced below.

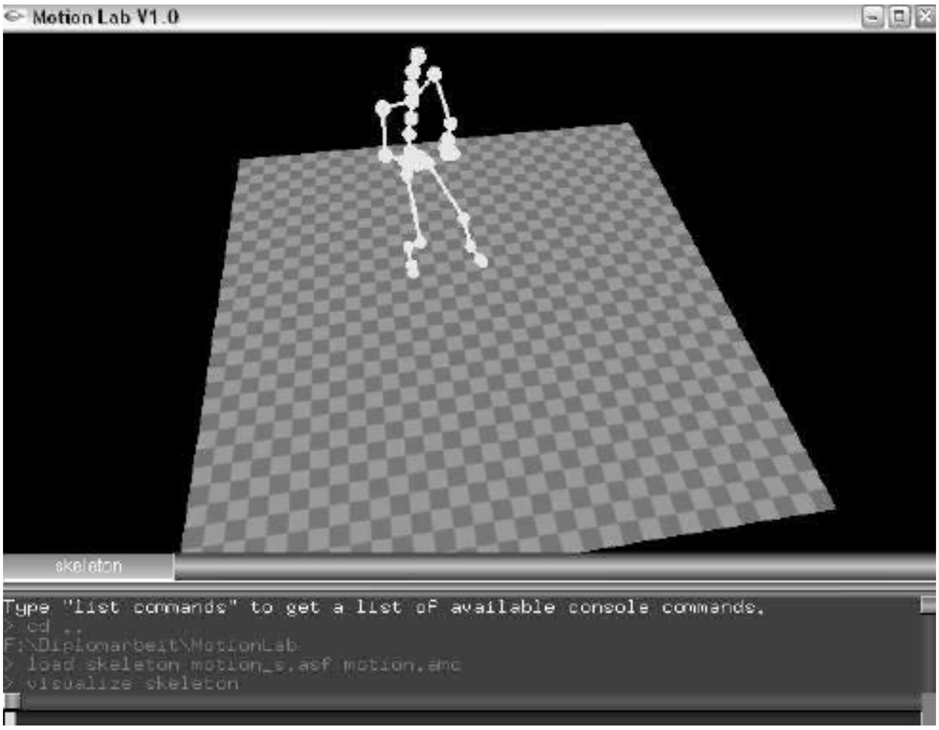
In 2004, John Dixon performed an experiment to compare two muscle groups and the way in which they were synchronized during certain types of physical activity. The aim was to investigate if the onset of EMG activity in a muscle on the upper leg was delayed relative to that of another muscle close to the knee in osteoarthritis patients.

However Dixon's investigation found no evidence of delay. Two years later Hunt & Pauletto took Dixon's data for a new piece of research regarding EMG data and ISon to see if it was possible to map EMG data into sound and then analyse it effectively. They connected EMG sensors with the existing medical ADC (analogue digital converter) and used a computer to run their mapping application written in PureData (Pd). The data was converted to sound via a pre-designed sonification algorithm. As a result, "*The sonification was found to be effective in displaying known characteristics of the data. The "roughness" of the sound's timbre was found to be correlated to the age of the patients*" (Pauletto and Hunt, 2006). Figure 2.6 shows the clinical set-up for gathering data. These experiments also showed that Dixon's original hypothesis was correct – that there was in fact some phase delay between the firing of the different muscle groups.

Figure 2.6: Data gathering for EMG Sonification

(3) MotionLab

ISon systems can be used effectively for the portrayal of human body movement data. Alfred Effenberg has worked with elite athletes for many years, and has discovered the benefits of using sonification as an effective feedback system. He developed a program called 'MotionLab Sonify', which is *'a framework for the sonification of human motion data'* (Effenberg et al., 2005). It is used for analysing kinematic movements, and mapping them into sound. The movement is captured by the Vicon motion-tracking system which generates a real-time motion capture data stream from a series of precisely aligned high-definition cameras. Markers were put on the athlete's body to enable the rendering of a virtual kinematic skeleton which is shown on a visual display (see Fig 2.7). With this framework "*a large number of different problems in sport science, sports and rehabilitation can be explored and treated in an advanced mode*" (Effenberg et al., 2005). This shows us that we can pay special attention to the human perceptual system, and to the use of multi-modal displays, in portraying complex real-time movement.



```
Type "list commands" to get a list of available console commands.
> cd ..
F:\Diplomarbeit\MotionLab
> load skeleton motion_s.asf motion.amc
> visualize skeleton
```

Figure 2.7: MotionLab showing the 'skeleton' calculated from cameras

(4) Aerobic Exercises

Hermann and Zehe introduced a method for measuring body movements (Hermann and Zehe, 2011). Wearable goniometers collect data and send it to a computer via Bluetooth. A computer program was developed for rendering data sonifications in which pre-recorded data and real-time data are both accepted. This system can sonify "*coordinated body movements for a single performer, as they occur in physical exercises and particularly in aerobics*". Figure 2.8 shows the user interface of the system which synchronises the data playback and the recorded video, allowing playback control and real-time adjustment of the mapping functions. Users found that when using the system they were able to do the movements more effectively.

level: -6
pos: 0
rate: 1
198

Figure 2.8: User interface of Hermann's system

(5) Elite Swimmers

Alfred Effenberg was convinced that there may be additional information from the Vicon camera system which could not be detected visually. Indeed in some of his work with Schmitz studying elite swimmers, he discovered (using sound only) some very subtle differences in the dynamic motion of the best swimmer, which enabled him to quantifiably improve the performance of the whole team.

Figure 2.9 from Schmitz-Effenberg experiment shows that *"in the congruent condition frequency and amplitude modulations of electronic sounds represented changes in the relative distance between the wrist joints or the ankle joints to the center of the pelvis"* (Schmitz et al., 2013).

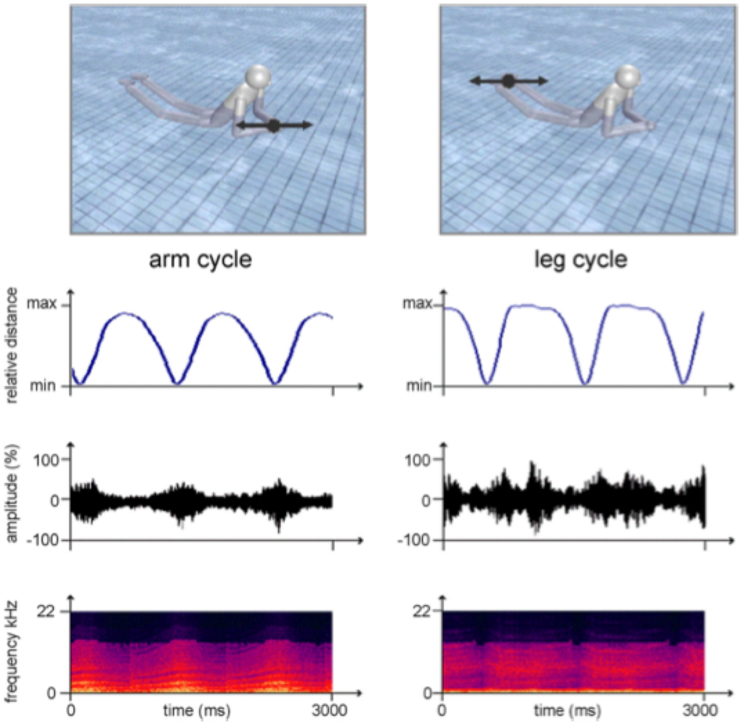


Figure 2.9: Kinematic-acoustic mapping (Schmitz et al, 2013)

(6) Rowing sonification

The system “Sofirow” (Schaffert et al., 2010) can also be used for the sonification of on-water training sessions, particularly for determining the quality of a rowing stroke (see Figure 2.10).

Figure 2.10: Sofirow system (Schaffert et al., 2010)

The experiment showed that certain errors in rowing-stroke action, which could not usually be measured or perceived, can be found through sonification. This allows athletes to correct their actions in real time using the detailed information fed back from their actions.

(7) Feedback system for instrumental practice

As an audio-based technology, ISon would seem a likely candidate for the analysis of musical-related data. However, in practice, visualisation methods tend to be chosen for learning musical skills, and interactive sonification methods are barely considered. A reasonable explanation is that people cannot concentrate on two sounds at the same time. But if we can fit the feedback sound *into* the musician's sound, the ISon approach might be more likely to be adopted. With this concept shown in Figure 2.11, Sam Ferguson described an ISon system for giving feedback to a musician for their instrumental practice. "*The system acts to provide the musician knowledge of their results, in turn associating their actions directly with their musical results and thereby developing muscle memory and technical musical skills.*" (Ferguson, 2006).

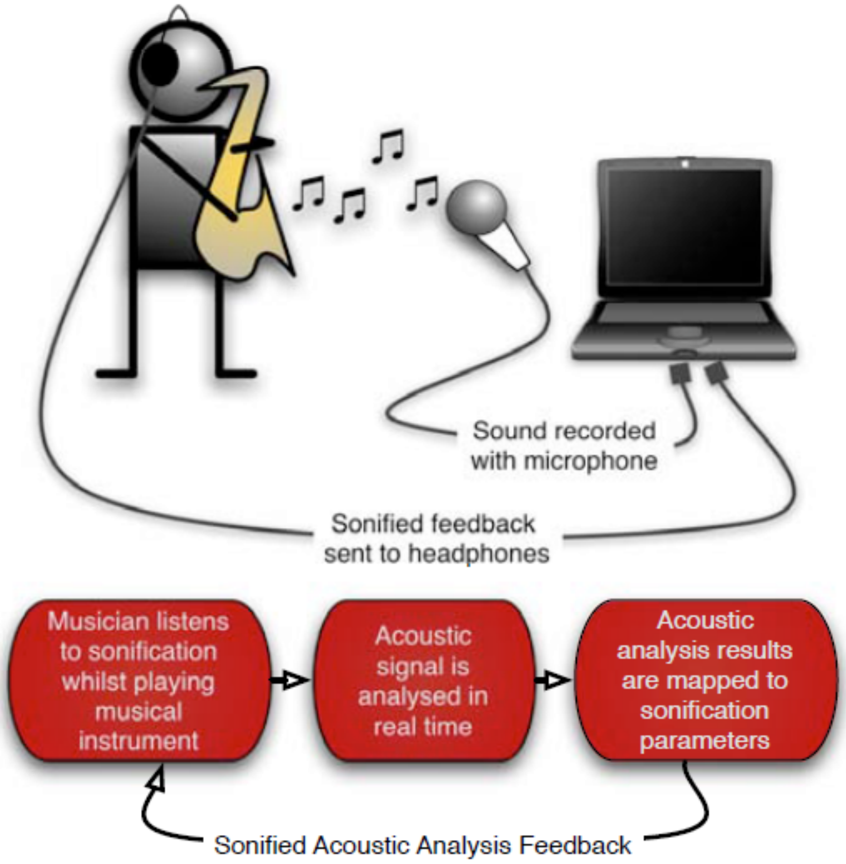


Figure 2.11: Concept of Ferguson's system

2.6 Discussion

The applications given above show great usability of applying Interactive Sonification on movement capture, despite most of the applications are not targeting general public. This research indeed is interested in human actions / movements, hence it is very natural to think of using ISon as the tool for analysing the status of muscles during actions. Even better is, with the backing of development of small sensor and wearable technologies, it becomes more and more convenient to make portable / wearable devices for sound feedback, and these kind of devices will be more and more affordable. The mobile app market (e.g. Apple iOS app store) is quickly growing, catalysing easy-use programming language such as Apple Swift for app development, as well as making mobile device to be a terminal of various functions in daily life pervasively.

Yet, in this particular research, especially when the focus is finally on piano players, ISon can have a few limitations. First thing to consider is whether piano players can accept playing piano with ISon device attached on them, not only because it definitely reduces comfort, but also it does not sound ideal to disturb piano players using feedback sound when concentration is generally needed. Meanwhile, any sound has one or multiple “pitch”, which can affect the piano sound perception more or less depends on people; it is unknown that whether this factor can actually influence muscle tension if it does indeed.

Although there are limitations, the advantages of using sound feedback over visual feedback is obvious: it frees eyes which are needed for looking at music scores; piano players can concentrate more on playing music without being distracted from the necessity of looking at the visual thing regularly; using sound can achieve real “real-time” feedback of muscle tension as aimed by this research, as well as mentioned in the hypothesis.

2.7 Conclusion

This chapter has summarised the fields of Auditory Display and Interactive Sonification (ISon). The advantages of ISon have been explored, and it seems that in recent years there has been a blossoming of research applications which utilise this technique to yield new insights into complex and real-time data. Also, possible limitations are mentioned in this chapter. An area of special focus is the use of sound to feed back information on human movement *as the actions are performed*. This has multiple applications in sports and exercise monitoring, and music performance supervision, both of which have been features of the research described in this thesis.

In the next chapter, we see the introduction of piano-related injuries and a possible way for prevention – using surface EMG for biofeedback.

Chapter 3 Piano Related Injuries & Biofeedback

3.1 Introduction

Nowadays uncountable children start learning piano when they are very young, in addition to the many adults who begin to learn piano at various ages. The piano is one of the most popular instruments across all levels of music tuition. Elite pianists have to undertake intense levels of practice, and these high physical loads can lead pianists to a range of Playing-related musculoskeletal disorders (PRMD). PRMD to the pianist is like RSI (work-related musculoskeletal disorders) to office workers.

This chapter describes what PRMD is, followed by the biofeedback section which explains the Electromyography (EMG) used for obtaining biofeedback in this research.

3.2 Problem of Musicians: Playing-Related Musculoskeletal Disorders (PRMD)

Instrument-related arm and hand injuries have been annoying musicians for more than a century (Harman, 1982). However, there are not many etiologies available because the relationship between injuries and bad technique / improper training has not been confirmed by much scientific evidence (Ziporyn, 1984).

The definition of PRMD was given through qualitative research by Zaza, Charles and Muszynski where PRMD is considered to be serious problems by musicians: *"...pain, weakness, lack of control, numbness, tingling, or other symptoms that interfere with your ability to play your instrument at the level you are accustomed to"* (Zaza et al., 1998). This definition reflected the musician's perspective. As a result, the characteristics and meaning of PRMDs to musicians were figured out as below:

a) PRMDs affect playing

As people can imagine, PRMD has a bad effect on playing, mainly by distracting musicians from the concentration needed to play an instrument. Musicians will not notice or admit the problem until they really feel the pain is affecting their playing. In particular, if aches or pains do not affect playing, it is not a PRMD.

b) PRMD symptoms are chronic

This is the most commonly described characteristic of a PRMD. Musicians feel if symptoms do not go away, they would consider them to be a problem. However, before the problems are considered chronic, the duration of the problem varies – it can be over weeks or months that symptoms occur.

c) PRMD symptoms are severe

PRMD symptoms are often described by strong words such as “burning”, “excruciating”, “shooting pains”, “spasms”, and “incapacitating” by musicians. By contrast, “just”, “mild”, “little”, “slight” are usually used to describe pains and aches that are not PRMDs.

d) PRMD symptoms are unusual

Musicians describe PRMD symptoms and their effects on playing as abnormal and unusual, unlike typical pains and aches.

e) PRMDs are determined by the individual

PRMDs are identified subjectively by the individual musician rather than by objective means. Some musicians describe that PRMD is a personal thing that they notice changes in their performance ability such as not being able to play as fast as before.

f) PRMDs are beyond the musician’s control

Musicians do not have the ability to control the symptoms as shown in the experiment by Zaza et al.. Many musicians define this as a characteristic of PRMDs; many claim that they will be aware of a PRMD if they cannot control the symptoms.

The debate among health professionals regarding work-related musculoskeletal disorders still remains, but the consistency in the experience of PRMDs and work-related musculoskeletal disorders is clearly shown in Zaza et al.'s research. Therefore the PRMD warrants great attention to reduce its debilitating effects.

3.3 PRMD for piano players

Injuries are reasonably widespread among pianists since playing piano is a repetitive task where the hands and the arms are used, involving various kinds of movements. It is common to increase muscle tension by focusing on playing the right notes and getting the correct sound. Even some of the greatest pianists cannot avoid this: Leon Fleisher; Ignaz Friedman; Alexander Scriabin; Wanda Landowska; Gary Graffman; Artur Schnabel… (Lim, 2014). In fact, research by Bragge et.al suggests that PRMD is a substantial problem amongst pianists, where PRMD is associated with muscle tension and increased levels of stress (Bragge et al., 2006). In 1988 Revak distributed a questionnaire to 71 piano students in 7 Philadelphia area music schools in Pennsylvania, *"42% of the respondents reported experiencing discomfort that lasted more than one week and 87% of students suspended practice for a period of time or made adjustments at the piano. Pain/aching was the predominant discomfort reported among students*" (Revak, 1989). Similarly, Furuya et al. surveyed 203 senior pianists and discovered that *"77% of these pianists suffered from PRMDs in at least one of their body portions, and 44% of these were serious enough to warrant medical treatment"* (Furuya et al., 2006).

These examples show that PRMD is widespread among piano players.

One main source of stress comes from sustained intense practice of advanced piano techniques. Allsop and Ackland's undertook a set of comprehensive experiments for finding out the prevalence of PRMD in relation to playing techniques and practicing strategies. In their report, 214 (42.4%) of the total 505 respondents experienced PRMD; also a higher proportion of professional musicians (71.9%) reported PRMDs in comparison with 38.1% of non-professionals. For the statistics of piano techniques, *"96 respondents reported that PRMDs were associated with specific piano techniques and exercises; 59 respondents reported the occurrence of PRMDs when playing octaves, 27 when playing fast passages, 20 when playing chords, 20 when playing* *fortissimo, 13 when playing arpeggios, 11 when playing trills, 11 when playing scales, two when playing polyphonic music and one when playing pianissimo."* (Allsop and Ackland, 2010).

There is more than one "correct" hand posture, however, there is a lack of scientific information regarding how PRMD is related to the use of different hand postures. As a consequence piano teachers cannot point to any specific evidence for recommending to their students which posture should be used to prevent PRMD. Worse still there are different schools (Russian, French, etc.) using different theories to promote different hand positions (see Figure 3.1).

Figure 3.1: Three different techniques (Allsop & Ackland, 2010)

Also when looking at hand postures of some greatest pianists (Figures 3.2 - 3.5) (Labrande and Sturrock, 1999), the differences of their playing style are quite noticable. However this does not seem to be a handicap for achieving virtuosity – clearly they have all mastered piano techniques.

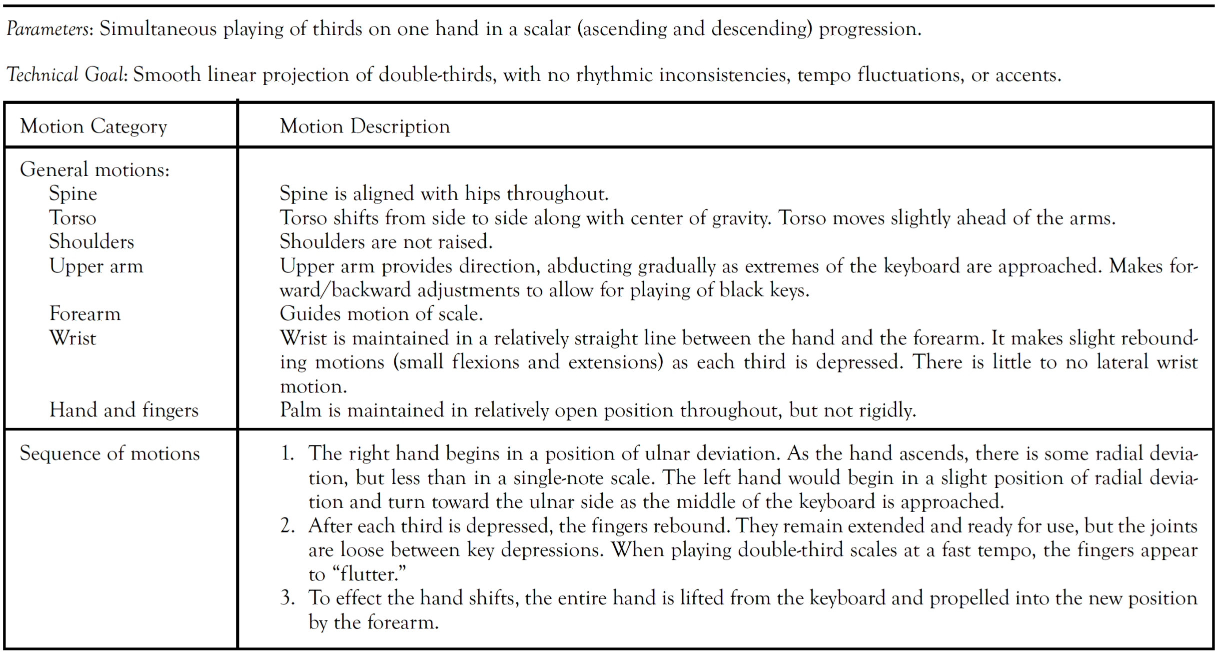
Figure 3.2: Wanda Landowska

Figure 3.3: Vladimir Horowitz

Figure 3.4: Claudio Arrau

Figure 3.5: Gyorgy Cziffra

In 2000, B. Wristen proposed a theoretical procedure for biomechanical analysis of piano technique for developing an injury-preventive technique. In that research 7 piano techniques were assessed: scales, arpeggios, trills, double-third scales, octave scales, broken chords and broken octaves. Subjects were asked to play pieces containing these techniques whilst their playing was observed and compared to the motion patterns formatted into checklists (see the example of double-third scales in Fig. 3.6). Eventually, based on the analysis a few recommendations for preventing injuries were suggested, including "never practice through pain", and "avoid suddenly increasing the time and/or intensity of practice”. However, for long-term monitoring, it is nearly impossible to find an exclusive analyst who can observe the playing every single time for all individual piano players; therefore a system that can be operated by the players themselves will be a better medium for observation.



