Enhancing the Quality and Motivation of Physical Exercise Using Real-Time Sonification

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Abstract

This research project investigated the use of real-time sonification as a way to improve the quality and motivation of biceps curl exercise among healthy young participants. A sonification system was developed featuring an electromyography (EMG) sensor and Microsoft Kinect camera. During exercise, muscular and kinematic data were collected and sent to custom design sonification software developed using Max to generate real-time auditory feedback. The software provides four types of output sound in consideration of personal preference and long-term use.

Three experiments were carried out. The pilot study examined the sonification system and gathered the users' comments about their experience of each type of sound in relation to its functionality and aesthetics. A 3-session between-subjects test and an 8-session within-subjects comparative test were conducted to compared the exercise quality and motivation between two conditions: with and without the real-time sonification. Overall, several conclusions are drawn based on the experimental results: The sonification improved participants' pace of biceps curl significantly. No significant effect was found for the effect on vertical movement range. Participants expended more effort in training with the presence of sonification. Analysis of surveys indicated a higher motivation and willingness when exercising with the sonification.

The results reflect a wider potential for applications including general fitness, physiotherapy and elite sports training.

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In the end, I wish to present my special thanks to Clare Sutherland and Xiaoyin Yang for the time working together at the final period of the thesis writing.

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.

The results of pilot study (Chapter 7) have been published in (Yang and Hunt, 2013). The full paper is attached in Appendix A.

The results of between-subjects comparative experiment (Chapter 8) have been published in (Yang and Hunt, 2014). The full paper is attached in Appendix B.

The results of crossover experiment (Chapter 9) have been published in the 2015 International Conference on Auditory Display (Yang and Hunt, 2015). The full paper is attached in Appendix C.

Chapter 1

Introduction

1.1 Motivation

In recent years, assistive technology and wearable devices have become increasingly popular. To many people, they are still relatively new, but these technologies already existed back in the 1970s (earlier than the Apple Macintosh (1984) - the first commercially successful graphical user interface computer). However, wearable technology has not been widely applied to consumer products until very recently, thanks to the advancement of sensory technology and the miniaturisation of computing.

Currently, modern society is progressing into the 'smart' age. At the time of writing this thesis, Apple has just officially released its smart watch product to compete with other similar products on the market, and indeed it aims to be the market leader and industry standard for wearable computing and timekeeping. A smart watch is not just about having the phone functions such as messaging, emailing and making phone calls. More importantly, the gadget can be used as a fitness tracking device with various internal sensors to collect data on the user's physical activity.

Whether or not smart watches become another global success like smartphones is beyond the author's ability to predict, yet it highlights the inevitable trend of increasing attention on health data. For many years 'gathering health data' has conjured up images of bulky, wire-filled, clinical devices being connected to a person in a hospital or a scientific laboratory. Such devices not only look complex but also appear scary and intimidating to users. Nowadays, health data tracking devices have improved greatly with many sleek designs, consumer-affordable prices, high measurement precision and more importantly integration with common computing technology such as computers and mobile phones. It is the author's firm belief that health-related gadgets will be playing an important role in improving our general health and fitness in the near future.

Sonification, as a relatively new discipline, is a means of displaying data through the use of sound. It can provide real-time interaction for physical activity as it is not restricted by screen size problem or the demand for visual attention. Also, there are many features of our hearing system that make sonification a suitable option for portraying real-time health data in order to improve exercise quality, which will be discussed later on in the thesis.

As sonification designers, we see several issues and opportunities.

Firstly, many fitness-tracking devices, or software applications, focus on giving post-exercise reports rather than real-time feedback.

Secondly, screen displays can be problematic in various exercise conditions. Take a smart watch as an example. The screen's size physically limits the amount of information which can be displayed.

Thirdly, visual display of exercise feedback may not be practical or preferable in many scenarios, such as outdoor activities where the user's focus needs to be constantly on the environment where the exercise or sport is taking place.

These three issues can be overcome by using sound to convey real-time exercise feedback.

To sum up, computing technology is moving in the direction of small-size, sensor-focused devices. Health data is becoming an important focus for many technology companies, as well as the general public. This research aims to improve the quality of physical exercise by using real-time auditory feedback of the exercise information. We hope to encourage more people to become more engaged in physical activity via interactive technology.

1.2 Research Hypothesis

This section presents the research hypothesis, followed by a detailed description.

1.2.1 Statement of Hypothesis

> By listening to real-time sonification of healthy adults' muscle activity along with kinesiological data in biceps curl exercises, subjects are able to improve performance and make better progress, whilst at the same time experiencing improved motivation than subjects who do the same exercises but without any real-time audio feedback.

1.2.2 Decomposition of Hypothesis

First and foremost, this research focuses on real-time sonification. By the definition of Hermann et al. in *The Sonification Handbook* (Hermann et al., 2011), sonification is

> "the technique of rendering sound in response to data and

interactions [p.1]".

To put the definition in the context of the hypothesis, subjects' exercise movement information and muscular activity are the target data, which are used to render the sound feedback accordingly in real time. The properties of the sound, such as loudness, pitch and timbre are controlled by the exercise information. Therefore, the generated sound represents the variations of muscle strength and limb locomotion. By listening to the sound, the user is made aware of the quality of the exercise and can make adjustments if needed.

The real-time sonification adds additional cues to the user about various aspects exercise quality. Shams and Seitz (2008) state that multisensory conditions have beneficial effects on the operation of learning mechanisms. Multisensory training can also be more efficient than similar unisensory training conditions. Therefore, it is hypothesised that this additional sensory perception can provide extra information that is beneficial to maintaining the quality of the exercise.

In terms of general physical exercise, the biceps curl was selected as it is one of the most common exercises, which involves movement of the arm as well as muscular activities. Information about the muscles and kinesiological data during biceps curl exercises are electronically gathered using sensors, and a data transformation process converts these parameters into auditory content.

The decision to only involve healthy adults is based on two considerations. Firstly, it eliminates conditions or injuries that can affect the experimental outcomes. Secondly, this is the most common group in the University of York where the experiment took place. Therefore, this optimised the number of potential subjects who could participate.

This real-time sonification of biceps curls was hypothesised to be able to help the user improve their quality of exercise, as well as their motivation.

In order to gather evidence to support this claim, comparative experiments were conducted to investigate the differences between doing the exercise with and without the auditory feedback.

1.3 Contribution

This doctoral research focused on exploring the effects of real-time auditory feedback on the quality of physical exercise. To achieve this, a sonification system was developed featuring sensory devices including a Microsoft Kinect camera and an EMG sensor belt to measure user's exercise information. Sonification software was created using the Max graphical programming environment to generate real-time auditory feedback. The motion data was mapped to audio parameters such as pitch, loudness and filtering parameters in order to produce auditory events, which represent the variations in exercise movements. These acoustic events contain information related to the subject's kinematics and muscular activity.

Three experiments were conducted in order to support the hypothesis.

The first experiment investigated the user experience of the sonification system. Comments were gathered on whether sonification could provide sufficient feedback of the exercise movement and how much they enjoyed listening to the sonic feedback. The test also provided guidance for fine-tuning the system both in terms of operation and sound design.

The second experiment was a three-session between-subjects test, which compared the exercise quality between participants who did the exercise with real-time audio feedback and another group of participants who did the same exercise but without biofeedback.

Finally, the third experiment involved a crossover trial of two groups of participants doing the same exercise as the previous experiments. Two groups of participants exercised in two conditions (with and without sonification) but in different orders. The training quality was compared, and a qualitative survey was gathered and analysed.

This research presents an example of using purely audio-based feedback for physical exercise. The system creates a screen-free scenario that allows the user to receive biofeedback while exercising. It provides the possibility for a wider range of future applications such as outdoor physical activity assistive devices or physiotherapy training devices.

1.4 Thesis Structure

This section presents a brief description of the contents of each chapter.

1.4.1 Literature Review

Chapter 2 reviews the relevant literature of auditory display and sonification. Their definition and advantages are explained, and some examples of sonification of human body movement are provided.

Chapter 3 contains two parts. The first explains the psychoacoustic knowledge of how we perceive sound and its attributes such as pitch, loudness and timbre. This is followed by design guidance for constructing sonification mechanisms. The second part concerns sound synthesis techniques. FM synthesis and subtractive synthesis techniques are used.

Chapter 4 explains the knowledge of physical exercise and how bio-information can be extracted using sensors. It also highlights the current concern about physical inactivity among the general public. Examples of biofeedback in the physical exercise paradigm are presented.

1.4.2 Main Contents

Chapter 5 describes the research methodology, which includes the experimental design and analytical methods for testing the hypothesis.

Chapter 6 presents the design of sonification system, which includes the sensory device construction and the software environment.

Chapter 7 presents the first experiment of the research. This chapter includes the purpose of the study followed by a full implementation. Results of the experiment are then presented and discussed.

Chapter 8 presents the between-subjects comparative test, which compared the exercise quality of two groups of subjects, one exercising with the sonification and the other without. The implementation is described in detail. Results are explained and discussed.

Chapter 9 is the final experiment of the research. The experiment is a crossover trial to compare the difference in exercise quality with and without sonification for each participant.

Chapter 10 concludes the thesis. The hypothesis is reviewed, followed by the summary and an explanation of the key findings. The chapter also considers the scope of the research, its limitations and the potential future implications for the project.

Chapter 2

Auditory Display and Interactive Sonification

2.1 Introduction

The term *auditory display* (Kramer, 1994b) refers to the means of studying computer data through the use of sound. This chapter provides insight into auditory displays. It begins by explaining the definition and applications of auditory display, then a subset of auditory display - called *sonification* - is detailed. The last part of the chapter presents examples of sonification in the fields of human body movement and physical exercise, followed by a discussion on those examples compared to the research concept in this thesis.

2.2 The Definition of Auditory Display

The job of an auditory display is to help people understand data by converting it into various sounds. An auditory display converts processed data and maps it to sound pressure levels. In other words, an audio signal is used to objectively depict certain properties of the input data (Hermann, 2008) or represents some phenomena (Halim et al., 2006). Auditory displays typically generate (synthesis) audio signals from computing devices to convey information.

Auditory displays give an alternative way to display data in the context of human-computer interaction (HCI), which has been predominantly focused on visual displays. Since the establishment of the International Community for Auditory Display (ICAD) in 1992, the use of auditory display has been attracting more and more attention among researchers. Nowadays, a large range of applications can be found such as alarm systems, data mining, biofeedback, seismology, sports, smartphone applications, arts installations etc. As a medium of studying or portraying data, it is an highly interdisciplinary field- as it can encompass psychology, engineering, arts & music, cognitive science, computer science and many more (Hermann et al., 2011).

In 1994, Gregory Kramer published *Auditory Display: Sonification, Audification, and Auditory Interfaces* (Kramer, 1994a), which systematically established the discipline of auditory display. In this book, Kramer summarised the advantages of using auditory displays in data analysis and interaction. They are:

- The *Eyes-free* condition allows us to analyse or interact with data without visual contact. It can be highly beneficial in many situations. Firstly, visualisation cannot work for visually impaired users. Secondly, visual displays can sometimes be blocked by other objects or become difficult to perceive in low light conditions. Thirdly, some situations require the user to focus their visual attention elsewhere, such as during a medical operation, while undertaking outdoor physical activities, when working on a factory floor, which makes visual feedback harder or even dangerous to be included.
- *Rapid detection* indicates our auditory system is highly responsive in picking up acoustic energy variations. This hints that variations in the data can also be detected promptly via an auditory display. This

advantage is also strongly linked to the next point.

- Auditory display can be very *alerting*. Sound is often the default option in alarm systems. Visual displays in these situations lack the ability to deliver urgency in comparison to sound because they are selective and can be easily blocked. An auditory alarm, on the other hand, can quickly deliver a sense of urgency and it is almost unavoidable as long as enough acoustic energy can reach the person's ears (Guillaume et al., 2002).