Parameters: Simultaneous playing of thirds on one hand in a scalar (ascending and descending) progression.

Technical Goal: Smooth linear projection of double-thirds, with no rhythmic inconsistencies, tempo fluctuations, or accents.

Motion Category	Motion Description
General motions:	
Spine	Spine is aligned with hips throughout.
Torso	Torso shifts from side to side along with center of gravity. Torso moves slightly ahead of the arms.
Shoulders	Shoulders are not raised.
Upper arm	Upper arm provides direction, abducting gradually as extremes of the keyboard are approached. Makes forward/backward adjustments to allow for playing of black keys.
Forearm	Guides motion of scale.
Wrist	Wrist is maintained in a relatively straight line between the hand and the forearm. It makes slight rebounding motions (small flexions and extensions) as each third is depressed. There is little to no lateral wrist motion.
Hand and fingers	Palm is maintained in relatively open position throughout, but not rigidly.
Sequence of motions	1. The right hand begins in a position of ulnar deviation. As the hand ascends, there is some radial deviation, but less than in a single-note scale. The left hand would begin in a slight position of radial deviation and turn toward the ulnar side as the middle of the keyboard is approached. 2. After each third is depressed, the fingers rebound. They remain extended and ready for use, but the joints are loose between key depressions. When playing double-third scales at a fast tempo, the fingers appear to “flutter.” 3. To effect the hand shifts, the entire hand is lifted from the keyboard and propelled into the new position by the forearm.

Figure 3.6: Checklist for double-third scales (Wristen, 2000)

3.4 Some examples of piano techniques that may cause PRMD

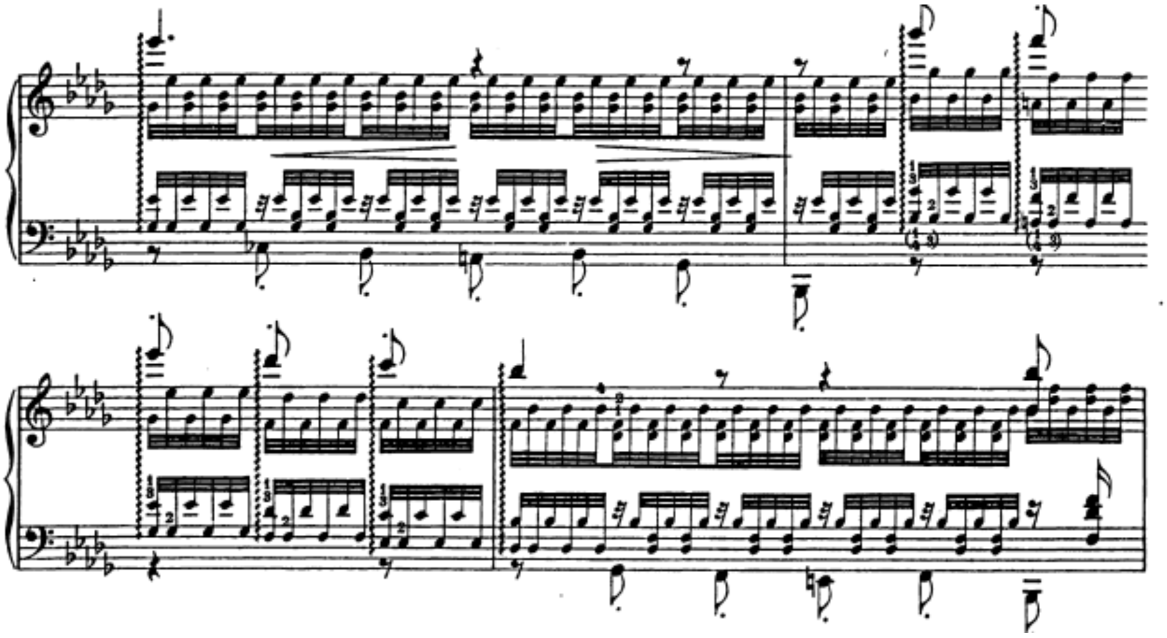
Claudio Arrau, one of the greatest pianists in history said: *“If you keep your body relaxed, the body is in contact with the depth of your soul. So if you are stiff in any joint, you impede the current, the emotional physical current, the music itself dictates to you. If you have stiff joints, you don’t let it come through into the keyboard.”* (“The Art of Piano - Great Pianists of 20th Century” [DVD], Sturrock, 1999).

However most people cannot keep relaxed all the time, as Arrau suggests, especially when playing pieces of virtuosity or working hard to keep playing the correct notes. Below are some examples of techniques whereby muscles will easily become tensed when practicing, and the subsequent tension has a negative effect on the practice quality. This also corresponds to the research of Wristen and Allsop et al., which was mentioned in the previous section. All examples are captured from the IMSLP Petrucci Music Library (Guo, 2006).

(Sound examples are provided with the accompanying disk).

1. Octaves: Etude op.8-12 (Scriabin)

2. Double-thirds trills: Chasse Neige (Liszt)



3. Scales: Mazeppa (Liszt)

4. Broken Chords: 3rd Piano Concerto (Rachmaninoff)

5. Leaps: 2nd movement of Fantasy op.17 (Schumann)

6. Doubles: Feux Follets (Liszt)

7. Arpeggios: Piano Sonata op.57 (Beethoven)

3.5 Biofeedback – EMG

3.5.1 The purpose of using biofeedback

“Biofeedback” was described as *“techniques using instrumentation to give people information about a specific physiologic process which is under the control of the autonomic nervous system, but not clearly or accurately perceived”* (Gartha, 1976). However, this definition had been developing over years, until year 2008 an official definition was developed by AAPB[5]. This latest definition emphasises the point of giving a user additional "control". The 2008 official definition of biofeedback is: *“Biofeedback is a process that enables an individual to learn how to change physiological activity for the purposes of improving health and performance. Precise instruments measure physiological activity such as brainwaves, heart function,*

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[5] The Association for Applied Psychophysiology and Biofeedback (AAPB) was founded in 1969 as the Biofeedback Research Society. https://www.aapb.org/

breathing, muscle activity, and skin temperature. These instruments rapidly and accurately feed back"information to the user. The presentation of this information — often in conjunction with changes in thinking, emotions, and behaviour — supports desired physiological changes. Over time, these changes can endure without continued use of an instrument.("Schwartz and Andrasik, 2017)

A common purpose of using biofeedback is for actively improving health. The instruments of biofeedback can monitor heart rate, muscle tension, blood pressure and so on, so that people can choose what to do based on the information.

Piano players may not be aware of injury until it becomes a big problem, especially when during daily practice they may not notice the tension of muscles when concentrating on playing the right notes. Seeking treatment after suffering from PRMD is a passive reaction to a chronic injury, whereas using a possible tool to observe tension in real-time to prevent or minimise PRMD would be a more proactive approach, which could potentially save much suffering. Normally it is not possible to monitor muscle activities by the human players themselves, so a system of biofeedback would be the proper tool to achieve this.

3.5.2 Surface EMG

EMG (Electromyography) is “a technique for evaluating and recording the electrical activity produced by skeletal muscles” (Kamen and Graham, 2004). Electrical potential is generated whenever a muscle is activated. Sensors are placed on the surface of the skin and connected to a machine called an *electromyograph*, which is used to produce a visual representation of electric potential generated by muscle cells when they are activated - a suitable instrument for biofeedback. EMG is typically used for medical purposes, using sensors (for collecting data from muscles) that are sensitive enough to allow any abnormal activities to be easily detected.

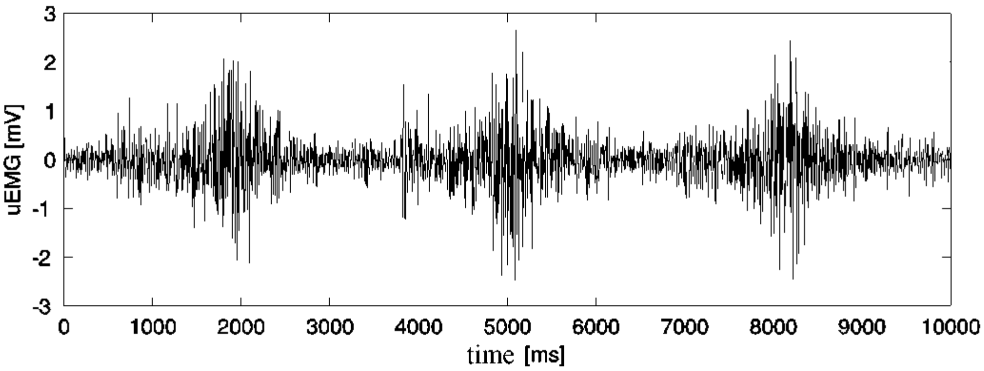

Figure 3.7: EMG signal data[6]

Figure 3.7 shows an example EMG signal. The ‘thick horizontal line’ across the centre is called the baseline, and represents the electrical value when the muscle is relaxed. It is important to check the baseline before any EMG measurement. The quality of results can be improved by using a high quality EMG amplifier that reduces the noise.

There are two main methods of measuring EMG: surface EMG (abbr.: sEMG, where only muscles close to the surface of skin can be detected) and intramuscular EMG (where deeper muscles which are covered by surface muscles or bones still can be detected). The latter method uses a fine wire electrode inserted into the muscle (see Figure 3.8), which can cause pain and impede movement; whereas the former method is more patient friendly and easier to administer as it uses only silver/silver chloride pre-gelled electrodes to stick on the skin (see Figure 3.9) close to the active muscle.

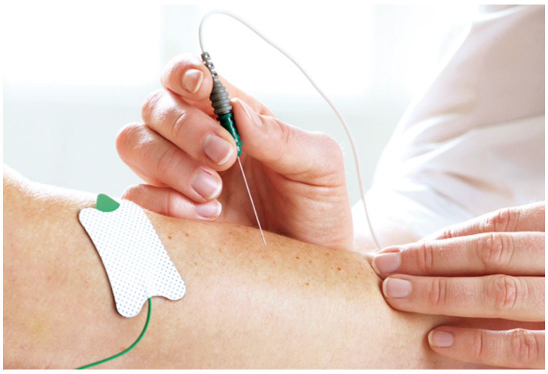

Figure 3.8: Needle electrodes[7]

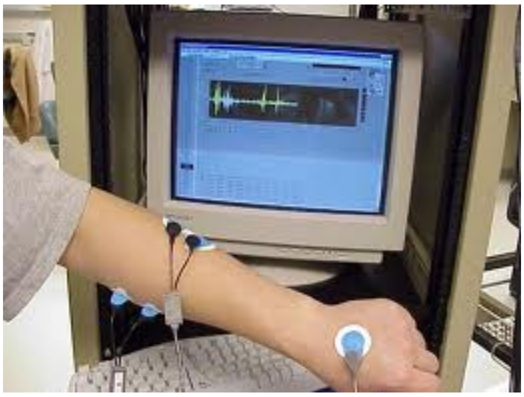

Figure 3.9: Surface electrodes[8]

Surface EMG is more widely used than intramuscular EMG because it is a safe, non-

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[6] http://www.intechopen.com/source/html/19664/media/image2.png

[7] http://www.ambu.com/Files/Billeder/Product%20Images/Media/PMD/ConcentricMedia2.jpg

[8] http://3.bp.blogspot.com/_SIl46YOSYD4/TICooDF0FyI/AAAAAAAAAuY/hGIRPPVQDBM/s400/EMG.jpg

invasive, easy way to allow objective quantification of muscle energy without causing pain or discomfort. It also enables EMG to be used by general users and researchers. The servant of the biofeedback field has been surface EMG for long time. In the mid-1600s Francesco Redi discovered that the energy of the electric ray fish comes from a specialised muscle (Criswell, 2010), which shows that the study of muscle voltages can be traced back very early. Practitioners use EMG feedback for treating disorders and symptoms such as tension headaches and tension myalgias, etc. *(Schwartz and Andrasik, 2017)*

While surface EMG has great advantages, there are several external factors that can influence the EMG shape and characteristics. These are summarised below (Konrad, 2005):

a) Tissue characteristics

The electrical conductivity varies with human body tissue properties including thickness, type, physiological changes and temperature. For example if the fat layer is very thick, the connection between EMG electrodes and skin will be poor.

b) Physiological cross talk

Neighbouring muscles can produce signals that are detected by the electrode on the muscle under study. Also the thick fat layer increases cross talk from other muscles (Kuiken et al., 2003). Usually though the cross talk does not exceed 15%.

c) Changes in the geometry between muscle belly and electrode site

The EMG reading can be changed by the shift of distance between signal origin and detection site.

d) External noise

In noisy electrical environments, there is direct interference of power hum, which is usually created by wrong grounding of other devices.

e) Electrode and amplifiers

The internal amplifier noise and the quality of electrodes may add unwanted signals.

Over the last few years, EMG method using multiple surface electrodes becomes more and more popular. In 2004, Nakajima et al did the first study of using a multi-surface electrode on forearm to estimate EMG-CT, providing a new view in EMG studies. Its experimental procedure is shown in Figure 3.10:

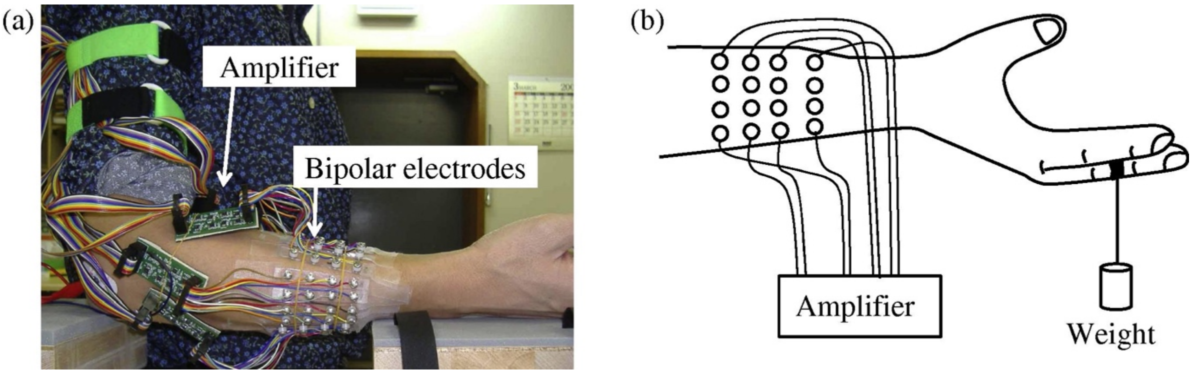

Figure 3.10: Multiple surface electrodes

The forearm is placed on a flat table, with elbow joint flexed at 90 degrees, a weight was hung on the middle finger. 20 custom-built electrode plates are attached on forearm for recording the sEMG signals. As a result, the position of active muscle during the contraction are shown clearly, which can be seen that the muscle activities are unevenly distributed, with the positions of activated muscle consistent with the position of the muscle area from MRI, hence muscle activities were computed from the sEMG signals. The results were also verified by physical experiments. The novelty of this method is that “the active muscle area can be located non-invasively during contraction”. (Nakajima et al, 2014)

Another example is recently developed “Myo Gesture Control Armband” by Thalmic Labs[9]. It is a wearable gesture / motion control device allowing people to take control of phones, computers and so on. 8 EMG sensors are equipped with the MYO armband, take responsibility of recognising and performing gestures. The MYO also uses Bluetooth for the connection. (Fig 3.11)

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[9] https://www.myo.com/

Figure 3.11: MYO armband[10]

3.5.3 Signal processing

To optimise the EMG raw signal so that more useful information can be gathered from it, the following signal processing methods can be applied as examples (Konrad, 2005):

a) Rectification (Fig 3.12)

All negative amplitudes are converted to positive amplitudes as the first step, so the negative waves are moved up to plus by the baseline. Now that not only the signal can be read easily, but the curve of the signal can also be applied with standard amplitude parameters such as mean, peak value, while the mean value of raw EMG signal is always “0”.

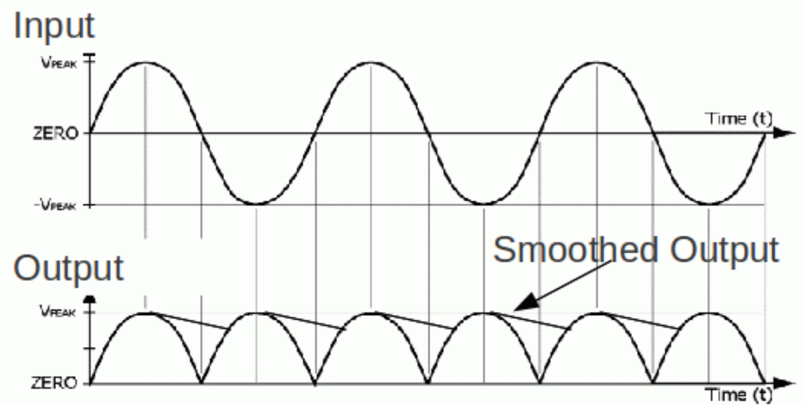

Figure 3.12: Full wave rectification[11]

b) Smoothing

There are two algorithms established for smoothing the signal, “Moving average” and “Root mean square”. Both algorithms can build a linear envelope of the signal.

c) Digital filtering

Additional digital filters may be applied in certain situations. As an alternation of the two smoothing algorithms mentioned before, a low pass filter at 6Hz can also be used to create a linear envelope. The benefit from this is mainly reduce possible phase shift. For fine wire studies, instable contact between probe and skin can happen, in

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[10] http://i.huffpost.com/gen/1910669/images/o-MYO-facebook.jpg

[11] https://astarmathsandphysics.com/o-level-physics/full-wave-rectification-html-cb6b316.gif

this case a high pass filter (20-25Hz) can be applied to stabilise the baseline shifts.

3.6 Conclusions

This chapter has given an outline of Playing-Related Musculoskeletal Disorders (PRMD) for piano players, and listed some piano techniques which might cause PRMDs. There is certain urgency of preventing PRMD among piano players. Using surface EMG (a safe, easy way to monitor muscle signals) as well as making proper response might be a good solution to what can be a severe problem.

Chapter 4 Research Methodology

4.1 Introduction

This chapter describes the research methodology used in this research. The hypothesis is restated, then the research objectives are described, and the experimental design and data analysis are explained.

4.2 Main focus of PhD

This research aims to seek possibilities of building a system to give some aid to people in order to reduce the chance of suffering from RSI.
Therefore, there were 4 categories of people this research was particularly interested, they are piano players, office typists, mobile phone users and badminton players. In the early stages, this research investigated how sound could be used to monitor tension which is extensively involved in activities of all 4 categories of people, and thus via feedback to release it.
So, the initial hypothesis is:

"By using Sonification feedback it is possible to inform keyboard users, (e.g. piano players or office typists) of activity which could otherwise cause long-term injury."

Please note the badminton players are not even mentioned in the initial hypothesis because at the stage of thinking the initial hypothesis, some ideas and small test were carried on and showed that doing badminton route may not be a good idea because most of the test results were negative, this will be explained in the next chapter, pilot study. And then after the pilot study, it became clear that a full test of this hypothesis would be almost impossible to carry out because the experiments on piano players would need to have prolonged sessions (a few hours) as well as long period tracking (a few months to years). Also during multiple initial tests on QWERTY keyboard

users, only very little bad effect (discomfort) could be seen from purely typing activity, no matter how fast they typed or for how long.
So, as stated in chapter 1, the main hypothesis of this research is finally shrunk into:

"By using Sonification feedback it is possible to inform piano players of muscle tension in real-time, which will allow them to reduce tension".

The principal aim is to find out if Sonification feedback can provide useful information for piano players to let them reduce tension actively. On the basis of the hypothesis, a real-time sonification system was developed to monitor the muscle tension during piano playing.

4.3 Points summarised from the literature review

Chapter 3 discussed the situation that injuries are widespread among pianists since playing piano is a repetitive task where the hands and the arms are used, involving various kinds of movements, therefore it is going to be useful to build a system if can offer some help to deal with those muscle problems. In this particular research, especially when the focus is finally on piano players, ISon can have good advantages despite there are limitations. It does free subject's eyes and mind, can give real-time feedback from muscle status through feeding alert sound into human ears.
There are a few things need to be considered when design the feedback sound, such as how to minimise the bad influence on piano playing activity; does the pitch of the sound produce discomfort of human ears especially to people have absolute pitch perception, etc.

4.4 Research Objectives

The objectives of this research are listed below:

- Finally aim to piano players, for both amateur and elite players.

- The development of a real-time sonification system. The system should be able to reflect muscle tension as well as produce appropriate sound to give piano players feedback to encourage them try to actively relax.
- Design experiments to achieve sonification and put the hypothesis into a trial.

4.5 The Experiments – an overview

The first experiment was an initial study focusing on the final route chosen (piano players), it also examined the effectiveness of the whole system. Useful suggestions and information were gained and used for making improvements.