- Auditory displays can be used as a background signal with low attentional priority, which allows operators to focus their attention on the main task yet still maintain awareness of the auditory information. Background auditory displays are used to improve pilot situational awareness. In (Kazem et al., 2003), spatial audio is explored in aircraft operating situation to sonically project environmental objects such as mountains, other in-flight aircraft, etc. Information including the type of object and its spatial location is projected sonically to the pilots as background sound. This helps to improve pilot's awareness of the environment, and also being non-disruptive, allows pilots to focus on flying the aircraft.

- Multiple streams of auditory displays can be monitored simultaneously because of our ability of *parallel listening*. We can perceive and distinguish multiple sounds at the same time, which makes high-dimensional auditory displays feasible, such as the analysis of multivariate data sets (Flowers, 2005). Effenberg et al. took the approach of mapping four movement attributes during indoor rowing to the musical notes of four different musical instruments to provide real-time sonification to the rower (Effenberg et al., 2011).

- Kramer considers the *acute temporal resolution* as one of best assets of auditory displays, as our ears are highly accurate when perceiving variations in acoustic energy. Our temporal acuity is in the region of a few milliseconds to several thousand milliseconds, which indicates a great potential in analysing time-sequenced data sonically. In McIntosh et al.'s study, rhythmic auditory cues were used in an attempt to improve gait patterns of patients with Parkinson's disease (McIntosh et al., 1997). They found that the physical action when accompanied by an auditory cue is 10% faster than their baseline movement, and thus significant improvement is shown with the use of auditory display. This suggests that auditory information has influenced patients' movement and the patients made an effort to match their gait pattern to the rhythmic cue.

- Lastly, *auditory gestalt formation* means that we can perceive the overall trend of data via sound, which can help us to pick out meaningful events from a stream of data. Auditory patterns can be easily recognised and remembered.

However there are some disadvantages, which should be taken into account when designing an auditory display system. Some auditory display designs use monotonous sounds, e.g. a direct pitch change of a sine tone in correspondence to temperature change (Walker and Kramer, 2005). These types of mapping are straightforward and easy to understand but also prompt annoyance and listening fatigue over long term use. Non-speech sound is not good for delivering absolute values from the data. A single graph of data (X-Y plot) can visually display output values (Y) given the input (X) on the graph. To achieve the same result using auditory display is very difficult. However, auditory displays have been found useful in perceiving the general tendencies, distribution and variability of the data. The studies from (Flowers and Hauer, 1992, 1993; Peres and Lane, 2003) explored the use of auditory displays in analysing histograms and boxplots. Flowers and Hauer found that auditory display can be effectively used to study these types of statistical graphs (Flowers and Hauer, 1992). Yet in the follow-up study in (Flowers and Hauer, 1993), the combination of auditory display and visualisation was used to study numeric distributions. No improvements were found. (Peres and Lane, 2003) continued Flower's research on studying auditory display of boxplots by asking participants to match auditory display representation of a box with visual graphs. Although participants found it difficult, improvement in the accuracy of matching was found after a certain amount of practice. In summary, although auditory displays are not effective at presenting the absolute values of the data, distribution/centre tendency can be conveyed effectively, which are often considered to be more important in statistical analysis.

2.3 Sonification

This section presents the insight of a more focused area of *auditory displays* called *sonification*. Techniques and examples of sonification are also presented.

2.3.1 The Definition of Sonification

Sonification was first established by Kramer in 1994 (Kramer, 1994b) as a subset of auditory display. Sonification is defined as the interpretation and transformation of data into perceivable non-speech acoustic signals for the use of conveying information. The definition of sonification gravitates more towards the *rendering* of sound from data through specific algorithms whilst auditory display refers to a more general approach for using sound to portray data. Sonification has been applied to many disciplines from scientific analysis to musical composition (Grond and Hermann, 2012).

There are many reasons why increasing attention has been focused on studying data through auditory perception, one of which is that the temporal perception is highly accurate. Human are highly capable of hearing not just slight frequency shift, but noise, pulses, repetition, rhythm, glitches (discontinuities) and level changes. Another beneficial aspect of acoustic perception is that it is possible to perceive multiple simultaneous audio signals (Kosunen et al., 2010), in other words we are highly capable of multitasking while using sonification systems. The auditory signal provides extra cues of the user's action e.g. motor control learning as a mean to increase the awareness and performance.

Figure 2.1 shows a basic outline for the process of sonification. The process itself consists of two major functions: data transformation and algorithmic implementation. Input data sources are shown on the top left side of the figure, which could be anything such as human gestural movements, astronomical information, seismic records and so on. Data generated from these sources is stored in a computer in numeric form. Then, the sonification algorithms define how the data is processed. Algorithms can be regarded as representation strategies with precise mathematical calculations for processing the input data to produce certain output values (Cormen et al., 2001). The algorithms convert the input data into control parameters, which are used to drive the audio engine and generate sonic outputs accordingly.

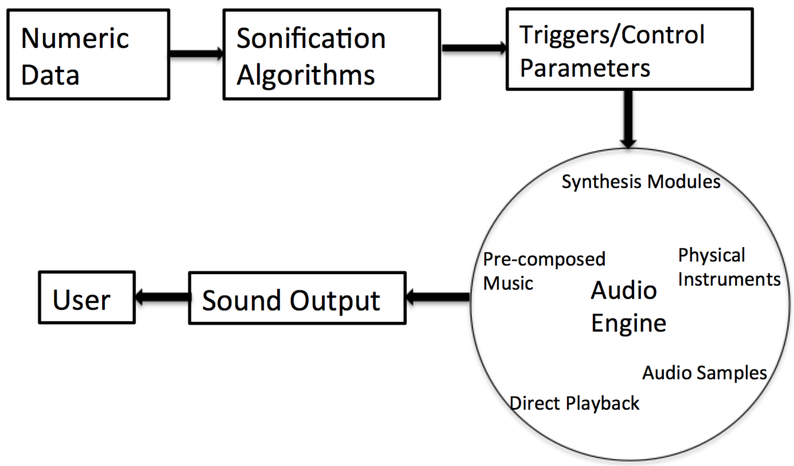


Figure 2.1: Pictorial representation of the sonification process

In an artistic system, (sometimes the term sonification is used by artists to describe the composition of music which is based on data) algorithms can be freely designed without any restriction. In other words, for an artistic system it is the aesthetic quality of the resultant sound which is the more important goal. However, for scientific analysis, good algorithms are needed to preserve the unique information of the sources. Such algorithms link up the output and the input logically so that by studying the output sound the user will gain insight about the original data.

Sonification processes, such as found in alarm and auditory monitoring systems, are referred to as “Open-Loop” systems because the resultant sound marks the end of the processing chain. In these systems, the current output will not affect any further output as it is directly representing the data. By contrast, when a sonification is *interactive*, it serves an additional purpose which is to allow the manipulation of data based on the user’s perception of the sonified data. Hence, instead of perceiving data passively, users make actions based on the output sound, which creates new data, which in turn leads to new sonic feedback. Under this procedure, the system becomes a *Closed Loop*, which means that the system’s output is dependent on the system’s input as well as previous output (via the user’s actions).

2.3.2 The Classification of Sonification

Hermann et al., in *The Sonification Handbook* (Hermann et al., 2011), state that there are five main sonification techniques: audification, parameter mapping sonification, auditory icons, earcons, and model-based sonification.

(1) Audification

This is the most direct method of sonification, to be used where the input data is rich in content and can be directly played as a *waveform* (Kramer, 1994b). Mainly, this technique is suited to dealing with the study of single dimensional data, which is time-ordered, but is not originally in the form of sound. Also, it also requires the data to have a wave-like shape (Dombois and Eckel, 2011) e.g. an EEG/EMG signal[1]. A comparison is shown in Figure 2.2, in which the muscle activity recorded using an EMG sensor shared some similarities as the audio signal.

[1]EEG: brain activity. EMG: muscular activity. Details of EMG are presented in Section 4.4

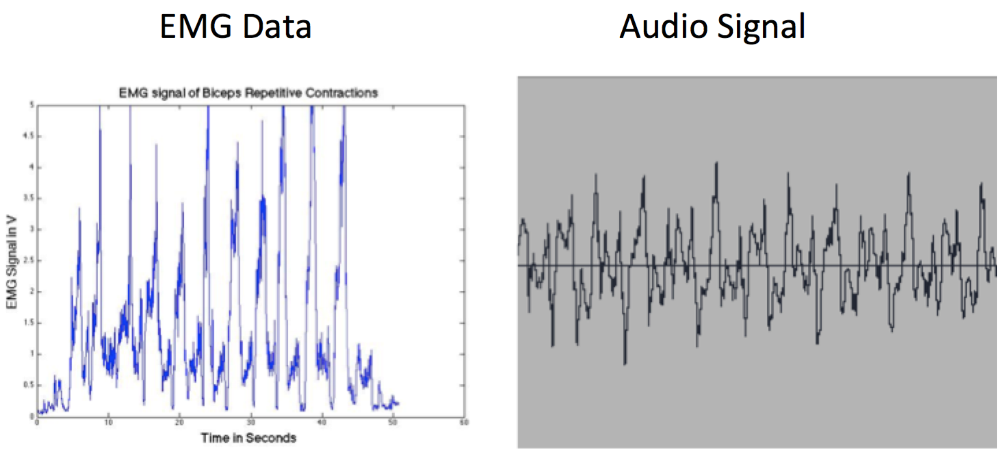


Figure 2.2: An graphical comparison of a muscle activity graph and an audio signal

For example, seismic data are usually presented via seismograms which indicates the movement of the earth through time. However, the amount of the data points is enormous and the data themselves are similar to acoustic waves. By accelerating playback of the data to a point that the variations in data can form audible speaker vibrations and compressing the amplitude we are able to hear the data directly. This auditory seismology in conjunction with data visualisation improves the quality of the analysis (Dombois, 2001). (Pirro et al., 2012) has also applied audification to sonify the acceleration of tremor movement data.

Despite the directness of *audification*, much data is not suitable for this method. *Audification* is normally suitable for one-dimensional signals. It often results in quite a noisy sonic output, and so using multiple dimensions/streams is very likely to result in an even noisier output, making it extremely difficult to analyse. If the data is too short or does not contain similar shapes to an acoustic wave, *audification* will not create appropriate speaker movements to generate sound.

(2) Parameter Mapping Sonification

Parameter mapping sonification offers more possibilities and complexity in sonifying either single channel or multivariate data. The word ‘mapping’ refers to the transfer function between input data and output data. In this case, a particular sound is generated because particular input characteristics are met. Parameter mapping often utilises audio synthesisers as they are the most direct medium for providing a wider controllability over sound parameters.

Parameter mapping has many advantages. The inherently multidimensional characteristic of sound indicates the possibility of displaying multivariate data (Grond and Berger, 2011). When we perceive a sound, we simultaneously perceive multiple parameters of the sound, including the pitch, volume, timbre and temporal structure. Then same process can occur with perceiving multiple sound sources simultaneously. Because of this ability, we can map multiple channels of data to these sound parameters and the user, in theory, will be able to perceive them all.

The cartography of mapping is shown in Figure 2.3, which presents three types of parameter mapping.