Next was the main experiment. An updated system was made based on the feedback from the pilot study. At least 16 people were chosen as subjects (as it is widely believed that by choosing 16 people, the effectiveness can achieve 90%[12]).

As mentioned in the previous chapters, amateur piano players often find it hard to improve their technique because it is too troublesome to concentrate on both reading the score and paying attention to their body and hand postures simultaneously; for elite piano players, PRMD is always a potential serious problem, therefore the proposed system could be used for monitoring muscle tension to make an alarm sound to remind players when too much tension is occurring. Considering the above, two different groups are set: professional/elite pianists and amateur piano students (as well as piano hobbyists). Each group had the same setup so that we could evaluate how the system performed on different user groups.

4.6 Data Analysis

The concept of this research is to see whether an interactive sonification system allows piano players to monitor and thus reduce muscle tension. Therefore, the

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[12] Jacob Nielsen in https://www.nngroup.com/articles/how-many-test-users/ argues that most qualitative tests yield most significant user comments by as little as 5 users. As test subject numbers increase there is a decreasing return of problems and insights discovered. For newer or more complex situations 15 subjects is seen as a number beyond which few truly new insights are discovered.

following attributes were recorded:

- Time of a single experiment session
- Music repertoire used in the experiment
- The piece(s) of muscle to be monitored
- Average muscle tension of the session
- Peak muscle tension of the session.

Then, a statistical analysis is going to be carried, such as paired t-tests to examine whether the system can make difference after applying them on subjects of different groups.

4.7 Conclusion

This chapter briefly summarises the research methodology adopted in this research, including how the hypothesis has been developed, what important information has been summarised from the literature, and the objectives of this research as well as an overview of main experiments.

Chapter 5 Practical Development

5.1 Introduction

This chapter describes in detail the sonification system developed especially for this PhD in terms of both hardware components and software design.

5.2 System Overview

The concept of the whole system is shown in Figure 5.1, and the details are explained in the subsequent sections.

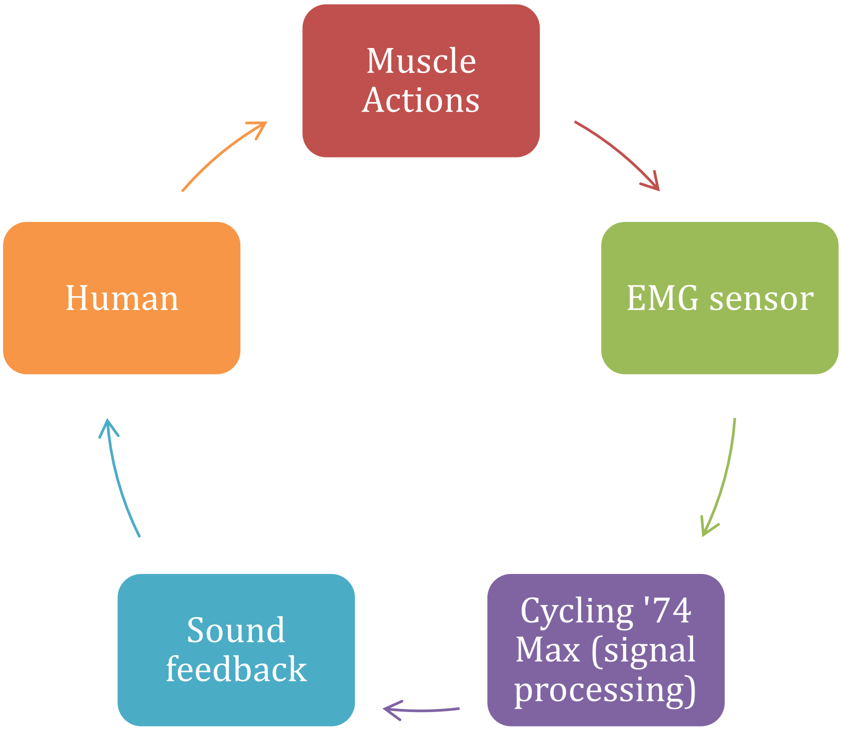

Figure 5.1: System structure

Figure 5.1 shows the circulatory way that the system works. When human use their muscles for doing activities, myoelectrical signals are produced and are captured by the EMG sensors connected to the skin above the muscle. Meanwhile the software "MAX" processes the signals into quantised data as the input to generate sound feedback to inform the human, subsequently letting them change their activities. These changes in turn influence the signal and the whole cycle begins again.

The system hardware is shown in Figure 5.2, which has been designed especially for this work, and is assembled with several components (listed in Figure 5.3) which are explained in the next section. This system is used for measuring the myoelectrical signal produced from the muscle activations. This figure also shows the visual appearance of the kit for experiments. From this figure a transparent acrylic box with two batches of wires extending out can be seen. The enclosure is easy to disassemble for convenience of operating inside the box, such as changing batteries or debugging the Arduino board.

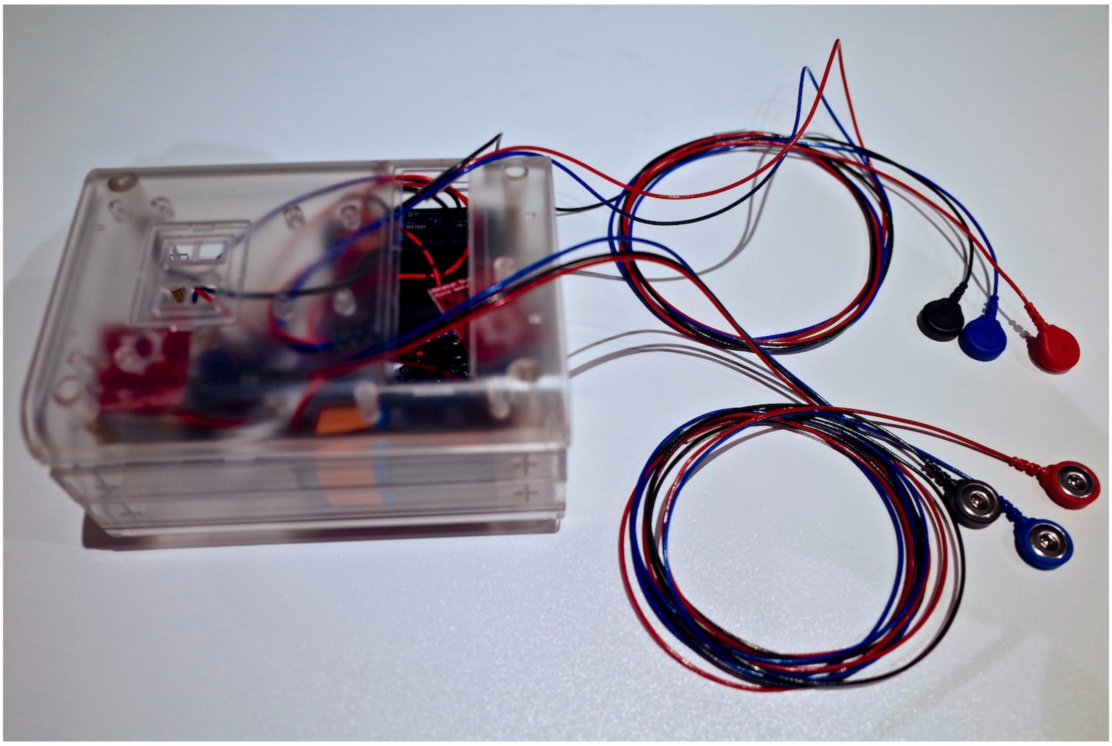

Figure 5.2: The system hardware

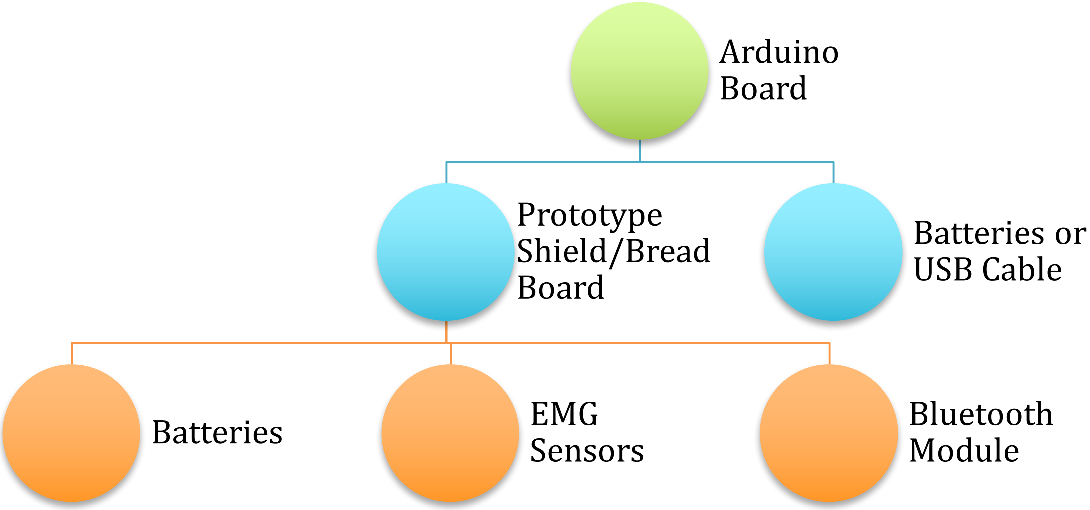

Figure 5.3 System structure

As shown in the figure above, a prototype shield with a bread board attached is stacked directly onto the Arduino board with all slots are inserted by corresponding from the Arduino board. The Arduino board can be powered optionally by a 9v battery if using Bluetooth (the Bluetooth module is connected on the shield), however another two 9v batteries are required to power the EMG sensor. The electrodes which are used for gathering myoelectrical signals are connected to the sensor by specially made cables; there is a standard 3.5mm jack for unplugging electrodes from the sensor more easily.

5.3 The Hardware Components

This section gives background details of the hardware used in the system.

5.3.1 Arduino

Arduino [13] is an open-source electronics prototyping platform which includes extensive choices of hardware board coupled with its exclusive programming language. On the hardware board a microcontroller is programmed by the Arduino

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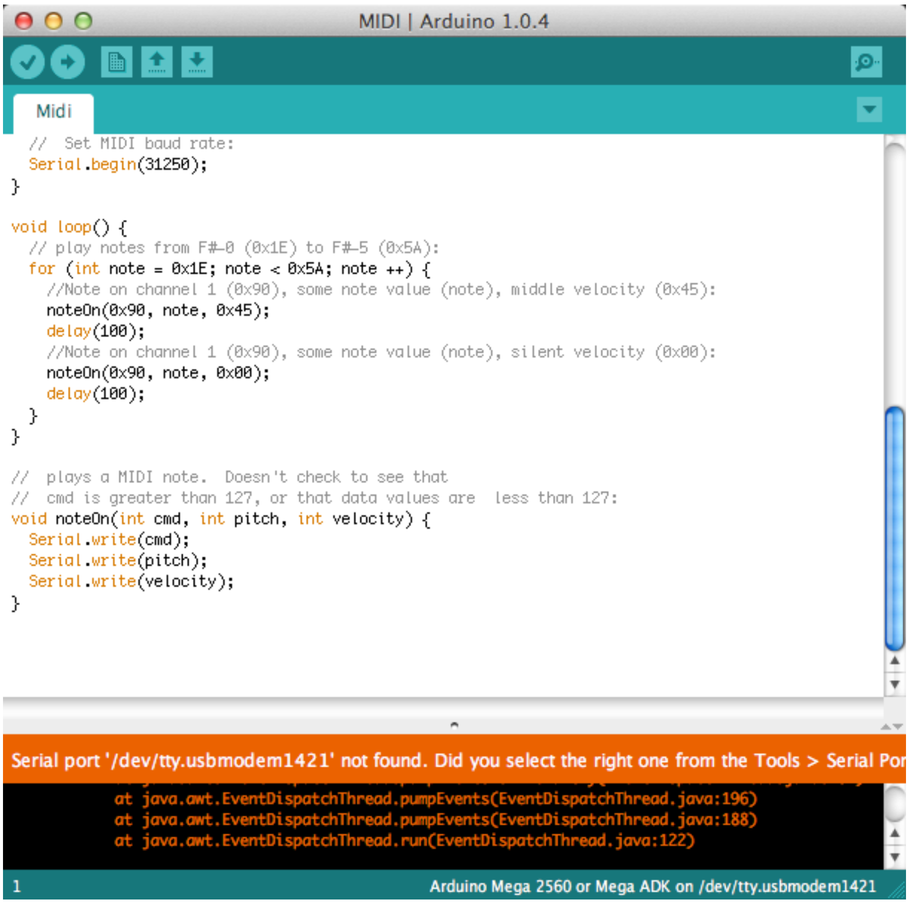
[13] https://www.arduino.cc/

programming language, which is based on "Wiring", an open-source electronics prototyping platform[14] (see Fig. 5.4). The Integrated development environment (IDE) of Arduino is based on the Processing[15] language (explained in chapter 5.4.1 later): it is based on a code editor and features colour syntax highlighting and one-click compilation/uploading. The design of the Arduino is based on controllers and microprocessors, supplied with sets of analog and digital I/O sockets for connecting with other circuits. Serial communications are possible for interacting with computers (using USB) or Tx/Rx pins for communicating with other devices (using TTL logic levels). A large variety of external devices can be used with Arduino boards, for example various sensors can be used as inputs to allow the Arduino to sense and process data from the environment. Arduino projects can be standalone or can run interactively with other software such as Processing and Max for maximum flexibility.



```
  //  Set MIDI baud rate:
  Serial.begin(31250);
}

void loop() {
  // play notes from F#-0 (0x1E) to F#-5 (0x5A):
  for (int note = 0x1E; note < 0x5A; note ++) {
    //Note on channel 1 (0x90), some note value (note), middle velocity (0x45):
    noteOn(0x90, note, 0x45);
    delay(100);
    //Note on channel 1 (0x90), some note value (note), silent velocity (0x00):
    noteOn(0x90, note, 0x00);
    delay(100);
  }
}

//  plays a MIDI note.  Doesn't check to see that
//  cmd is greater than 127, or that data values are  less than 127:
void noteOn(int cmd, int pitch, int velocity) {
  Serial.write(cmd);
  Serial.write(pitch);
  Serial.write(velocity);
}
```

```
Serial port '/dev/tty.usbmodem1421' not found. Did you select the right one from the Tools > Serial Por
        at java.awt.EventDispatchThread.pumpEvents(EventDispatchThread.java:196)
        at java.awt.EventDispatchThread.pumpEvents(EventDispatchThread.java:188)
        at java.awt.EventDispatchThread.run(EventDispatchThread.java:122)
```

Figure 5.4: Arduino Programming Interface

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[14] http://wiring.org.co/
[15] https://www.processing.org/

For data communication, an Arduino Mega 2560 (Rev.3) board was used (see Figures 5.5-1 & 5.5-2). This board has a 10-bit ADC, 16 analogue inputs and 54 digital input/output pins which are more than adequate for this research. One important reason this board was chosen is that the Mega 2560 board is fully compatible with most shields designed for the "Uno board" (a simpler alternative in the Arduino family) which was used initially in this research, but was eventually abandoned since it failed to perform consistently: it drops signal occasionally, or the signal sometimes keep being at peak value constantly. Figure 5.6 shows the appearance of the Uno board.

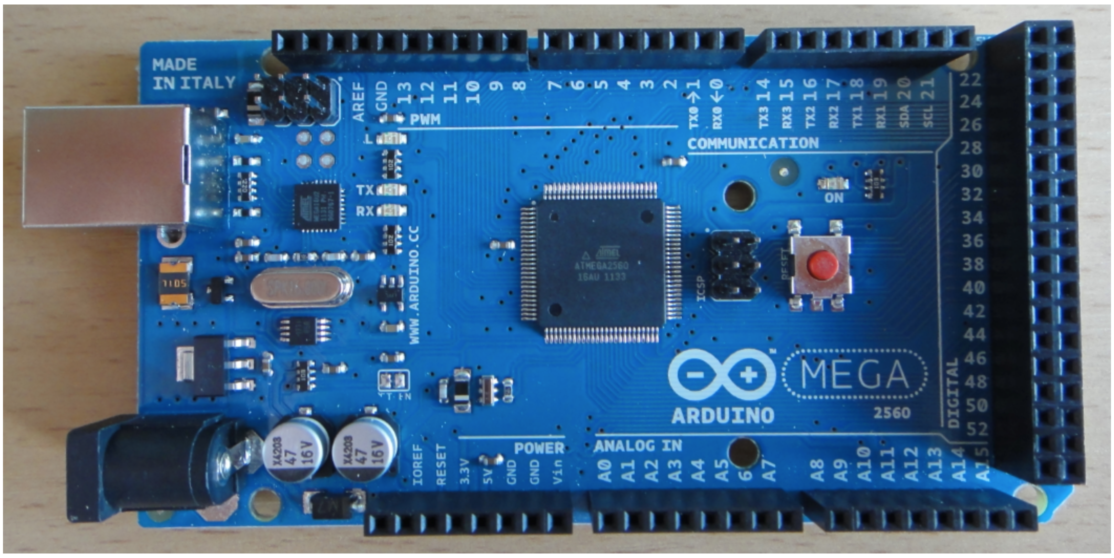


Figure 5.5-1: Arduino Mega 2560 Front

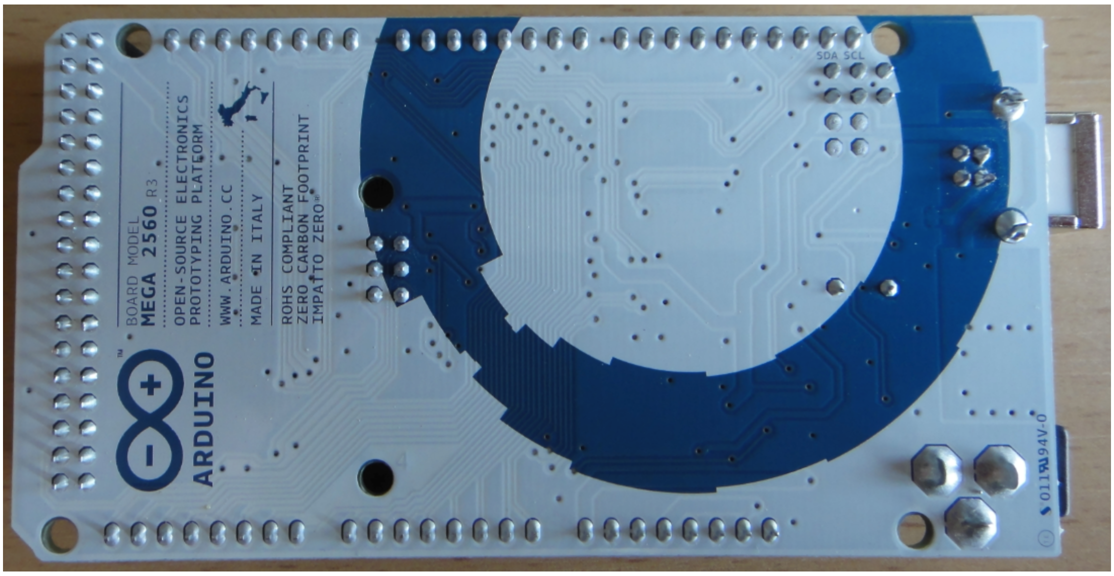


Figure 5.5-2: Arduino Mega 2560 Back

Figure 5.6: Arduino Uno Board

5.3.2 EMG Sensor

The EMG sensor “Advancer Technologies Muscle Sensor v3” was used for this research (see Fig. 5.7). This sensor measures filtered and rectified electrical activity of muscles. It outputs voltage from zero to a fixed value (implied by the voltage of the power source) depending on the activities in the connected muscle. The sensor is powered by two 9v batteries and it must be connected to ground. An on-board 3.5mm jack is used for connecting/disconnecting cables attached to sensor electrodes.

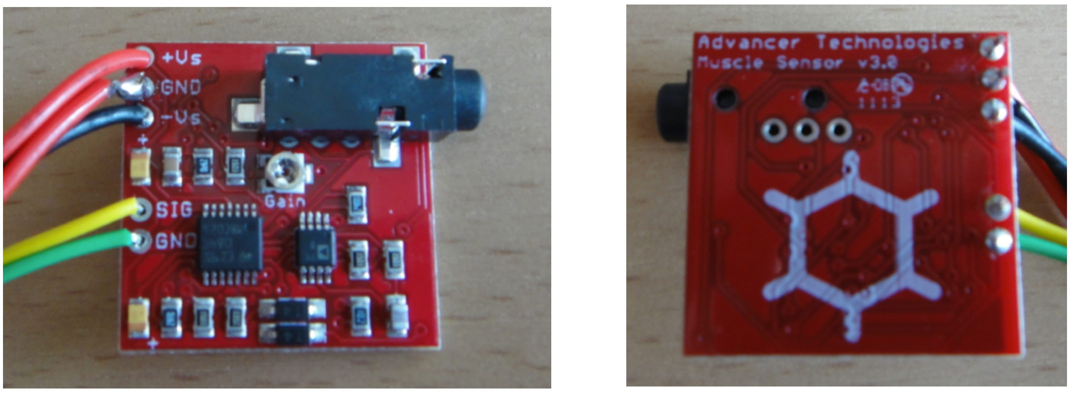
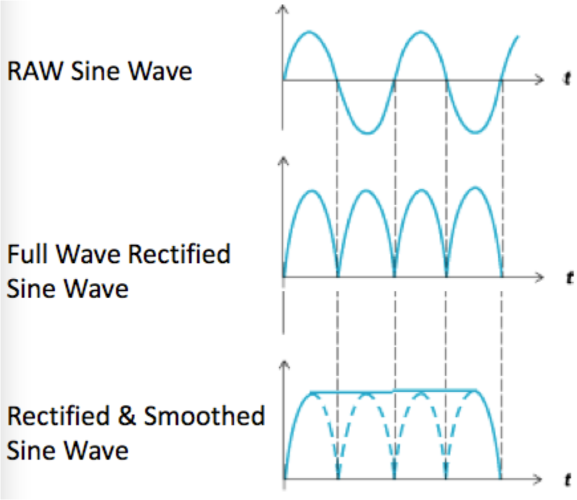


Figure 5.7: EMG Sensor

This sensor was chosen because it has some specific features that meet the needs of this research. They are:

- Small form factor (1inch * 1inch (25.4mm squared))

- Adjustable gain - the quality of the captured signal is improved
- On-board 3.5mm cable port - easy to replace cables and electrodes
- Designed for microcontrollers: the sensor does not output a RAW EMG signal but an amplified, smoothed and rectified signal, which works well with the ADC of Arduino boards. Figure 5.8 shows the official graphic demonstrating the concept:



5.8: Optimized signal output (ref from the EMG sensor manual)

The figure above indicates that a RAW sine wave is fully rectified and then smoothed.