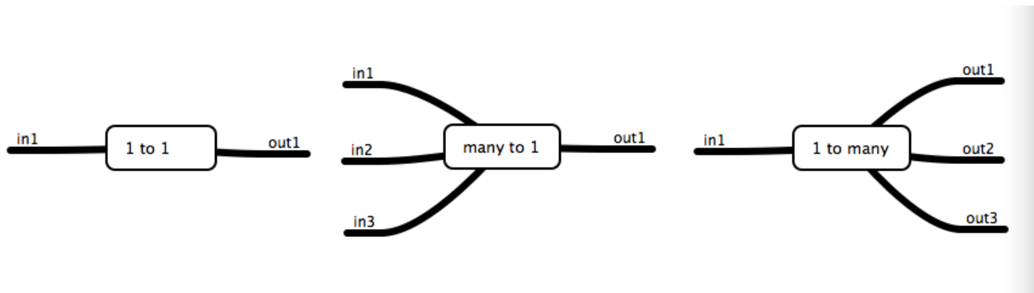


Figure 2.3: Three types of mapping method

1-to-1 mapping This is the most direct mapping type as it links only one stream of input data to serve as a single control parameter of the sound.

When, for example, mapping stock market values to the frequency of a synthesiser, we can perceive the changing values as a fluctuation in pitch (Brewster and Murray, 2000). Numerical 2D graphs (x-y) have been sonified to allow visually impaired users to study statistical data. This is done by mapping the y values of the graph to the pitch of a synthesis sound and x values to the timing (Mansur et al., 1985).

many to 1 This usually occurs in a more complex situation, where multi-channels of input data are being sonified and studied. *Many-to-1* mapping requires several inputs in order to generate one stream of output. In the physical world, this is a very common occurrence within musical instruments, where the acoustic outcome is dependent on more than one physical contact with the instrument using both the player's hands, mouth or feet.

1 to many This method uses one data stream to drive several parameters of the output sound simultaneously. An example can be found in (Degara et al., 2014), which presented a sonification challenge for creating an auditory display to play a walking video game (to control an avatar to walk to a destination while avoiding obstacles). The team proposed a method using a synthesis pulse sound to portray the distance between the avatar and the destination. The input parameter (distance) was mapped to the pitch and also the rapidness of the repetitive tone. As a result, the player could get a direct sense of distance through the pitch of the sound and at the same time the decrease of the sound interval made the sound more salient.

A concern in parameter mapping is that there seems to be a lack of standardized mapping schemes. Walker and Kramer (2005) conducted an experiment to study the subjective experience of four different sound parameters (pitch, onset sharpness[2], loudness and tempo) applied in four different data sets (temperature, pressure, size and rate). Four sets of mappings were created and compared, e.g. "Intuitive mapping" (pitch to temperature,

[2]The onset sharpness is the attack of the amplitude.

pressure to onset sharpness, size to loudness and rate to tempo) to “Bad mapping” (temperature to onset, pressure to pitch, size to temp and rate to onset sharpness). The results are not as expected since the “Bad” mapping actually performed better. This emphasizes the importance of empirical tests for sonification mapping. For individual sonification designers, it is important to conduct user experience studies before finalising the sonification design in order to achieve a better performance. And the mapping strategy ought to maximise its reasonable connection with the data stream to provide the user with a cognitive impression that makes most sense. This leads to considerations such as:

- Should the increase of input value cause the increase of output parameter(s), or the opposite?
- Should the input and output both have the same linearity?
- What is the appropriate scaling? e.g. Whether the sound will be in a reasonable level of volume and pitch?
- How natural is the relationship between the sound parameter(s) and the input(s)? This is a more open question which normally requires actual testing to find out.

The complexity of mapping varies in different applications. A simple mapping scheme can be more intuitive than a complex one, and this reduces the time taken to learn it. A complex mapping scheme may risk causing confusion and difficulty during the interaction, yet has the potential to create a more sophisticated interaction. People tend to quickly lose interest in oversimplified interaction as it is not so engaging as challenging interaction (Hunt and Kirk, 2000), so a good balance of complexity can enhance the aesthetics of use of a sonification system and optimise its usability.

(3) Auditory Icons

Auditory icons use non-speech sounds that are familiar in the physical world to represent related events. It is a metaphorical method of representing events sonically using commonly known sounds, which have a natural relationship with the events. Hence, auditory icons can in situations where the events to be presented have some natural sonic connections with particular sounds.

Auditory icons have been widely applied in many computer interactions and alarm-based systems. For example, when deleting a file on a PC, the paper crumpling sound is a typical *auditory icon*. The sound of thunder can indicate something urgent. The use of applause denotes a successful event. Similar to visual icons, auditory icons create impressions and representations of particular objects or processes using sounds (Walker and Kramer, 2004). Also, auditory icons have application to improve safety issues. Simulated car engine sound can be used in electric cars driving as they tend to be too quiet and can be lack in awareness for both pedestrians and drivers (Nyeste and Wogalter, 2008).

Auditory icons generally use either pre-recorded samples or synthesised sounds. Pre-recorded samples capture or represent real-world sounds to be used in the icon. However, we can also use a synthesiser to mimic everyday sounds. The advantage of synthesised auditory icons is that the sound can be varied more easily, and tweaked to suit the data. No matter what design method is chosen, the key requirements of auditory icons are being identifiable and concise (a few seconds or even less than a second).

(4) Earcons

Earcons are also sonic representations of iconic information or events. They are non-speech audio messages used in human computer interaction to inform the user about the progress of the interaction or the operation being made (Blattner et al., 1989). However, the main difference between *earcons* and *auditory icons* is that an earcon itself does not have a natural relationship with the event. Earcons instead convey data based on their musical impression, which is a combination of melody, rhythm, and timbre. For example, the iconic musical sound played when a PC starts up contains all the elements mentioned above and can be considered as a very small musical piece. Yet the purpose is not related to its musical quality but rather as a notification to let people know that the computer is ready for use. The connection between the sound and the message is purely metaphorical. This also means that if a person has not heard of these synthetic tones before, they will not have any implicit understanding of the meaning of the sounds. Hence *earcons* must be learned in order to understand their meaning.