The cable is connected by three “Kendall/Tyco ARBO* Ag/AgCL” EMG Electrodes (Fig. 5.9) which are applied on the skin’s surface as close as possible to the active muscle’s middle/end part and reference point (GND).

Figure 5.9: Electrodes

5.3.3 Bluetooth Module

For this research, a portable/wireless device was preferred as people usually do not like to work while tethered by wires to a computer. This is particularly true of piano players who require a full degree of arm movement. Therefore, Bluetooth was chosen as the connection method between the Arduino board and the computer (see Fig. 5.10). A “JY-MCU ‘linvor’” v1.05 module was used here. It supports AT commands as well, which means that it is configurable in terms of pairing password, baud rate and name of the device.

Another reason to use the Bluetooth is that Apple Macbooks are known for having a mains leakage problem[16], which means that if the system were to be applied on any Macbooks there would be the potential of incorrect results, and in fact delicate hardware could be damaged. Hence for the universality and the manoeuvrability, the Bluetooth module is essential in providing electrical isolation between the sensor system and the computer.

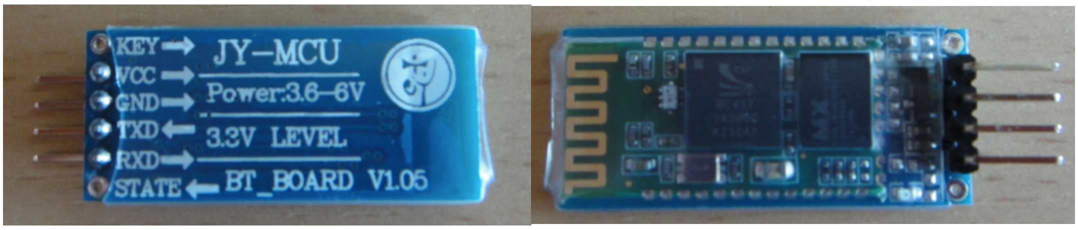


Figure 5.10: Bluetooth Module

Four pins are connected to the corresponding slots on the Arduino board. The VCC/GND are used for power supply while TXD/RXD work for data transmission.

5.4 The Software

This section gives a detailed explanation of the software / programming code used in this system, and written especially for this research.

5.4.1 The ‘Processing’ language

Processing is an integrated development environment (IDE, see Fig. 5.11) and programming language used by many designers, artists and people who work with graphics and interaction. It is very like the Arduino language – and in fact they are sister projects.

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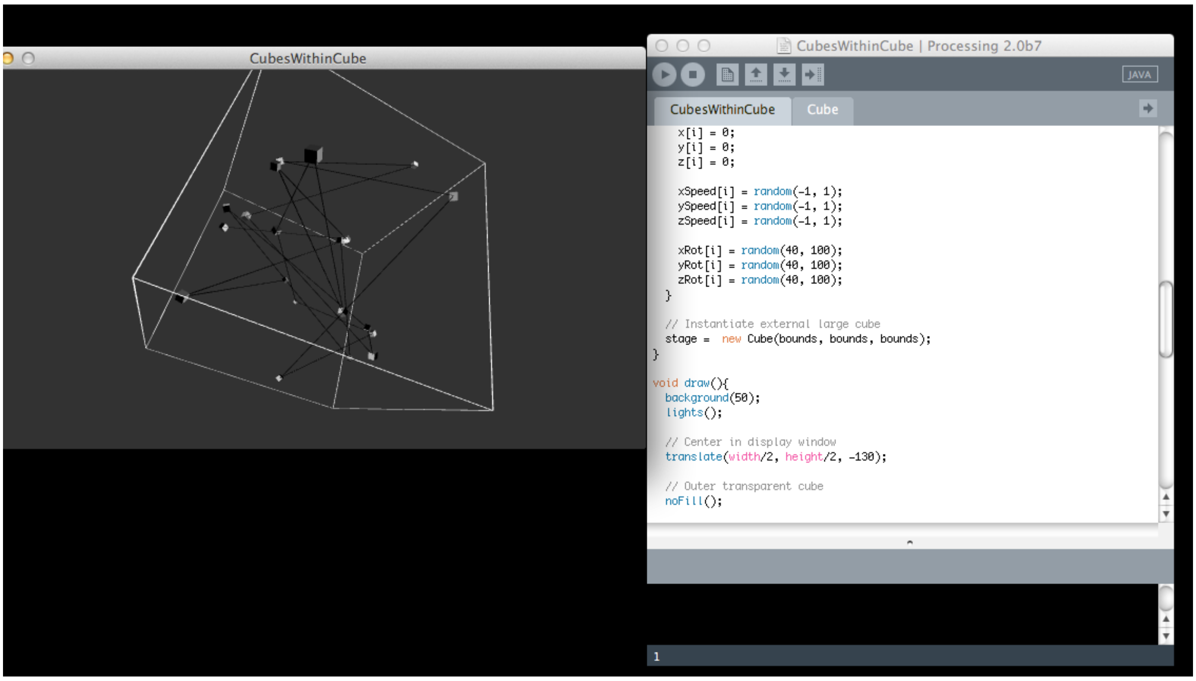
[16] For example see https://discussions.apple.com/thread/3969131?tstart=0



```
    x[i] = 0;
    y[i] = 0;
    z[i] = 0;

    xSpeed[i] = random(-1, 1);
    ySpeed[i] = random(-1, 1);
    zSpeed[i] = random(-1, 1);

    xRot[i] = random(40, 100);
    yRot[i] = random(40, 100);
    zRot[i] = random(40, 100);
  }

  // Instantiate external large cube
  stage =  new Cube(bounds, bounds, bounds);
}

void draw(){
  background(50);
  lights();

  // Center in display window
  translate(width/2, height/2, -130);

  // Outer transparent cube
  noFill();
```

Figure 5.11: Screenshot of Processing interface and code

It has some useful features which make it one of the most popular programming languages among people working with visual elements[17]:

- Free to download and open source
- Interactive programs with 2D, 3D or PDF output
- OpenGL integration for accelerated 3D
- For GNU/Linux, Mac OS X, and Windows
- Over 100 libraries extend the core software
- Well documented with many books available.

As as example of its application, Aaron Koblin has mapped the flight paths (air traffic) of Florida into a beautiful pattern[18]. The data was parsed and plotted using Processing (see Fig 5.12).

In this research processing is used in system test and pilot study because its capability of producing high quality image results.

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[17] Features from processing.org

[18] http://www.aaronkoblin.com/work/flightpatterns/

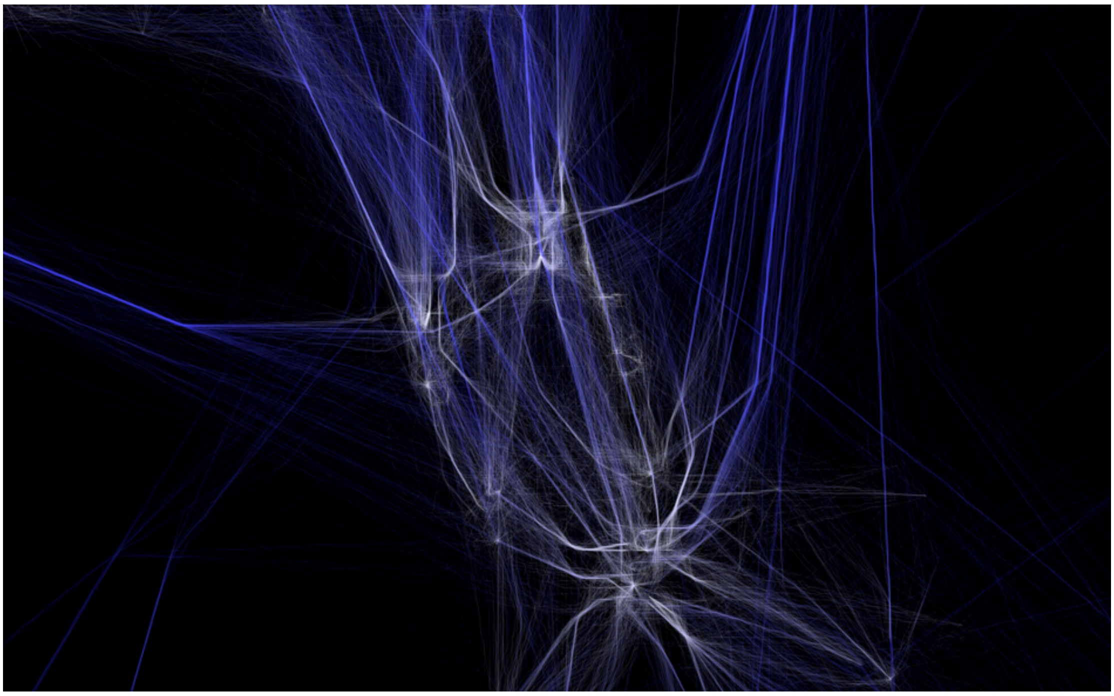

Figure 5.12 Flight patterns[19]

5.4.2 Cycling '74 *Max*[20]

Max (see Figure 5.13:1-7) is a visual programming language for music and multimedia. It is very popular among composers, performers and artists. Max has a modular code base of objects for building blocks for its patches (programs).

The main characteristic of *Max* is its data-flow system. A *Max* program (also named a "patch") includes many "objects" which are actually self-contained programs. Objects are connected and arranged on a "visual canvas" (named a "patcher"), where messages are passed through from outputs of objects to inputs of other objects.

In addition, *Max* includes other two packages: *MSP* and *Jitter*. MSP provides the possibility of real-time manipulation of digital audio, allowing customised synthesizers and effects to be created by users. Jitter provides the opportunity of using real-time video, matrix processing and 3D. *Gen* was added later for compiling codes within patches; in the latest version of Max (version 7) *Beap* and *Vizzie* were newly added, providing high-level analog synth and visual processing modules.

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[19] http://www.aaronkoblin.com/work/flightpatterns/wallpaper/florida.png

[20] https://cycling74.com/products/max/#.WOG8F461vLg

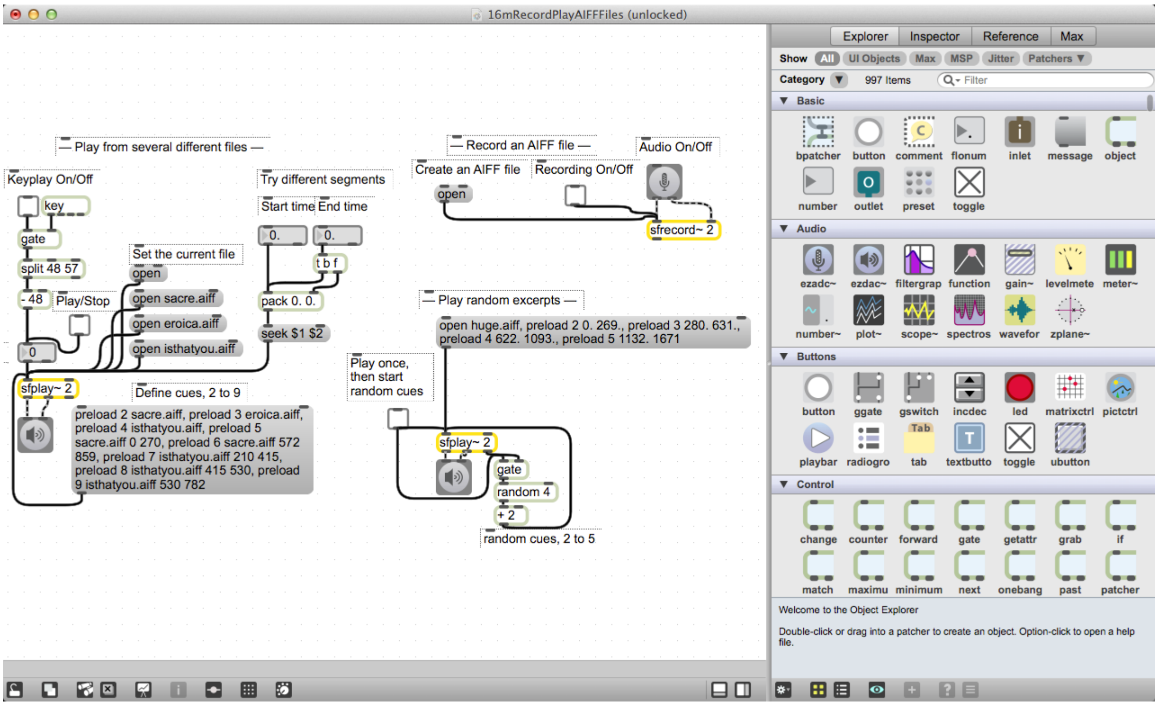


Figure 5.13-1: Max Running Window showing a patch (left) and object library (right)

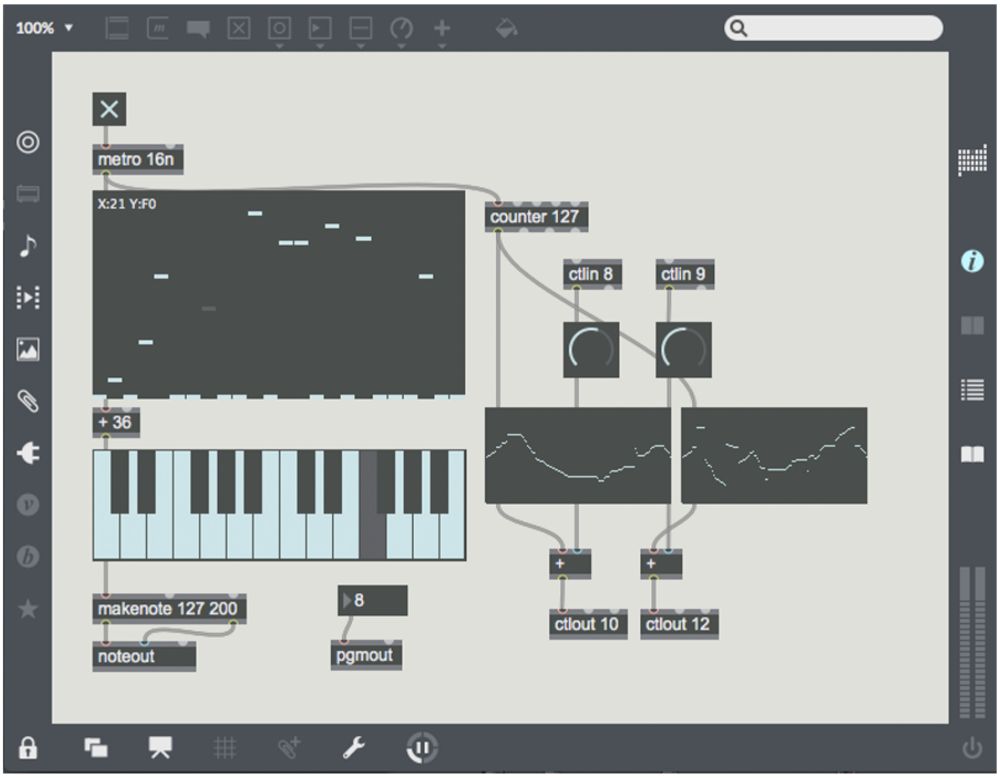


Figure 5.13-2: Max is connected with MIDI and external controllers

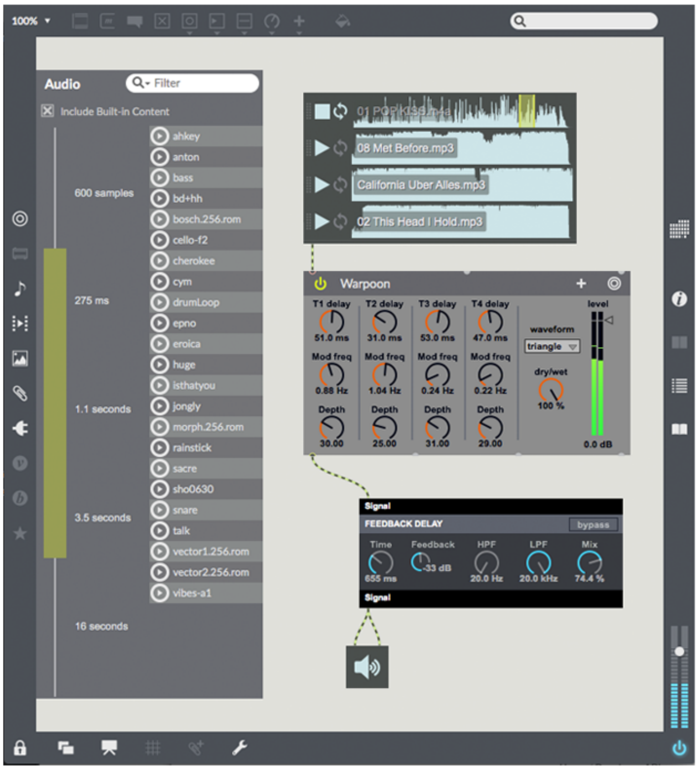


Figure 5.13-3: MSP can create customised synths and effects

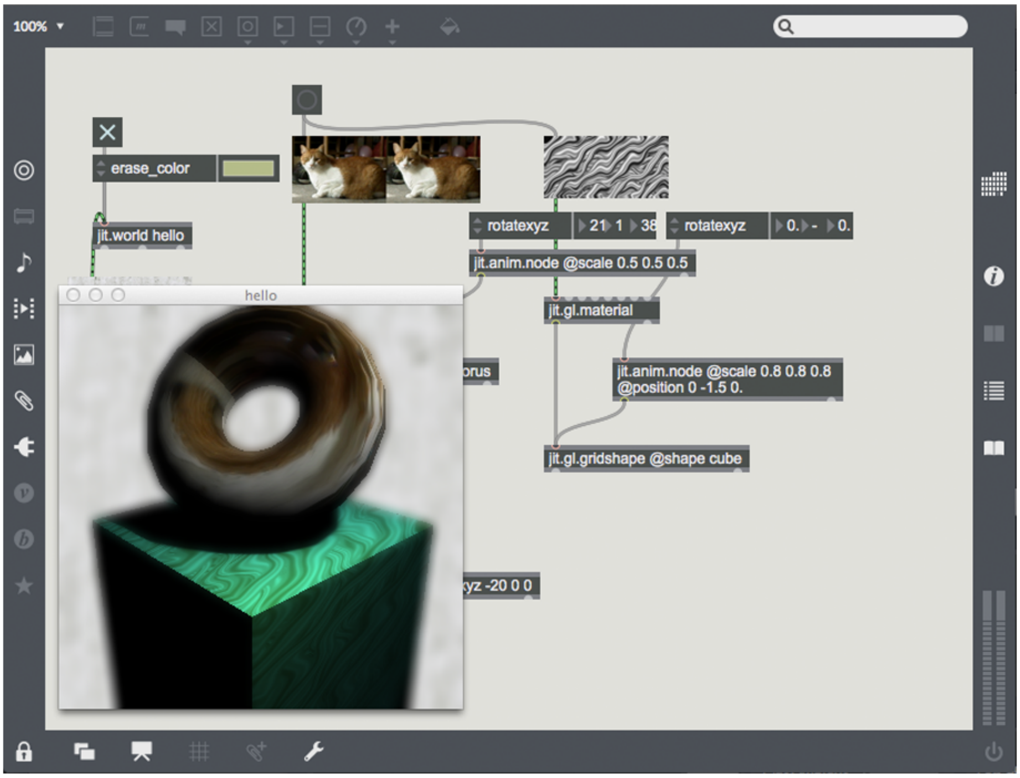
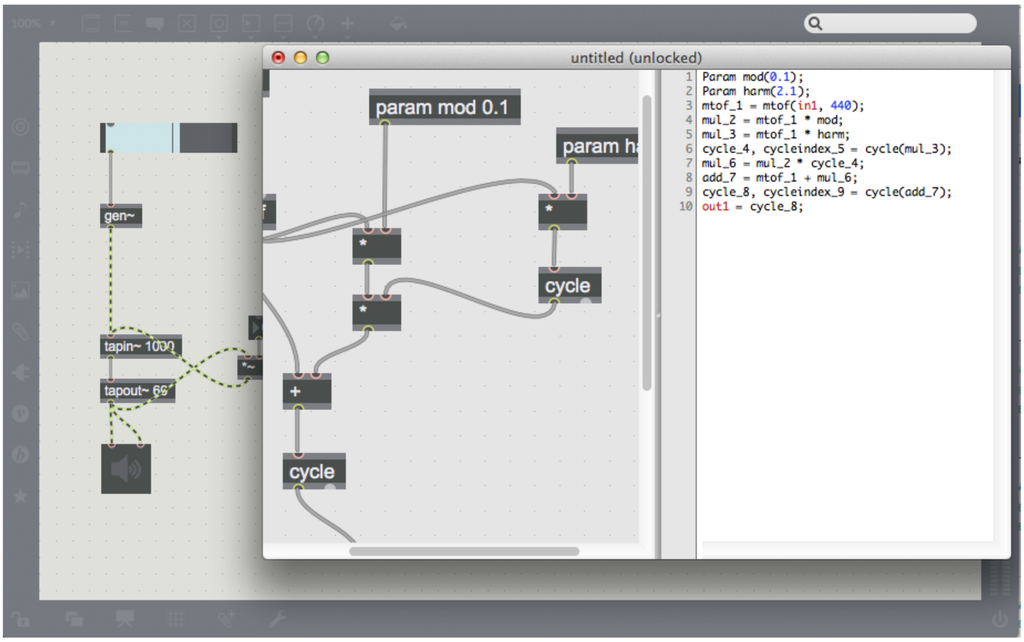