The synthetic characteristic of earcons provides a wealth of possibilities for designers (Brewster et al., 1993). For instance, we often use the word 'catchy' to describe a popular song as being appealing and memorable. A well-designed earcon shall carries the same characteristic of delivering information effectively and being easily remembered. Earcons are often found in games, where sounds indicate particular events being triggered or completed. An ascending melody can be used to indicate that the player has completed a mission, whilst a descending one may indicate failure. The connection between *earcons* and data is often unique, meaning that one earcon will only deliver one particular message from the data.

There are some design guidelines provided by other researchers. Firstly, (Brewster et al., 2014) suggests that the length of earcons should be kept short, which is similar to auditory icons. It would be irresponsible to play a one-minute song to let people realise there is a fire and get out of the building. Most earcon designs consist of only a few musical notes and last less than a second or two. Secondly, if multiple earcons are played simultaneously or with overlaps, it is better to use distinctive timbres for each stream of audio to prevent masking[3]. Thirdly, the icons should be attention grabbing.

[3] Masking describes a sound source being made harder to perceive - or even inaudible - by the presence another. Details of masking are presented in Section 3.2

(5) Model-Based Sonification

Model-based sonification (MBS) provides virtual physical models for the user to interact with in order to make sound. The sonification responds to excitation from the user's actions (hitting, scratching, stepping, popping, clicking and etc.) so that the sonic output can be triggered and will evolve according to the interactions. Model dynamics are determined by algorithms which respond to the change of input states in time. This type of sonification is also highly capable of achieving not only complex but also natural sonic outcomes, which can logically link to the physical excitations of the models (Hermann, 2011). Physical modelling synthesis is a common method for generating auditory output as it is also built from mathematical models of real-world physics. Yet the downside of MBS is that it can require relatively large amounts of computational power. Other synthesis methods such as sample-based synthesis, FM synthesis and etc. are also capable of being applied in MBS.

MBS has been used in data exploration including data particle trajectory and sonograms, designed in (Hermann and Ritter, 1999). Multi-touch interaction for data sonograms using MBS was carried out in (Tünnermann and Hermann, 2009). Musical gesture analysis also embraces the use of model-based sonification. Grond et al. (2010) developed an interface combining gesture modelling and movement sonification of timpani playing. The timpani player's gestural movement and muscular activity were both recorded in order to create the virtual model.

(6) Summary of the Classification

In summary, the five sonification methods are all capable of conveying information. For time indexed data, audification and parameter mapping can be good options. To deliver short pieces of information such as notifications, icon-based sonifications (auditory icons and earcons) are designed for this purpose as they are compact. Model-based sonification is capable of creating continuous dynamic interaction, which makes it suitable for more complex data interaction with a user in real-time.

2.4 Examples of Interactive Sonification

This research studies the use of interactive sonification in general physical exercise. Therefore, this section presents some of the related examples using interactive sonification in human gestural movement and physical exercise.

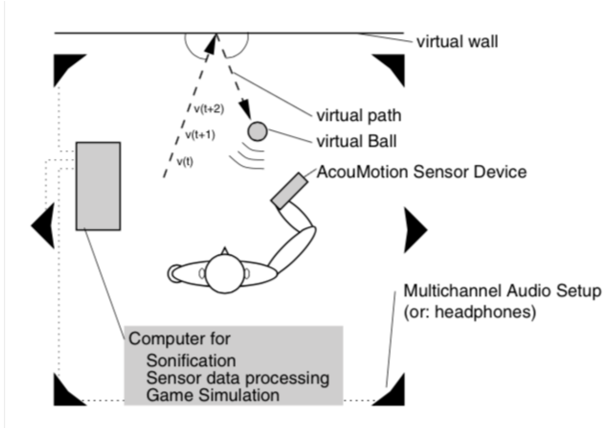


Figure 2.4: Pictorial demonstration of the Blindminton setup. Picture is taken from (Hermann et al., 2006).

(1) Blindminton (Hermann et al., 2006) is an eyes-free interactive sport game developed using a sonification system called AcouMotion. The game is similar to badminton except that sounds are used instead of real shuttlecocks. The movement of a virtual ball is simulated in a virtual 3-D space with walls and floors. The trajectory of the ball is presented as sound and therefore the changes in sound indicate the change in ball position. A haptic motion sensor device is used as the racket to interact with the virtual ball. The player needs to listen to the sound to deduce the distance and position of the ball in order to make a successful hit. A graphical representation is shown in Figure 2.4. This research is an excellent example of exploring the use of sonification in the realm of human body movement and physical exercise. It is a sonification-oriented sport/game activity. This application illustrates that

tactics and movements in sport can be guided by auditory information only.

(2) In PhysioSonic (Vogt et al., 2009), a camera tracking system with markers attached on subject is set up to study shoulder movement and to provide both metaphorical and musical audio feedback (auditory icons). The system motivates patients with arm abduction and adduction problems via the synthesised or sampled feedback. The audio content is generated according to the height of lifting the arm and the velocity of the lifting action. This extra acoustic cue can enhance the awareness of limb spatial movement. This research targets rehabilitation patients specifically, yet the concept can also be applied to healthy subjects in general physical exercise.

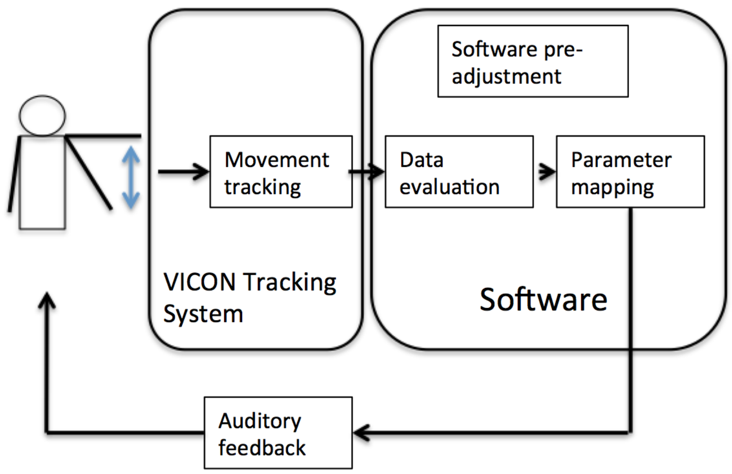


Figure 2.5: Block diagram of the system setup

(3) MotionLab Sonify is a sonification program developed by Effenberg et al. (2005) to detect kinematic movement and force and to appropriately map those parameters into sound generation in order to aid motor control and motor learning. In testing, a user's movement was captured by the VICON motion-tracking system[4]. Markers were put on the user's body and from this, a kinematic skeleton was reconstructed and displayed on the monitor. At the same time, kinematic information was sonified based on the movement