Figure 5.13-4: Jitter’s ability of controlling graphics



```
Param mod(0.1);
Param harm(2.1);
mtof_1 = mtof(in1, 440);
mul_2 = mtof_1 * mod;
mul_3 = mtof_1 * harm;
cycle_4, cycleindex_5 = cycle(mul_3);
mul_6 = mul_2 * cycle_4;
add_7 = mtof_1 + mul_6;
cycle_8, cycleindex_9 = cycle(add_7);
out1 = cycle_8;
```

Figure 5.13-5: Gen: code compilation

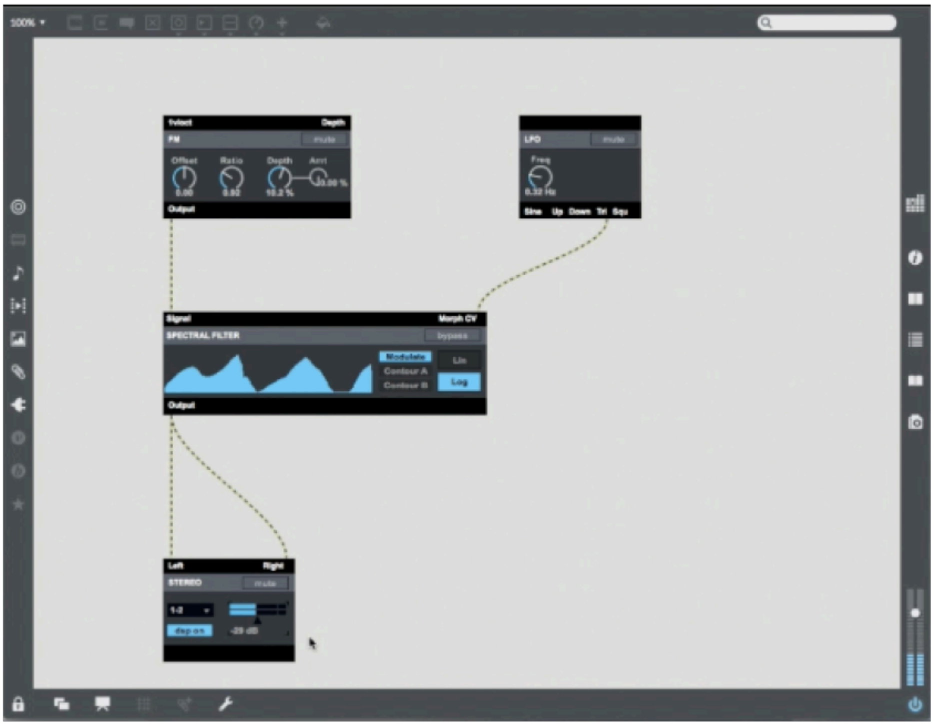


Figure 5.13-6: BEAP: sound modules

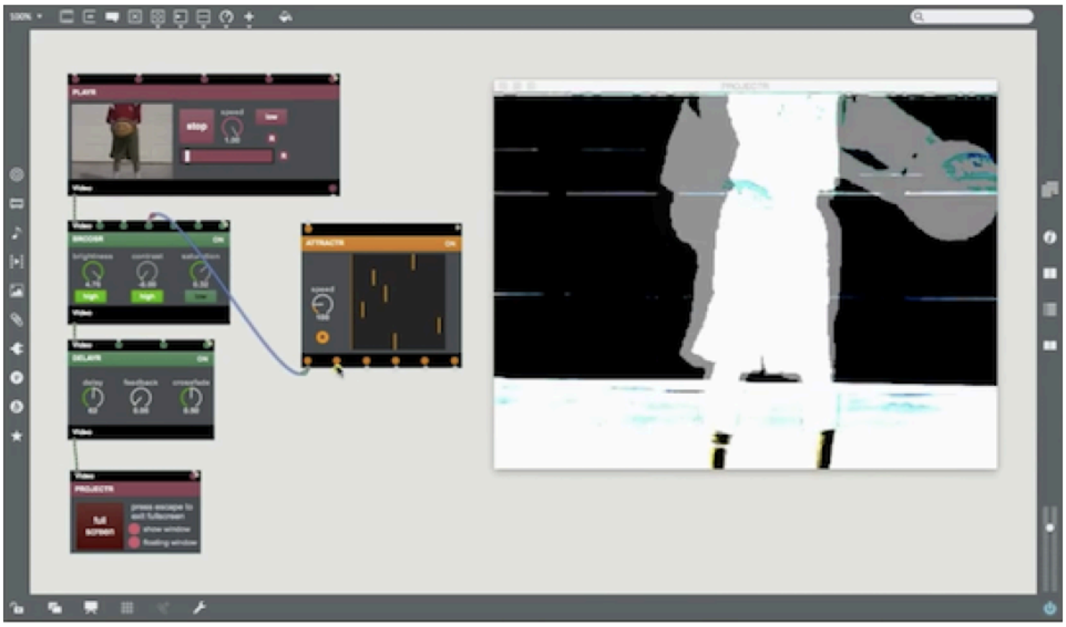


Figure 5.13-7: VIZZIE: visual manipulation modules

Figure 5.13 (7 pictures) shows all main components of Max.

5.5 System Design

This section introduces the main system design ideas, the details of hardware connections and programming.

5.5.1 The Concept

The system needed to satisfy these functions:

- Portable (wireless)
- Gather EMG data in real-time
- The EMG data to be displayed on a graph so that the users have a visual indicator of their muscle tension

- Data can be stored into a file, or read from a file.

Therefore, the flowchart of the system is shown below in Fig. 5.14:

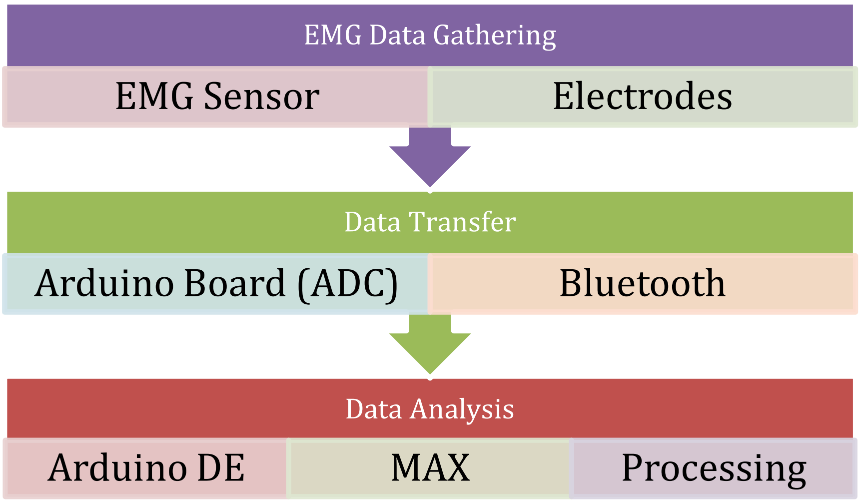


Figure 5.14: System Flowchart

5.5.2 Hardware Setup

Following the chart above, the solution to the hardware setup became clear (see Fig. 5.15). One end of the EMG sensor with the electrodes is placed on the skin over the muscle to be monitored; the other end (with the signal processing board) is connected to the Arduino board for transferring data. Between the Arduino board and the computer, Bluetooth is used as the serial communication (as the Macbook has a built-in Bluetooth adaptor). 9v batteries are required - two for each of the EMG sensors and one for the Arduino board.

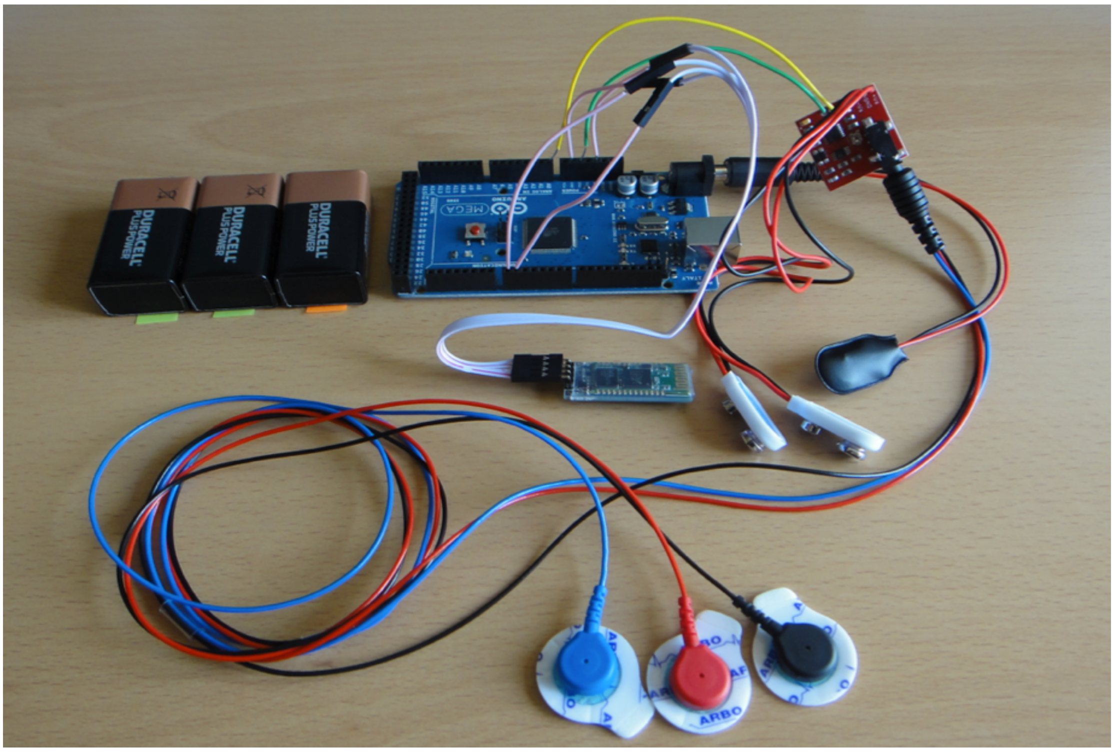


Figure 5.15: Hardware Setup

5.5.3 Programming

As stated above there are three components to the software:

1) Arduino component: to operate the Arduino board to receive signals from the EMG sensor;

2) Max component: to process the signals from the Arduino;

3) Processing component: the use of the Processing language as a prototyping tool, for processing data and producing visual and audio feedback.

Each of these components are now described and illustrated as sections below.

a) Arduino Component:

The Arduino board is only used for data transfer via serial communication. The code is given in Fig. 5.16:

```
// only a0-a6 on arduino are used

int a0 = 0;
int a1 = 0;
int a2 = 0;
int a3 = 0;
int a4 = 0;
int a5 = 0;

void setup(){
  Serial.begin(9600); //symbols per second
}

//In digital systems with binary code, 1 Bd = 1 bit/s.
//Analog systems use a continuous range of values to represent information and
//in these systems the exact informational size of 1 Bd varies.

void loop (){
  a0 = analogRead(0);
  Serial.print ("analog0");
  Serial.print (".");
  Serial.println(a0); // ASCII 13 = enter (ignored in MAX); ASCII 10 = println (send the list)
  a1 = analogRead(1);
  Serial.print("analog1");
  Serial.print(".");
  Serial.println(a1);
  a2 = analogRead(2);
  Serial.print("analog2");
  Serial.print(".");
  Serial.println(a2);
  a3 = analogRead(3);
  Serial.print("analog3");
  Serial.print(".");
  Serial.println(a3);
  a4 = analogRead(4);
  Serial.print("analog4");
  Serial.print(".");
  Serial.println(a4);
  a5 = analogRead(5);
  Serial.print("analog5");
  Serial.print(".");
  Serial.println(a5);

}
```

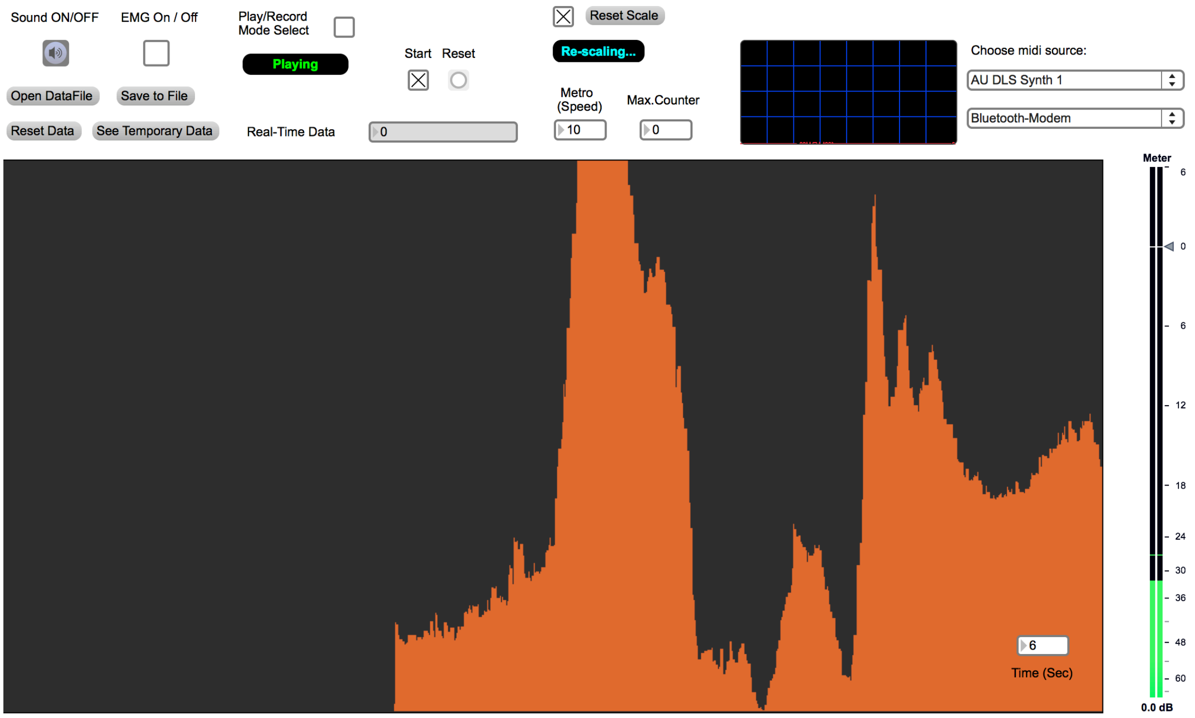
Figure 5.16 Arduino Code

Six pins (a0-a5) pins are identified as the analogue input sockets, initially set as value "0" The baud rate is set as 9600 (symbols per second) by the line "Serial.begin(9600)". A loop is then followed for gathering data continuously from the pins. Visual outputs are printed as "analog*+.+value of analog pins+line break" respectively.

When all codes are uploaded to the Arduino board, the board acts as a standalone chip, even without being connected to a computer it can still function as it is has been programmed.

b) Max Component

Figure 5.17 shows the Max interface which has been designed for this project.



Choose midi source: AU DLS Synth 1

Bluetooth-Modem

Real-Time Data 0

Metro (Speed) 10

Max.Counter 0

Time (Sec) 6

Figure 5.17 MAX Interface

The functions of the buttons are expressed by button names, including EMG gathering on/off, sound play on/off, data save/load/reset/check, reset scale and real-time data value/graph display. Users have full control of all the functions that this Max patch provides.

The graph is used as a visual muscle tension indicator. Once the Max patch is started, the EMG data gathered by the sensor will be shown in both the number box (on the right side of "Real-Time Data") and the "multislider" object (the orange graph window). All the data is stored temporarily as a hash table in the "coll" object, which users can choose to look at in real-time or save into a text file (buttons at the upper-left corner). The patch also supports the reading of EMG data files saved by the patch itself. On the right side, the volume can be adjusted to satisfy the needs of different people.

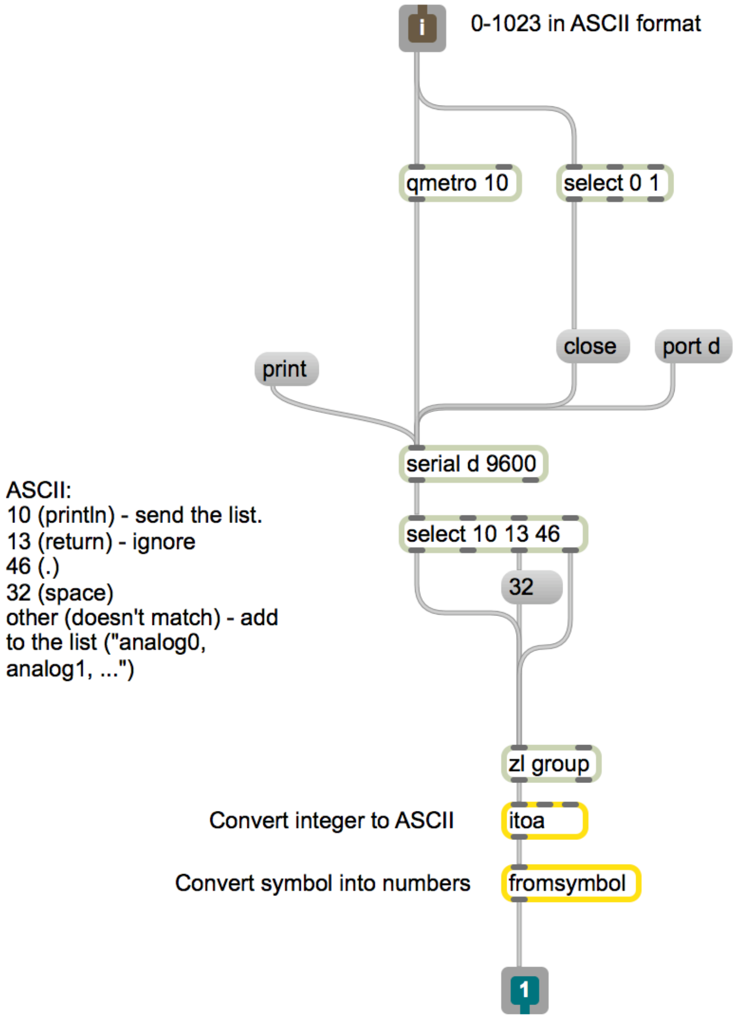


Figure 5.18 EMG module

Figure 5.18 shows the MAX code for carrying out serial communication in order to receive data from the Arduino. The [Serial] object gathers all information coming from the Arduino via the Bluetooth port (port d). When ASCII code "10" (println, linebreak) is detected, the whole message is sent to [zl group] for re-grouping them together as an ASCII stream. During this step all unwanted keywords such as ASCII code "13" (return) or ASCII code "46" (symbol '.') are replaced with "space" (ASCII code 32). Then the signal goes through the [fromsymbol] object which converts original ASCII code into numbers. Finally the signal is sent out every 10ms (set by the [qmetro] component, an internal clock of Max), and then is received by sub-patch [arduinoAD] which divides the signal stream into 6 groups by recognising the keyword "analog+number" in Fig. 5.19-1.

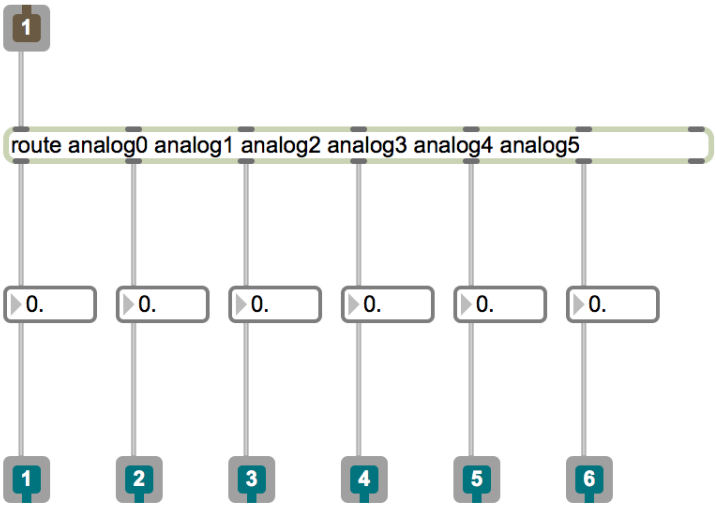


Figure 5.19-1 Signal Routing in MAX

Considering that muscle tension from different subjects varies, the signals of all subjects are re-scaled to prevent clipping or too weak a signal. When the "re-scaling" (reset scale) option is ticked on, the objects [peak] and [trough] find the maximum and minimum values respectively of the incoming signals and rescale them into the range 0-1000. To obtain the maximum signal, subjects will be required to tense their muscle as much as possible before the experiment starts (see Fig 5.19-2).

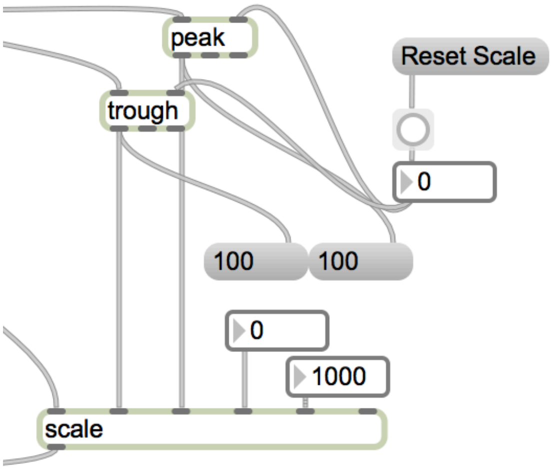


Figure 5.19-2 Incoming signal scaling

The [coll] object, along with [counter], (see Fig. 5.20) stores all data into an index table at the speed of incoming signal (also every 10ms) to preserve as much information as possible. The index file is simply combined with an index number and the data, and can be easily saved as a text file (.txt).

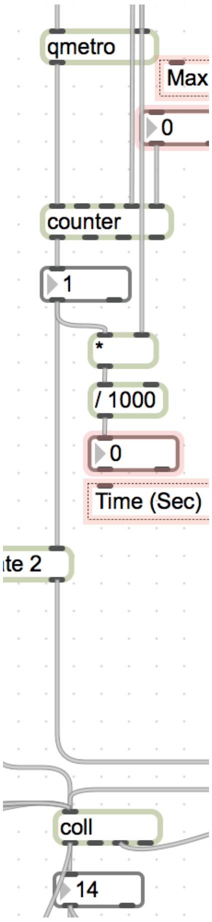


Figure 5.20 The coll object

For the sound feedback, the sound module (Figure 5.21) generates a simple real-time parameter-mapped sonification, based on the value of EMG signal. The function 2*value was used as the frequency to modulate a sine wave; as the signal value is from 0 to 1000 therefore the frequency range of the sound feedback is 0-2000, which is convenient to listen to[21]). The volume adjusts its value accordingly, from mute to 0db within the MAX patch.

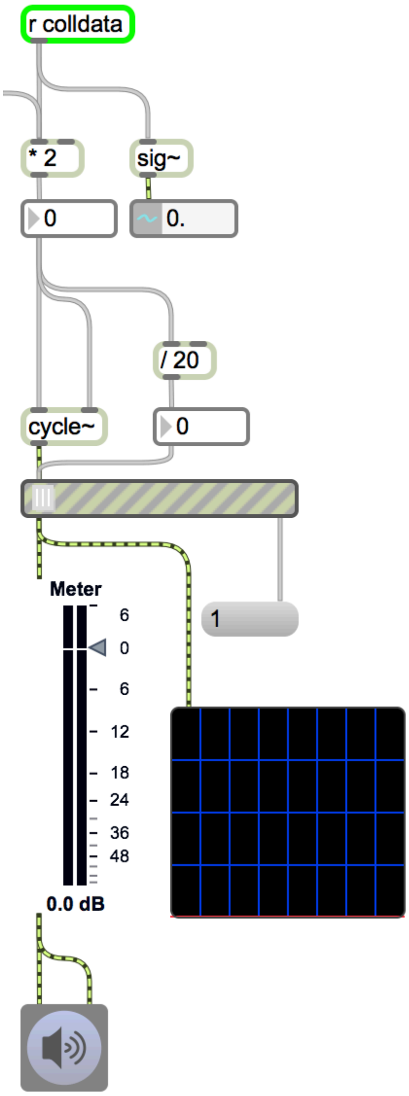


Figure 5.21 Sound module

The reason for using a simple sine wave as the feedback sound is explained in the next chapter (Pilot Study); the sine wave being the choice after many different sounds were tried.

Figure 5.22 shows the full view inside the MAX patch (excluding some sub-patches

---

[21] Although the few very lowest values will be inaudible as the human hearing range begins at 20Hz. This does not appear to have been a problem since it is the higher end of the signal range which really needs bringing to the listener's attention).

explained before).

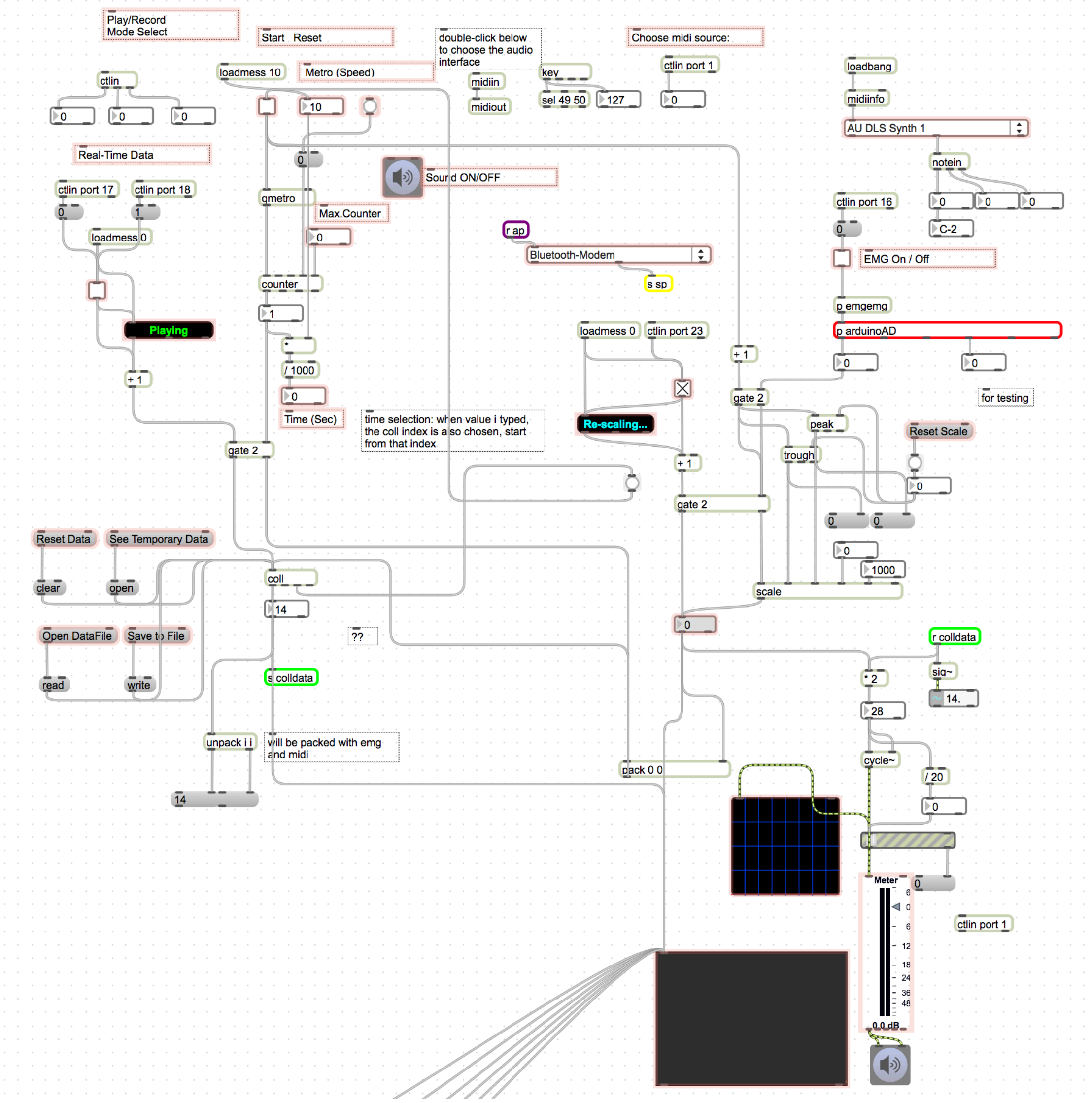
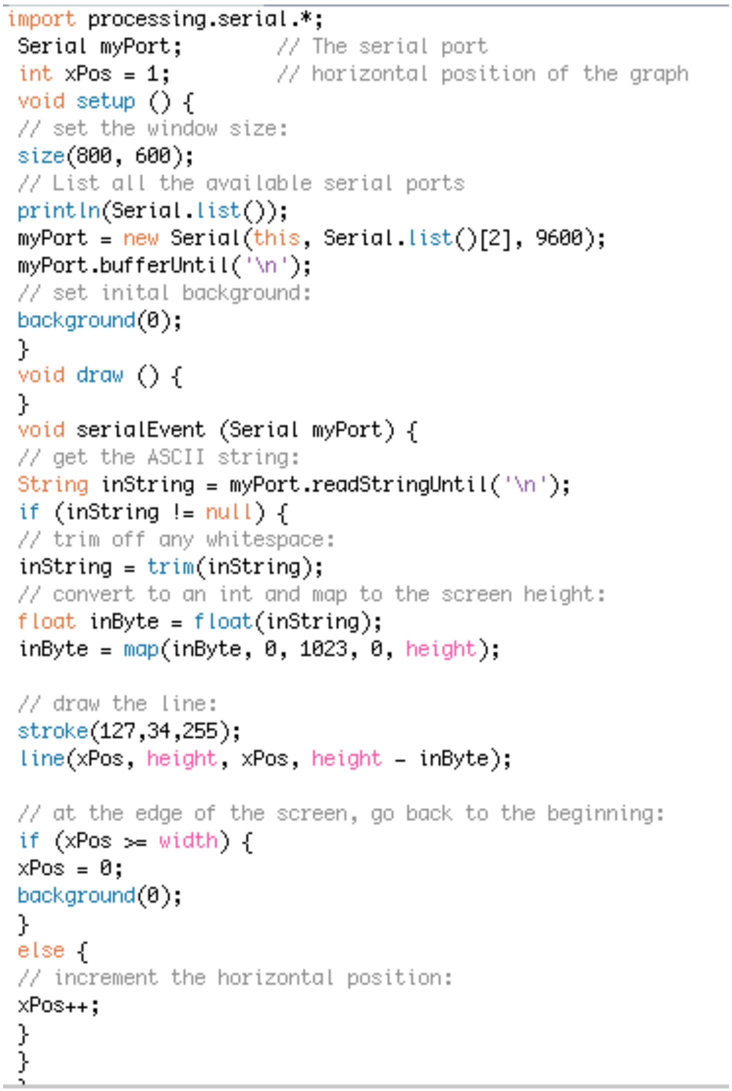


Figure 5.22 Max patch full view

c) Processing Component

Although the MAX can draw a graph, the *Processing* language is superior in terms of image quality and display smoothness. Therefore for testing devices, Processing is used to provide a better real-time graphical experience.



```
import processing.serial.*;
 Serial myPort;         // The serial port
 int xPos = 1;          // horizontal position of the graph
 void setup () {
 // set the window size:
 size(800, 600);
 // List all the available serial ports
 println(Serial.list());
 myPort = new Serial(this, Serial.list()[2], 9600);
 myPort.bufferUntil('\n');
 // set inital background:
 background(0);
 }
 void draw () {
 }
 void serialEvent (Serial myPort) {
 // get the ASCII string:
 String inString = myPort.readStringUntil('\n');
 if (inString != null) {
 // trim off any whitespace:
 inString = trim(inString);
 // convert to an int and map to the screen height:
 float inByte = float(inString);
 inByte = map(inByte, 0, 1023, 0, height);

 // draw the line:
 stroke(127,34,255);
 line(xPos, height, xPos, height - inByte);

 // at the edge of the screen, go back to the beginning:
 if (xPos >= width) {
 xPos = 0;
 background(0);
 }
 else {
 // increment the horizontal position:
 xPos++;
 }
 }
```

Figure 5.22 Processing code

In the Processing program (shown in Fig. 5.22) the serial is chosen manually according to the serial port list (use “println [Serial.list]” to show all ports, in this case it is port 2). An 800*600 pixel “canvas” is defined and initially cleared by the line “size (800, 600)” and “background (0). All EMG data streaming from the Arduino board are scaled within a range of 1024 (0-1023) and then are continuously fed into the variable “height”, which is used for drawing a line in purple colour (specified with RGB code 127, 34, 255). Every time the graphical window is filled, the line “if (xPos >= width), xPos=0” clears the window and draws the line again from the original position (far left).

5.6 System Initial Test

The first task was to make sure that all the devices were connected correctly; then apply the electrodes to the skin surface above the target muscle (as in Fig. 5.23). Then the programs of Max and Processing were run and the results could be seen. Below are some pictures demonstrating the process. Some testing videos are available on the accompanying DVD disk, showing different parts of the system in operation.

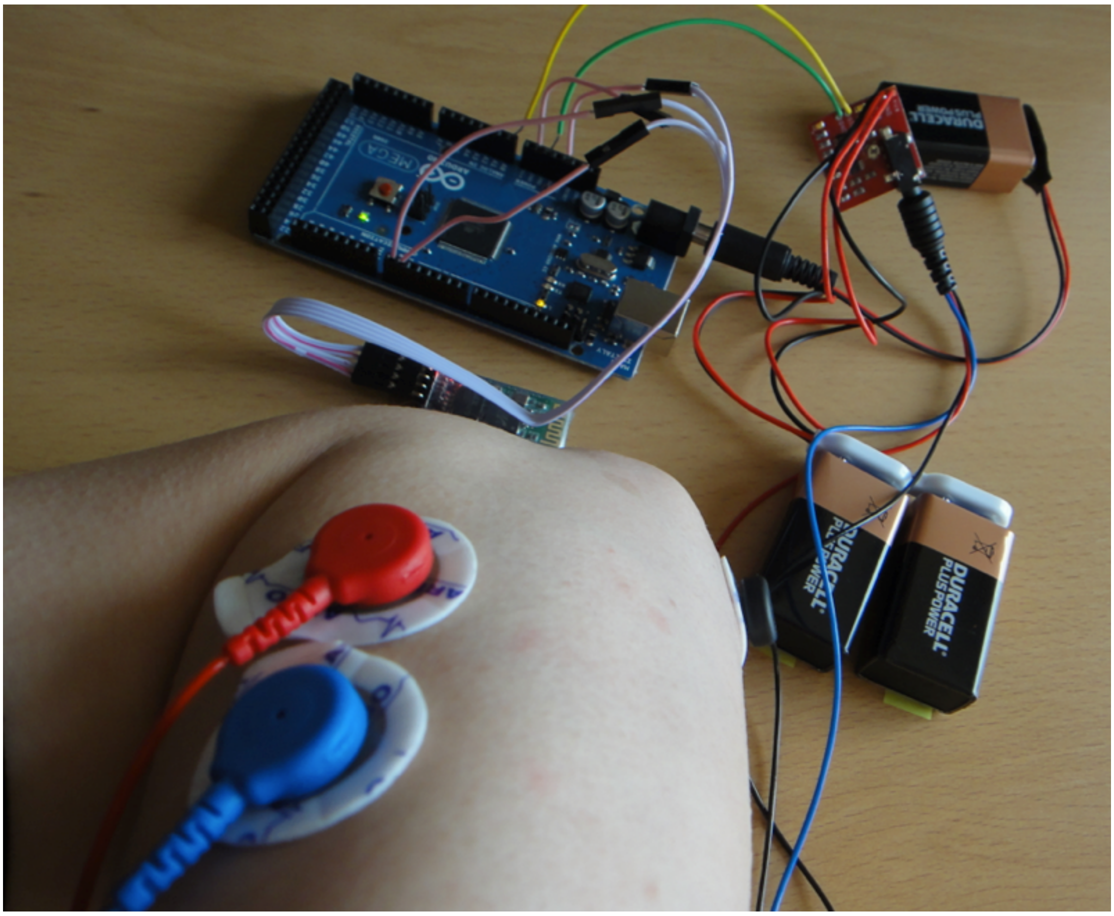


Figure 5.23: Device Setup

1) Results from the Processing program

After everything was set properly, a clear graph was obtained, as shown in Fig. 5.24. The graph sensitively indicates the muscle tension in real-time, and the shape also looks smooth and useful for visual analysis. Informal testing showed that users appreciated the real-time visual response, and commented on its clarity.

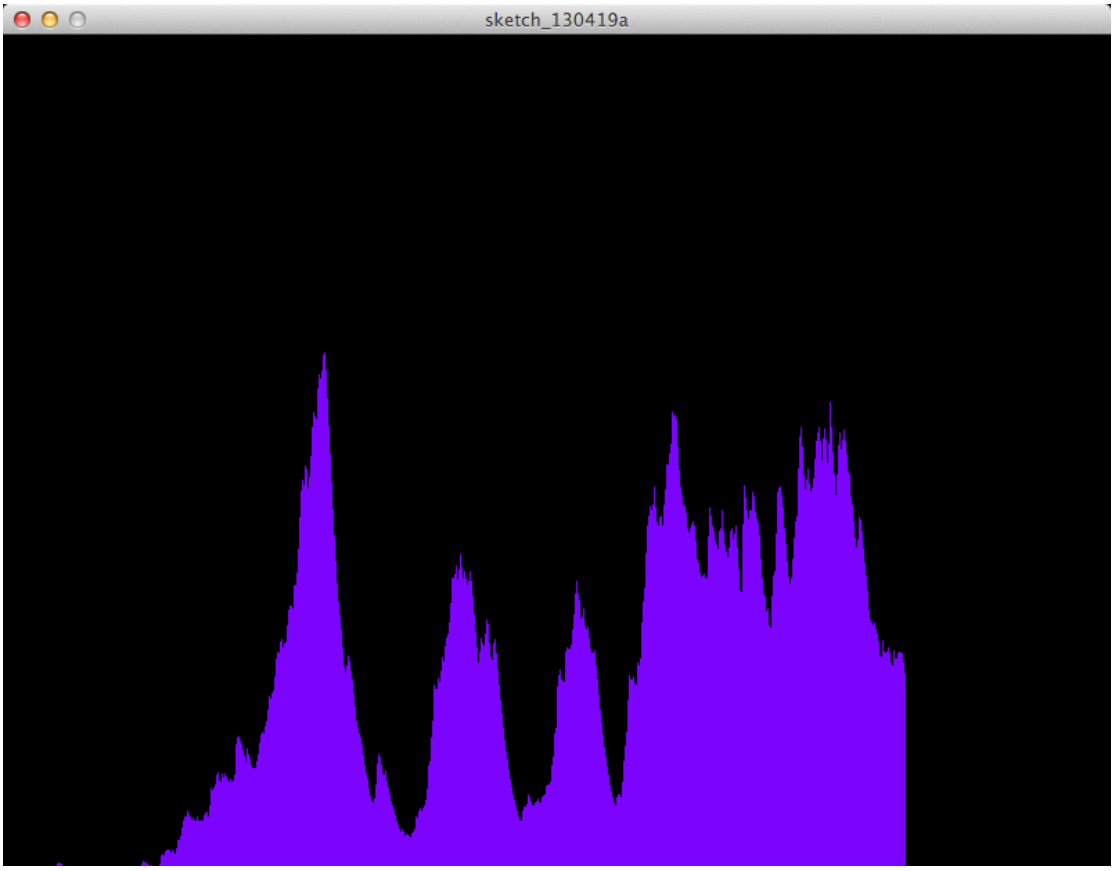


Figure 5.24: Processing Sketch

2. Results from the Max program

With the same hardware setup, the use of Max also brought good results. It has good graphic quality (see Fig. 5.25); and in addition a real-time audio signal which increases/decreases with the rise/drop of muscle tension can be heard clearly.