[4]http://www.vicon.com/

dynamics. The sound used in this research was based on musical notes using MIDI. Figure 2.6 presents a screenshot of its software environment. The above research provides wide possibilities to enhance movement perception e.g. temporal precision providing with extra acoustic cues. It has the potential to integrate in applications for sport science, rehabilitation, psychology of perception and cognition, etc.

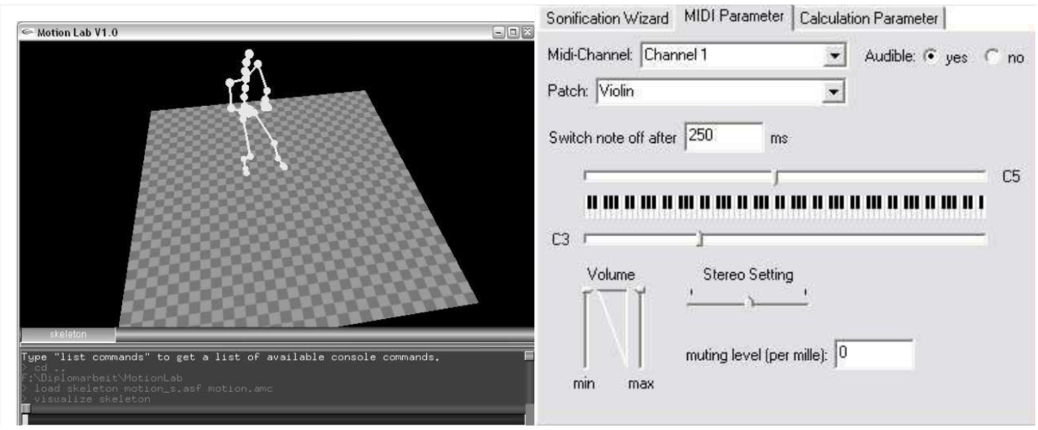


Figure 2.6: MotionLab, picture is taken from (Effenberg et al., 2005).

(4) Ghez et al. developed an accelerometer-based device combined with the graphical programming software Max/MSP[5] to sonify patients' spatial location and joint motion in order to compensate for a lack of proprioception (Ghez et al., 2000). Proprioception is a positional sense allowing humans to make accurate limb movements without looking at them directly (Surve, 2009). This sense allows us to accomplish many complex tasks in daily life, such as driving. In Ghez's research, two experiments were conducted. The first was to make an out-and-back action with the arm, mimicking the gesture of slicing a loaf of bread in time, with an external auditory timing signal provided. The second experiment used auditory feedback of the elbow motion to guide the out-and-back movements to a specific spatial trajectory. For sonification, a downbeat sound was played when the action onset occurred, whilst an upbeat sound was played when the reversal action occurred. These were accompanied with melodic and notification sounds (reminding user of

[5]https://cycling74.com/

the correctness of the time of actions). Patients with proprioception deficits would try to focus on reproducing the 'correct' sound, which indicated a 'correct' run.

(5) In Matsubara et al.'s study, both visual and auditory feedback were applied in the voluntary ankle dorsi- and plantarflexion exercise (ankle movement exercise as shown in Figure 2.7) (Matsubara et al., 2013). Participants were asked to put on a sensory device called an ankle-foot orthosis, which is a wearable device for ankle rehabilitation. The experiment involved asking participants to move their ankle based on a reference movement, which was presented either visually or sonically (directly mapping the ankle angle to the audio frequency). The results show that the performance of using visual feedback is better than using the auditory feedback in both timing and accuracy. However, the difference is not considered to be very large. The researchers argue that the auditory feedback has good potential to be applied in situations where visual feedback is impractical, such as bedridden and visually impaired patients. Although visual feedback is still more effective in many cases, this example shows that the effectiveness of auditory feedback can also be satisfactory. This opens up a wider possibility to develop multimedia assistive tools for monitoring and improving human body movement.

Figure 2.7: Experimental set-up. Picture is taken from (Matsubara et al., 2013).

(6) Chiari et al. (2005) developed a prototype of a real-time sonification system for balance control/training in physical therapy. In the experiment, an accelerometer-based device was developed and used to extract the horizontal acceleration of the trunk kinematics. This kinematic information was mapped to control synthesiser parameters such as frequency, volume and panning. In the experiment, participants were asked to stand on a force plate (Fig. 2.8) with three different conditions: eye-closed (to eliminate any visual cues), eyes open/closed with foam under the feet (to increase balancing difficulty). The auditory feedback was given based on the movement acceleration in the anterior-posterior (front-back) and medial-lateral (left-right) direction to display to the participants the movement of the body (body sway).

The results show a significantly smaller distance adjustment of center of pressure in eyes closed and eyes closed with foam conditions, which means subjects adjusted the balance more efficiently. A significant improvement was found in the mean velocity of center of pressure (quicker and more frequent postural adjustment) under the eyes-closed with foam condition. The results show a potential for use in rehabilitation at a clinic or in the home environment.