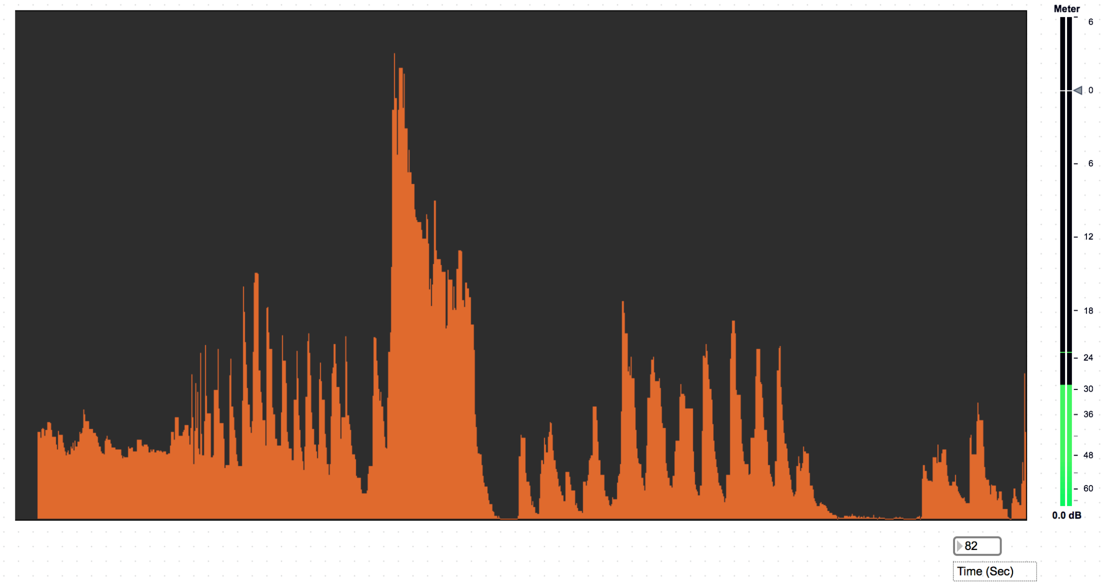
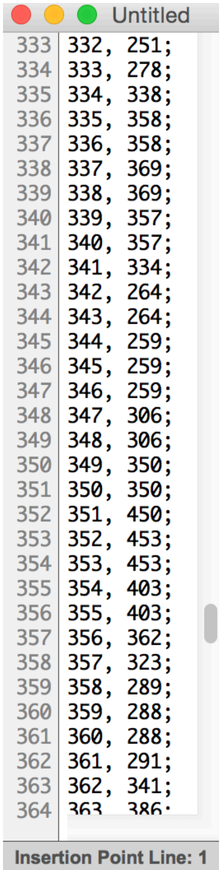


Figure 5.25: MAX result (Graph and value number)

The data operation function was tested as well. Signal data could be stored or read as a text file; users or the researcher could check the data at any time. Figure 5.26 shows the temporary data after clicking the “see temporary data” button.



```
332, 251;
333, 278;
334, 338;
335, 358;
336, 358;
337, 369;
338, 369;
339, 357;
340, 357;
341, 334;
342, 264;
343, 264;
344, 259;
345, 259;
346, 259;
347, 306;
348, 306;
349, 350;
350, 350;
351, 450;
352, 453;
353, 453;
354, 403;
355, 403;
356, 362;
357, 323;
358, 289;
359, 288;
360, 288;
361, 291;
362, 341;
363, 386;
```

Figure 5.26: Temporary data stored in coll object

From the testing sessions some points were discovered:

- A higher sample rate (>100Hz) does not provide better results, but just wastes computer resources. This conclusion is taken from many tests: we tried many sample rates (many of them are >100Hz), the program gave the same results as using the sample rate 100Hz.
- The position of the electrodes applied above the muscle can make significant changes to the results. This was found accidently during one experiment session. Sometimes imperfect signals were caused because the electrodes were not applied on the proper position of skin.
- The system needs good power support; when the power of batteries was below 50%, the results were no longer reliable. The sensor is really sensitive to the battery level. When the level is close to 10%, a short out even may happen.
- Taking the above issues into account, the system worked very well and met the needs of this research.

5.6 Discussion

The whole system is described in this chapter, including both hardware and software sections. The functions this system has achieved satisfy the needs for testing the main hypothesis of this research *"By using Sonification feedback it is possible to inform piano players of muscle tension in real-time, which will allow them to reduce tension"* because this system is able to produce sound feedback based on the muscle tension status; and the muscles chosen represent the main part where piano players consistently report feeling tension. In the next two chapters (experiments), we can demonstrate that people can be successfully informed when they have high muscle tension.

To sum up, this system is fairly well-built and effective, with all components / programming languages reasonably chosen. All essential functions have been implemented, with good stability and reliability. The software user interface is easy to understand and operate, with clear presentation with output results.

There are some limitations as expected, such as the batteries much reduced the portability of the system because of the weight (3x9v batteries); the Bluetooth connection is sometimes fair-poor because of long distance or some obstacle between the computer and the system. Sometimes obviously wrong random results are shown hence a system restart is needed; For single muscle, 3 electrodes need to be adhered to skin with cables connected, which largely reduces the user comfort, etc. Therefore, there are a few improvements which can be considered:

- Using small scale Arduino board, such as an Arduino Mini Pro, Arduino Macro, or Arduino Nano. These chips have a very small size but still provide enough connections, which should help to greatly reduce the size / weight of the whole system. Hence a more portable or even wearable device can be made.
- Using a Wi-Fi module or Wi-Fi-integrated Arduino boards. Wi-Fi can provide much better connections than Bluetooth, and is becoming a standard for mobile devices. By using Wi-Fi, we could expand the possibilities of making an app for mobile devices such as iPhone / iPad.

- At the time of writing, a new sensor “MyoWare[22]” from the company Advancer Technologies is available. It has all functions of the custom sensor designed for and used in this research but offers more flexibility. This could be used in future work to give the system an update: 1) “Single power supply”, so now it could be plugged directly into 3.3V through 5V development boards. This is useful because two of three batteries could be eliminated. 2) “Embedded Electrode Connector”; electrodes now snap directly to MyoWare and can be attached to the skin, no cables are needed. 3) “RAW EMG Output”; this expands the possibilities if a raw EMG signal is required in further research. 4) “LED Indicators” give a little visual indication of muscle status because the LED brightens when the muscle flexes.
- A new wearable device “MYO band” made by Thalmic Labs is newly available and can be used for many kinds of EMG-related applications. It is a wireless arm band, has a few EMG sensors built-in. SDKs are available by free download, allowing users to develop their own applications. The band has very good connections and precision, which makes it an ideal device for future research in this area.
- The enclosure could possibly be made by a 3d-printer. With a small size Arduino board and a new sensor installed inside, a portable system with small dimensions can be achieved.
- Although not implemented in this research, a MIDI controller could be used to access all the functions of the software interface in Cycling '74 Max. With hundreds of different MIDI controllers available on the market nowadays, it would be fairly straightforward to select a small and handy controller for this system for a better user experience in the prototyping stage.

With all the above improvements implemented in the system, this opens a new world for audio muscle-monitoring applications. A wearable, light and wireless device with more precision becomes possible for developing mobile apps for various purposes. Also, this will have good impact on further work (mentioned in later chapters), for instance, expanding user operating range, such as the user having the system on a mobile phone, particulary useful for intensive users monitoring ongoing medical problems.

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[22] http://www.advancertechnologies.com/p/myoware.html

5.7 Conclusion

This chapter has explained the implementation of the custom-designed sensor and sonification system used in this research. This system is used to create real-time sound and visual feedback generated from information gathered from muscles. Towards the end of the chapter some alternative system and possible improvements are described. In the next chapter, we will see the pilot study for this research.

Chapter 6 Experiments & Analysis

6.1 Study 1 (Initial Experiment)

This section explains the initial experiment (study 1).

6.1.1 Introduction

After the sonification system had been developed, the initial study was conducted. In this chapter the experimental process and results are described.

6.1.2 Implementation

In the initial study there were 11 people participating in the experiment. 1 of them is a concert pianist, the rest 10 are amateur piano players. The whole process of the experiment is explained below:

1) When subjects arrived at the place where experiment took place, they were given a piece of music (Czerny op.740 No.1 Etude was used in the initial study) and asked to practice until they had learnt it.
2) Next their arm was swiped by alcohol pads, and then the EMG electrodes were put on their arms.
3) The electrodes were put on their brachioradialis. One electrode was placed approx. 4cm away from the elbow bone and the other 2cm further. For the extensor digitorum one electrode was placed about ¾ distance between the elbow and the wrist, and another 2cm further. The final electrode was placed over the bony area of the elbow, as shown in Figs. 6.1.1 & 6.1.2 (Criswell, 2010). These two particular muscle sections were chosen based on the experience of 21 piano players who have ever felt high tension. They were interviewed before the initial study. 8 of the people who attended the initial study were selected from the 21 interviewees.

4) Then they were asked to relax their muscles as much as possible, then to tense their arms particularly with those two muscles, while the minimum and maximum values were captured in the software.
5) A short training session was carried out to let them get familiar with the system. Questions raised in these sessions included: “what does the feedback sound mean?”, “how should I respond when I hear the sound” etc. This also enabled the system to be tested as well (to confirm that everything was working satisfactorily).
6) A pair of Grado SR225 open headphones or a Genelec 8010a speaker was provided for listening to the sound feedback. The subjects were requested to play as fast as possible; then they started to play. Without letting them know, a period of 90-second time was counted; and after that they were asked to stop.
7) They were asked to fill in the feedback form (see Appendix3).

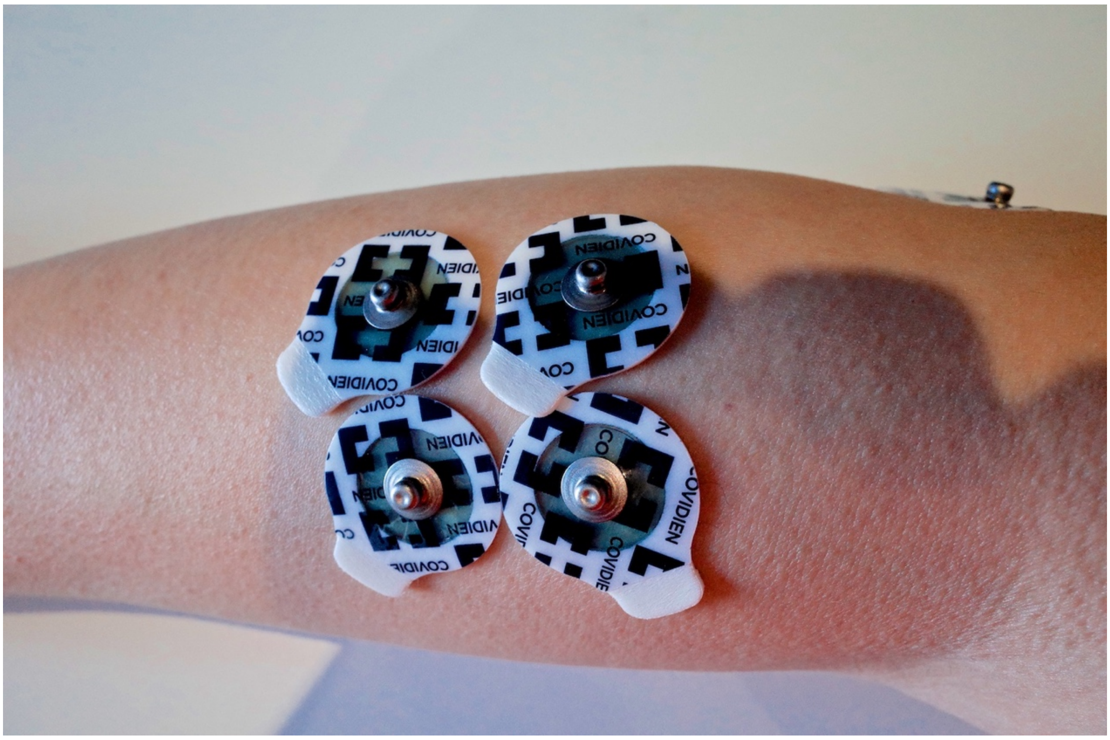
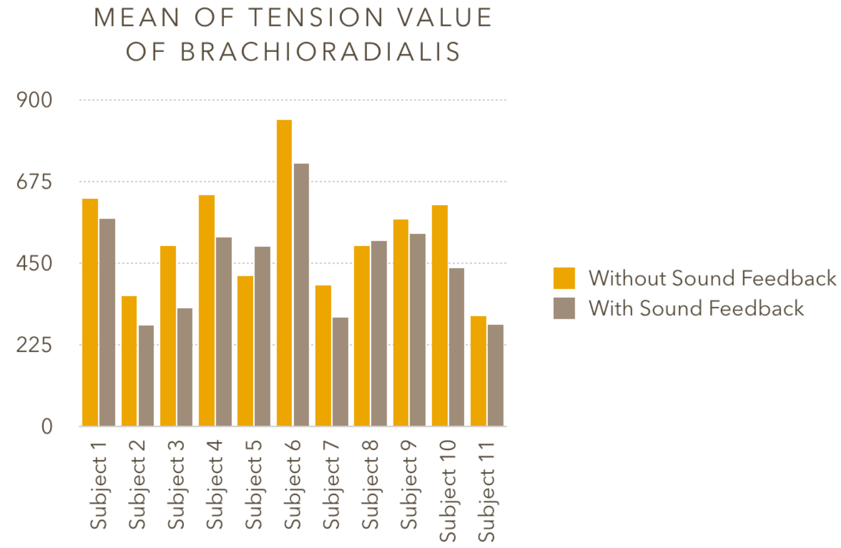


Figure 6.1.1 Placement of Electrodes (1)

Figure 6.1.2 Placement of Electrodes (2)

6.1.3 The Results

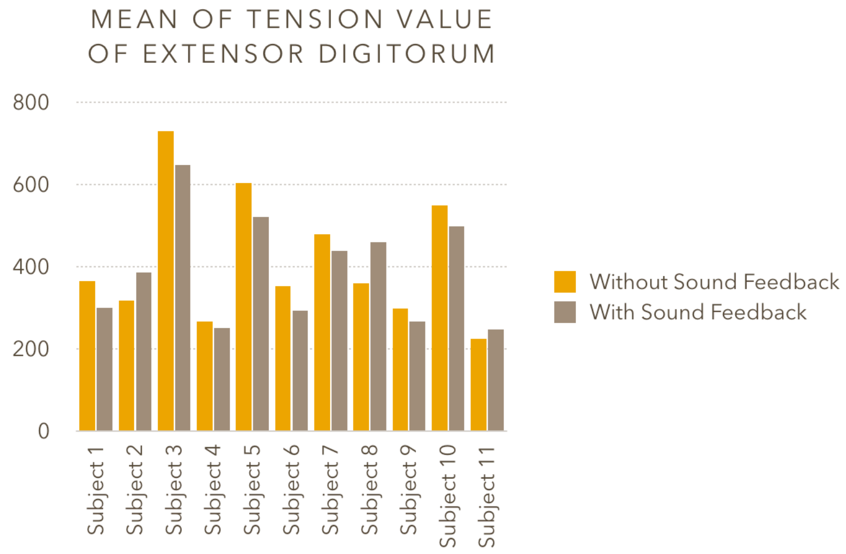
The results look promising. Summarised in Figures 6.1.3 & 6.1.4, 9 out of 11 (81.8%) people had the average tension of brachioradialis decreased, whilst 8 of 11 (72.7%) people had the average tension of extensor digitorum decreased.



SUMMARY

	Without Sound Feedback	With Sound Feedback	Difference
Subject 1	628	574	54
Subject 2	361	280	81
Subject 3	499	327	172
Subject 4	638	521	117
Subject 5	416	497	(81)
Subject 6	846	726	120
Subject 7	389	301	88
Subject 8	499	512	(13)
Subject 9	572	531	41
Subject 10	611	438	173
Subject 11	304	281	23

Figure 6.1.3 Tension differences of brachioradialis



SUMMARY

	Without Sound Feedback	With Sound Feedback	Difference
Subject 1	366	301	65
Subject 2	319	387	(68)
Subject 3	731	649	82
Subject 4	267	252	15
Subject 5	604	522	82
Subject 6	354	294	60
Subject 7	480	439	41
Subject 8	360	461	(101)
Subject 9	299	268	31
Subject 10	550	499	51
Subject 11	226	249	(23)

Figure 6.1.4 Tension differences of extensor digitorum

The statistics shows that the sonification system can potentially help piano players for reduce the tension on muscles.

6.1.4 The Feedback and Findings

The feedback from the subjects are summarised in Table 6.1.1 below:

Assessment	Type	Comment	No. Of Subject
Positive	Function	1. Helpful	3 people
		2. Interesting to use	4 people
		3. Gives confidence for long-time practice	1 person
	Sound	1. Very Clear	2 people
		2. Pleasing, can listen to the sound feedback regularly	3 people
		3. The volume is adjusted itself with the change of muscle tension which is nice	3 people
Negative	Function	Not helpful, toy-like	1 person
		I just don’t need it	1 person
		Uncomfortable to play while my arm is wired	1 person
	Sound	It makes bad influence on my sense of pitch	1 person
		Sounds a little stupid	1 person
		Annoying	1 person

Table 6.1.1 Feedback of the initial study

According to the table above, most of people were satisfied with the system and thought it was helpful.

There were also some useful findings:

- The quality of contact between the skin and the electrodes is crucial to get an effective signal. In one session a subject refused to use the alcohol swipe initially and the signal seemed really unstable. Then he agreed to use the alcohol swipe hence eventually clear signals were obtained.
- A thick fat layer can make the signal much weaker than average.
- The quality of electrodes is important too. During two sessions electrodes of a different brand were used, and the signal obtained were quite erratic; then the original brand of electrodes were resubstituted and the signals resumed to be fine.
- 10 subjects found that the extensor digitorum is the muscle they can really feel. For the brachioradialis they can barely feel anything. 8 subjects suggested

that they want to remove the monitoring of the brachioradialis so that they can have fewer wires, to make them feel more comfortable.

- 8 Subjects found that the Czerney Op.740 No.1 was a little too difficult for them to learn/play.

6.1.5 Conclusion

From this initial study we have been able to tell that this sonification system can be potentially helpful when it is used as a support for reducing muscle tension for piano players. In the next chapter some system adjustments are listed and the main experiments are explained.

6.2 Study 2 (Main Experiment)

This section explains the main experiment (study 2).

6.2.1 Introduction

This chapter describes the main experiment of this research. The research aims to show that the sonification system is an effective tool to help piano players to reduce their muscle tension, which corresponds to the main hypothesis.

The experiment setup was slightly changed based on the findings and results of the initial study. Also at this stage subjects were grouped into two categories – a) elite/professional pianists and b) amateur piano players/hobbyists - to see how the system performs with different kinds of subject. The main experimental process as well as data analysis is included in this chapter.

6.2.2 System Adjustments

After finishing the initial study, some adjustments were made:

1) Removed the brachioradialis monitoring while keeping the extensor digitorum.

This complies with the feedback from the initial study.
2) Modified the main interface of MAX patch.
3) Change the music piece to Hanon: The Virtuoso Pianist No.1 to reduce the difficulty but retain the effect that when playing fast the muscles can feel tensed.
4) Set the data sampling rate of MAX to be fixed at 100Hz, because this speed gathers the maximum amount of information but remains at low CPU usage.

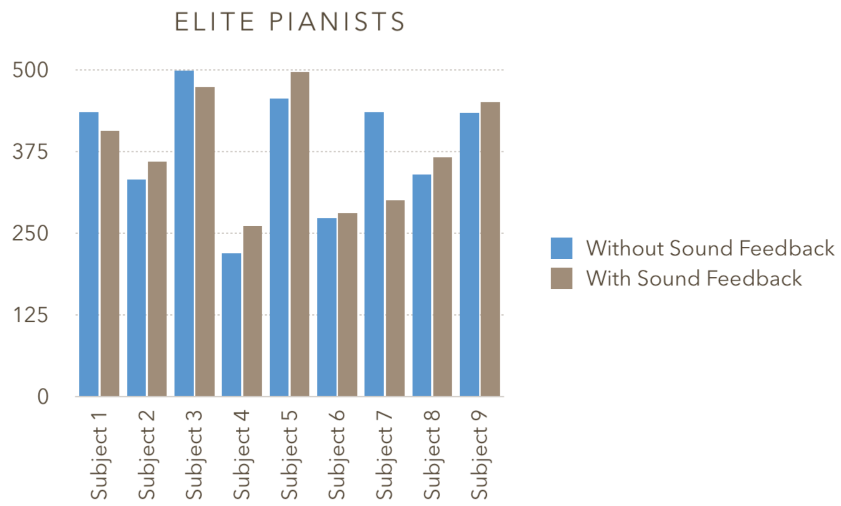
6.2.3 Implementation

In the main experiment the subjects were divided into two groups: elite/professional pianists (n = 9) and amateur piano players/hobbyists (n = 22), 31 people in total.

The process was the same as in the initial study, with the adjustments listed above. A consent sheet explaining the purpose of this experiment as well as data privacy was prepared for them to sign (see Appendix 1). All participants agreed to sign the consent sheet. A separate sheet was given for detailed instructions. After the experimental session subjects were given a questionnaire for feedback. The questionnaire was the same as used in the initial study, only removing the question "Which piece of muscle do you think are the most exhausted" because there was only one main muscle being monitored.

6.2.4 Results

The results of the main experiments are listed in Figures 6.2.1 & 6.2.2 below:



SUMMARY

	With Sound Feedback	Without Sound Feedback	Difference
Subject 1	436	407	29
Subject 2	333	360	(27)
Subject 3	499	474	25
Subject 4	220	261	(41)
Subject 5	457	497	(40)
Subject 6	274	281	(7)
Subject 7	436	301	135
Subject 8	340	367	(27)
Subject 9	435	451	(16)

Figure 6.2.1 Results for elite pianists

SUMMARY

	With Sound Feedback	Without Sound Feedback	Difference
Subject 1	596	505	91
Subject 2	666	280	386
Subject 3	569	521	48
Subject 4	607	550	57
Subject 5	318	279	39
Subject 6	603	726	(123)
Subject 7	365	301	64
Subject 8	648	512	136
Subject 9	475	531	(56)
Subject 10	611	438	173
Subject 11	622	521	101
Subject 12	618	588	30
Subject 13	426	425	1
Subject 14	532	499	33
Subject 15	497	427	70
Subject 16	442	446	(4)
Subject 17	570	427	143
Subject 18	663	616	47
Subject 19	511	563	(52)
Subject 20	580	498	82
Subject 21	568	470	98

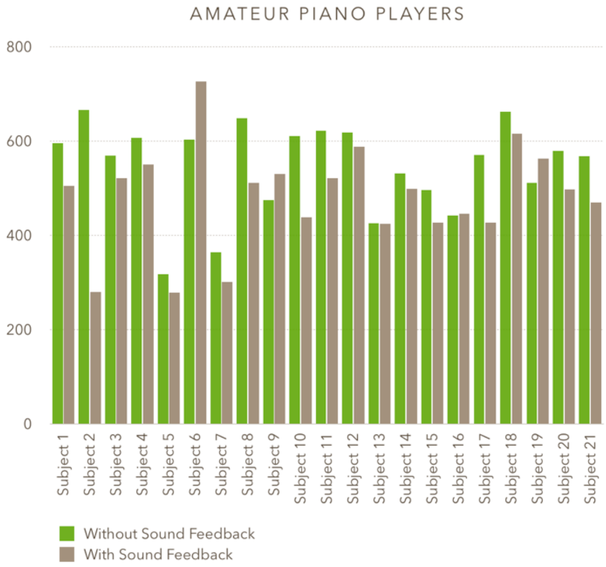


Figure 6.2.2 Results of amateur piano players

Firstly, for the elite pianist group, Fig. 6.2.1 shows that only 3 people (33.3%) had reduced average muscle tension with the addition of sound feedback. The rest actually had their average muscle tension *increased*. However whether increasing or decreasing, the amounts were very small (<50), therefore it is difficult to tell if the sonification system really made some impact on their playing. Also, from the feedback, all (9) of them concluded that their muscle was *not* tensed, despite them already playing the piece really fast.

For the amateur group, one subject quit the experiment halfway through without reporting the reason; therefore the actual total amount of amateur piano players was 21. The result is that 17 (81%) people saw reduced average muscle tension with the addition of sound feedback. Seven (23.5%) of the 17 people had reduced average tension by quite a decent amount (>90).

The feedback from both groups are listed below:

For the elite pianists:

Assessment	Type	Comment	No. Of Subject
Positive	Function	1. Interesting system	5 people
	Sound	None	
Negative	Function	1. I don't need this, it doesn't make sense 2. Almost unable to play piano while my arm is wired, it feels bad 3. The whole system is strange	7 people 1 people 1 people
	Sound	Sounds extremely out of tone Annoying	2 people 3 people

Table 6.2.1 Feedback from elite pianists

For the amateurs:

Assessment	Type	Comment	No. Of Subject
Positive	Function	1. Helpful 2. Interesting to use 3. I'll be using this system if possible	11 people 8 people 1 people
	Sound	1. Very Clear 2. Pleasing 3. The volume is adjusted itself with the change of muscle tension which is nice	7 people 6 people 2 people
Negative	Function	It's useless	1 people
	Sound	Strange, I don't like it Annoying	4 people 2 people

Table 6.2.2 Feedback from amateur piano players

6.2.5 Paired t-test

A paired t-test has been done for the study 2 (main experiment), see the results below:

Mode	ELITE PIANISTS		AMATEUR PIANO PLAYERS	
	Mean	SD	Mean	SD
With sound	381.111	93.5554	547	96.0979
Without sound	377.667	85.8909	482.048	108.346

Table 6.2.3 Paired t-tests

Elite pianists paired t test:

	Statistic	P-Value
Paired T	0.186238	0.856894

Table 6.2.4 result of elite pianists

To test the null hypothesis that the true mean difference is zero. We can see that we have ***no*** strong evidence to reject the null hypothesis in this group, which means that the results from without sound setting have not significant different with that of with sound setting, which means, from this study, the system does not work well on elite pianists.

Amateur piano players paired t test:

	Statistic	P-Value
Paired T	2.93754	0.00814116

Table 6.2.5 Result of amateur piano players

This time the p value is significantly small (0.008), which means after using sound feedback, the system does some help to amateur piano players.

Figure 6.2.3 & 6.2.4 are the bar chart of the t-tests:

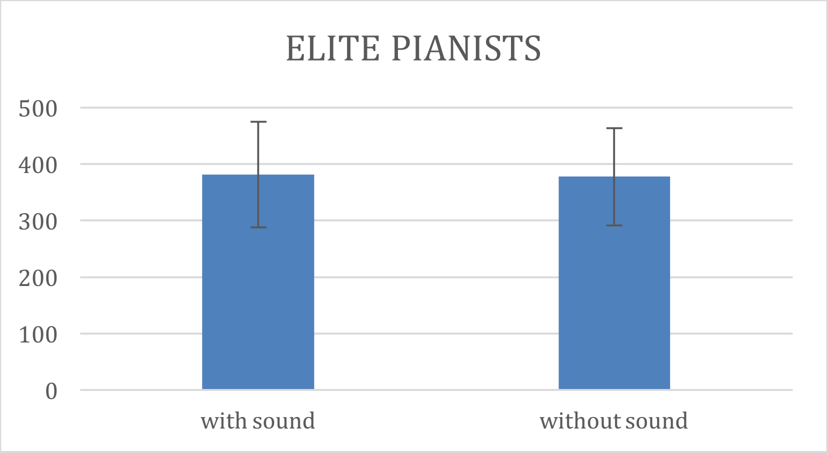


Fig 6.2.3 Bar chart of amateur piano players

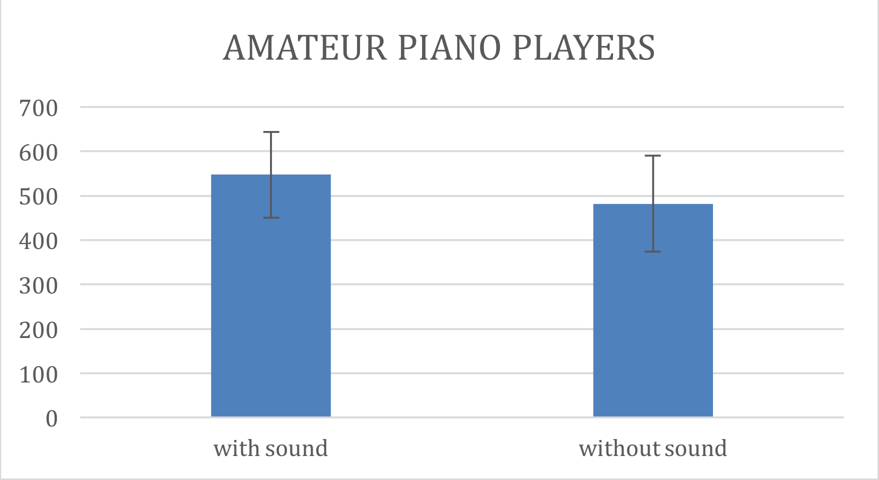


Fig 6.2.4 Bar chart of amateur piano players

6.2.6 Discussion

The differences in results between the two groups are really interesting.

The results from the elite group simply shows that this system does *not* work for them because:

1) they did not like it

2) it made their playing worse, at least they felt so,

3) the statistics show that they did not gain any real benefit from the system.

However, for the amateurs, from the results we can clearly see that the system had some positive impact in reducing their tension. Also from their feedback, 20 out of 21 (95.2%) people gave very positive feedback and only 1 (4.8%) subject disliked the functionality, and 6 (28.6%) people thought the sound was not good. Also from the result of paired t-tests it shows that the system works well on them.

The possible reasons for being more successful among amateurs could be:

- Amateurs are more likely to have bad practices (posture, tension etc.) which can be picked up by the system.
- Amateurs are in the process of learning, and so do not mind getting feedback.
- The elite pianists might be a self-selecting group which have only made it to that position due to extensive training and person-to-person feedback, of which tension reduction could be a part.

6.2.7 Conclusion

The main experiment shows that the system worked successfully with amateur piano players. To summarise, this system is potentially useful for amateur piano players whilst useless at the moment for elite pianists. In the next chapter the hypothesis is reviewed and future work is discussed.

Chapter 7 Conclusion & Future Work

7.1 Introduction

This chapter reviews the hypothesis and summarises findings from this research. The limitations of the research are discussed, with the further work is presented.

7.2 Review of Hypothesis

The hypothesis of this research is:

"By using Sonification feedback it is possible to inform piano players of muscle tension in real-time, which will allow them to reduce tension".

This research has presented a method to help piano players to reduce their muscle tension by using a sonification system. The system was developed with an EMG sensor and Arduino board as the core part of the hardware. For the software, a MAX patch was programmed for gathering and processing the data from the Arduino board. The feedback sound was designed to give piano players information about their muscle tension, but kept simple in order to prevent giving the players too many audio distractions.

The results of the experiment show that the hypothesis is well supported for the large subject group of amateur pianists. Many piano players were informed of their muscle tension in real-time, so that they profitably reduced their average muscle tension.

It was not at all well received by elite pianists, who are a small number of highly trained experts.

7.3 Findings from this research

1) Using sonification can effectively provide useful information regarding the status of muscle tension to users in real-time.
While it is difficult to concentrate on playing the right notes/tones and internally monitoring muscle tension at the same time, the sonification feedback can deal with this very well.

2) The sonification system is not for every piano player, especially elite pianists.
From the results it can be seen that this is true. Further research needs to be carried out to find out the possibility of fine-tuning the system for use with elite pianists.

3) Many people found that using the system is interesting, exciting and pleasing – it is enjoyable.
This supports the assertion that sonification method is an alternative and maybe better way of providing biofeedback.

7.4 Limitations

1) The most obvious limitation is that this system did not work well on elite pianists. Ultimately they do not seem to get very tense muscles as they have developed a good degree of self-awareness. Also due to the years of training, the sonification sound used in this research made them feel very uncomfortable and interfered with the musicality of what they were playing, ironically causing an increase in tension.

2) The hardware uses 3 x 9v batteries but cannot provide a very long battery life, which can cause the use of the system to be expensive; also those 3 batteries increase the total weight of hardware significantly.

3) The learning curve of this system is relatively long. It is not a system can currently be used immediately by new users.

4) Although most amateur players showed that their muscle tension reduced after using the system, it is still uncertain to tell that the system really worked for those people who only reduced the tension by a small amount.

7.5 Further work

During the time that this research has been carried out, various commercial products (especially medical products) have been developed that offer an increase in quality for future experiments. One possibility is to replace the AdvancerTechnologies EMG sensor with the relatively new MYO band (see Fig. 7.1)

Figure 7.1 The MYO sensor band

MYO offers superior quality and precision of gathering EMG data; also the development kit is open-sourced which mean anyone can program on it and use it as an advanced EMG sensor. There are already many applications of the MYO band[23].

For the experiment, subjects only attended a single session; however in order to discover the longer-term potential of the research it would be good if several people could try out the system over weeks or – if possible – months of practice.

Several different sonification methods or sounds could be developed, so that pianists could select the sound which interfered the least with their concentration. There is also the possibility of providing tactile alarm-based feedback, for example by utilising

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[23] https://market.myo.com/

the buzzer alert in a modern smartphone.

In fact if an app was developed for iOS or Android phones, the software could be written to receive data from the sensor device, process it accordingly, produce audio, tactile and/or visual feedback, all in one common device. The app could store and analyse the data over a long period of time.

Maybe a smartphone, combined with an EMG sensor, offers an off-the-shelf integrated package for monitoring muscle tension in real-time. If developed further this has the potential of revolutionising not only the tension monitoring in pianists, but in typists, gamers and office workers, but warning of tension that could otherwise lead to RSI.

For the piano players, they also have a high rate of shoulder injuries. Forward slouching is a problem with some pianists, but the opposite leaning backwards or more commonly over-arching the back, can be just as serious. Hence, the same system developed in this research can be applied on shoulder related muscles to see if the system can help as well as forearm.

7.6 Summary of Thesis

In conclusion, this research has examined the possibility of monitoring muscle tension using a sonification system. The approach was novel; there are rarely examples of using this method for supporting piano players for reducing their muscle tension. To achieve this a system was built containing both hardware and software design, and finally working together to providing useful data/sound feedback to users.

Ultimately, this research shows the benefit of using Interactive Sonification, which is being developed rapidly in relatively recent times. Due to the increased ubiquity of wearable devices, the future of Interactive Sonification is very bright because we can combine the effective ISon technology with the modern tendency towards small, wearable monitoring kits.

Appendix 1 Consent for Experimental Participants

Experiment: EMG Sonification
Experimenter: Lichi Sun
Affiliation: Audio Lab, Electronics Department, University of York

Description: You are invited to participate in the research investigating whether EMG sonification can reduce muscle tension for piano players. You will need to follow the instructions (a separate sheet will be given) of your category to do the experiment. You will have been informed of your category beforehand.
Time involvement: Your participation will usually take approximately an hour.
Your rights: All data taken will be stored *anonymously*. If you feel uncomfortable at any point you can ask for an adjustment to the hardware or software setup, as well as stopping the experiment if necessary.

If you agree with all of above, please sign below. By signing the form, you confirm that you meet the following conditions:

- You are at least 18 years old.
- You have read this consent, understood and agree to it.
- You want to participate in this experiment.

Name (print):
Date:
Signature:

Thanks for attending!
If you have any further questions please send me an email: ls807@york.ac.uk.

Appendix 2 Instructions

1) A few sensor pads will be placed on the skin of your arms (nothing to worry about, it does no harm at all) to collect data of your muscle tension. Before placing these on your skin, I may use alcohol pads to clean your skin's surface to get a better signal (feel free to refuse this for any reason).

2) You'll be asked to a) relax and b) tense your arm muscles for tension range calibration.

3) A pair of headphones will be given; you need these to hear the sound feedback; if you feel you are not comfortable with headphones you can ask for a pair of speakers of hear the sound feedback directly from the laptop as your preference. Please set the volume at a sensible and comfortable level. You'll have a test session to get familiar with the sound feedback system.

4) You'll be given a easy short piece of music, get familiar with it and until you've learnt it you can have as much practice time as you want!
The main experiment starts. Play the piece as fast as you can, repeat from the beginning when you've finished the piece.

5) During playing, you'll hear some sound feedback via the headphones. The sound becomes harsher when your arm tension increases. Please try to relax your arm/finger/wrist/body as much as possible (but please keep playing).
When hearing me saying "stop", stop playing and that's it. Please fill in the feedback form before leaving, thank you for attending!

Appendix 3 Questionnaire for Experimental Participants

Do you like the system? How do you think about it?

Do you think you can relax your muscle actively when there is sound feedback?

Did you feel tired during the session? Which piece of muscle do you think are the most exhausted (you don't need to know the name of it simply point it out)?

How do you find the feedback sound?

Do you think the sound gives you sufficient feedback?

Any comments / suggestions?

Name:

Date:

Signature: Thanks for attending!

Reference

ALLSOP, L. & ACKLAND, T. 2010. The prevalence of playing-related musculoskeletal disorders in relation to piano players' playing techniques and practising strategies. *Music Performance Research,* 3**,** 61-78.

BLATTNER, M. 1989. Earcons and icons: Their structure and common design principles. *Human–Computer ...,* 4**,** 11-44.

BRAGGE, P., BIALOCERKOWSKI, A. & MCMEEKEN, J. 2006. A systematic review of prevalence and risk factors associated with playing-related musculoskeletal disorders in pianists. *Occupational Medicine,* 56**,** 28-38.

BREWSTER, S. A., WRIGHT, P. C. & EDWARDS, A. D. Guidelines for the creation of earcons. Adjunct Proceedings of HCI, 1995.

CRISWELL, E. 2010. *Cram's introduction to surface electromyography*, Jones & Bartlett Publishers.

EFFENBERG, A., MELZER, J., WEBER, A. & ZINKE, A. Motionlab sonify: A framework for the sonification of human motion data. Information Visualisation, 2005. Proceedings. Ninth International Conference on, 2005. IEEE, 17-23.

FERGUSON, S. Learning musical instrument skills through interactive sonification. Proceedings of the 2006 conference on New interfaces for musical expression, 2006. IRCAM—Centre Pompidou, 384-389.

FURUYA, S., NAKAHARA, H., AOKI, T. & KINOSHITA, H. 2006. Prevalence and causal factors of playing-related musculoskeletal disorders of the upper extremity and trunk among Japanese pianists and piano students. *Medical Problems of Performing Artists,* 21**,** 112-117.

GARTHA, I. V. 1976. What is Biofeedback? *Canadian family physician Médecin de famille canadien,* 22**,** 105-6.

GAVER, W. W. 1986. Auditory icons: Using sound in computer interfaces. *Human-computer interaction,* 2**,** 167-177.

GUO, E. 2006. The IMSLP, Petrucci Music Library. *IMSLP/Petrucci Music Library,* 16.

HARMAN, S. 1982. Occupational diseases of instrumental musicians, literature review. *Maryland state medical journal,* 31**,** 39-42.

HERMANN, T. 2008. Taxonomy and definitions for sonification and auditory display.

HERMANN, T. & HUNT, A. 2004. The importance of interaction in sonification.

HERMANN, T., HUNT, A. & NEUHOFF, J. G. 2011. *The sonification handbook*, Logos Verlag Berlin, GE.

HERMANN, T. & RITTER, H. 1999. Listen to your Data : Model-Based Sonification for Data Analysis. *Advances in intelligent computing and ...,* 8**,** 189-194.

HERMANN, T. & ZEHE, S. Sonified aerobics-interactive sonification of coordinated body movements. The 17th Annual Conference on Auditory Display, Budapest, Hungary 20-24 June, 2011, Proceedings, 2011.

HEWETT, T. T., BAECKER, R., CARD, S., CAREY, T., GASEN, J., MANTEI, M., PERLMAN, G., STRONG, G. & VERPLANK, W. 1992. *ACM SIGCHI curricula for human-computer interaction*, ACM.

KAMEN, G. & GRAHAM, E. 2004. Research methods in biomechanics. *Electromyographic knesiology. Champaign, IL. Human Kinetics Publ.*

KONRAD, P. 2005. The abc of emg. *A practical introduction to kinesiological* *electromyography,* 1.

KRAMER, G. 1993. *Auditory display: Sonification, audification, and auditory interfaces*, Perseus Publishing.

KRAMER, G., WALKER, B., BONEBRIGHT, T., COOK, P., FLOWERS, J., MINER, N., NEUHOFF, J., BARGAR, R., BARRASS, S. & BERGER, J. 1999. The sonification report: Status of the field and research agenda. report prepared for the national science foundation by members of the international community for auditory display. *International Community for Auditory Display (ICAD), Santa Fe, NM.*

KUIKEN, T., LOWERY, M. & STOYKOV, N. 2003. The effect of subcutaneous fat on myoelectric signal amplitude and cross-talk. *Prosthetics and orthotics international,* 27**,** 48-54.

LABRANDE, C. & STURROCK, D. 1999. The Art of Piano: Great Pianists of the 20th Century; Les Plus Grands Pianistes Du 20ème Siècle; Die Großen Pianisten Des 20. Jahrhunderts; Arrau, Backhaus, Cortot, Cziffra, Annie Fischer, Edwin Fischer, Gilels, Gould, Hess, Hofmann, Horowitz, Michelangeli, Moiseiwitsch, Paderewski, Planté, Rachmaninoff, Richter, Rubinstein. NVC Arts.

LIM, C. Y. 2014. *Playing-related musculoskeletal disorder among classical piano students of tertiary institutions in Kuala Lumpur and Selangor, Malaysia.* Universiti Putra Malaysia.

PAULETTO, S. & HUNT, A. 2006. The sonification of EMG data.

PAULETTO, S. & HUNT, A. 2007. Interacting with sonifications: An evaluation.

REVAK, J. M. 1989. Incidence of upper extremity discomfort among piano students. *The American journal of occupational therapy : official publication of the American Occupational Therapy Association,* 43**,** 149-154.

SCHAFFERT, N., MATTES, K. & EFFENBERG, A. O. Listen to the boat motion: acoustic information for elite rowers. Human Interaction with Auditory Displays–Proceedings of the Interactive Sonification Workshop, 2010. 31-38.

SCHMITZ, G., MOHAMMADI, B., HAMMER, A., HELDMANN, M., SAMII, A., MÜNTE, T. F. & EFFENBERG, A. O. 2013. Observation of sonified movements engages a basal ganglia frontocortical network. *BMC neuroscience,* 14**,** 32.

SCHWARTZ, M. S. & ANDRASIK, F. 2017. *Biofeedback: A practitioner's guide*, Guilford Publications.

WALKER, B. N. & KRAMER, G. 2004. Ecological psychoacoustics and auditory displays: Hearing, grouping, and meaning making. *Ecological psychoacoustics***,** 150-175.

WRISTEN, B. G. 2000. Avoiding piano-related injury: A proposed theoretical procedure for biomechanical analysis of piano technique. *Medical Problems of Performing Artists,* 15**,** 55-64.

ZAZA, C., CHARLES, C. & MUSZYNSKI, A. 1998. The meaning of playing-related musculoskeletal disorders to classical musicians. *Social science & medicine,* 47**,** 2013-2023.

ZIPORYN, T. 1984. Pianist's cramp to stage fright: the medical side of music-making. *JAMA,* 252**,** 985-989.