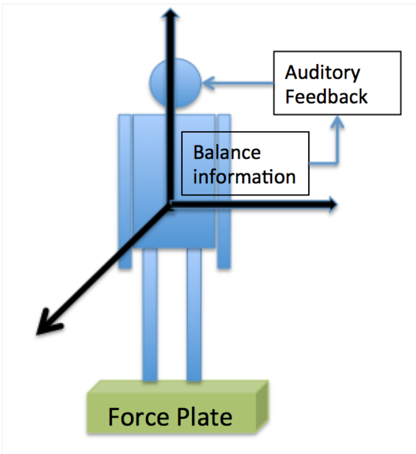


Figure 2.8: Pictorial demonstration of balance sonification setup

(7) Großhauser and Hermann (2010) developed a multi-sensory wearable sonification device to create real-time audio-haptic feedback of human body

movement. The sensory inputs consist of acceleration, rotations, switches and angles of lower limb movements such as dancing, jumping and walking. This device is designed to be used in virtual reality and motor learning situations. An advantage is that the device is adaptive and can be adjusted to suit different types of activity.

(8) Sonification has been used increasingly in rowing analysis in recent years, perhaps due to the real-time temporal feedback that can be given via audio to a team of rowers. Schaffert et al. developed a sonification system called Sofirow (Fig. 2.9) to be used in rowing during on-water training sessions (Schaffert et al., 2010a). Using this system, details of rowing-strokes can be perceived acoustically, so that athletes are able to judge whether the stroke is good or bad, and can thus make real-time adjustments. The experiment compared the time results of different training scenarios with and without sonification. Questionnaires were used to understand the effect of using sonification on the athletes. Through statistically verified results, the system shows an outstanding effect in increasing boat velocity yet very little effect on stroke rate. However, the questionnaires show delightful feedback from athletes as most of them are convinced by the system. Continuation of this research is documented in (Schaffert et al., 2012b, 2013). This application is an example which shows the advantage of using sonification to improve rhythmic movement. The high temporal resolution of sonic feedback can potentially link to an improvement of body coordination in sport activities.

(9) Dubus and Bresin point out that the conventional haptic feedback perceived in sports to distinguish good and bad movements can be technically difficult and obtrusive to perceive during training. Extra feedback can potentially improve the efficiency of training by allowing participants to better understand their quality of movement (Dubus and Bresin, 2010). A pictorial demonstration is shown in Figure 2.10. They measured stroke position and velocity among Olympic level rowing athletes using a mobile phone GPS receiver and wireless accelerometers and mapped to the frequency of a pure tone or MIDI notes to synthesise sound. The test survey indicates that rowers

Figure 2.9: Sofirow used in rowing training. Picture is taken from (Schaffert et al., 2010a).

and trainers found the sonification interesting to use and easy to comprehend. However, there is still room for improvement in the aesthetics.

Figure 2.10: A Symbian S60 smartphone was used in the experiment for acquiring movement information. Picture is taken from (Dubus and Bresin, 2010).

(10) Sonification researchers show interest in developing assistive tools for outdoor sports activities because generally the use of gadgets with sustained visual feedback is impractical in an outdoor environment, and while visual focussing on the sporting task itself. Barrass et al. (2010) conducted a pilot study with 15 adult participants to establish the preference between six different interactive sonifications during a 10-minute jogging session. The sonification software was developed on an Apple iPod Touch, and it sonified the x, y, z information collected from the iPod's accelerometer. Participants could select between six types of sonifications: Frequency Modulation based

algorithmic music, continuous synthesis sound, real-life sounds (weather sounds), vowel-like formant synthesis sound, composition-based music with a rhythmic sound and a rhythmic based sound which matches repetitive movement. Participants generally found the algorithmic music and continuous synthesis and composition sounds interesting to listen to while jogging. The research survey showed that some of the participants paid more attention to the quality of the listening experience instead of the information provided during the jogging session. This is a reminder to us that, as scientists, we maybe interested in the quantifiable data, yet users are more often concerned with the immediate aesthetics of the sound. Overall, the study showed the potential of creating a more mature and informative portable sonification device to let people do better quality outdoor recreational exercise.

2.5 Overall Review of the Past Examples

The above examples support the premise of applying sonification in improving the quality of physical movements, by serving as additional cues to the movement attributes. Some of them work as the direct representation of the movement; others work as a reminder to notify the user about the quality of the analysed movement.

Notice that most of these projects have highly specific users; most of them are professional athletes or patients who require physical rehabilitation. Many of the projects appear to be cutting-edge and distanced from the general public. A possible result of this trend is that sonification could be marginalised from the general public and give the impression that sonification tools are created just for ‘special needs’. Note now this is opposite to the trend of wearable technology. In the past, most medical devices for bio-information measurement were highly expensive and could be only afforded by organisations such as major hospitals. Fitness-tracking devices were regarded as advanced technology and only existed in high-end sport facilities. However, in recent years, with the advance of mobile technology and sensory technology, we are experiencing a new age of affordable mobile device and wearable technology. The popularity of the mobile application market creates the chance of developing useful health related devices or apps, which are affordable and easy to use for the general public. Hence, sonification should stay close this trend to become closer to the general public.

The difference in target groups can also affect the sonification design both functionally and aesthetically. For example, in elite sport training, athletes are not only highly driven but also generally obedient to the coaches. Therefore, the motivation and attitude of feedback device are very positive. In this situation, the sonification design can gravitate towards delivering the most accurate display of data to precisely reflect the quality of movement. Yet for the general public, things can be very different as the usability and aesthetics are more important to retain their interest. The sonification designs require a balance between being informative and interesting/pleasant to use in order to attract more users. This often involves certain levels of trade-off as it generally difficult to achieve great results in both aspects.

From another aspect, very few publications are found which conduct studies on auditory feedback in general physical exercise. Hence, after a thorough literature survey we conclude that there is potential to investigate the effects of doing general physical exercise while listening to the sonification among healthy adults.

Chapter 3

Sound and Hearing

3.1 Introduction

Hearing can be regarded as the processing of frequencies and intensities of the received acoustic energy (Palmer, 1995). Sound allows us to instantly answer questions such as '*What does that sentence mean?*' '*Is the car getting closer to me?*' '*Is it made of wood or metal?*' etc. We are also capable of perceiving acoustical attributes such as whether the pitch goes higher or lower; how loud one instrument is compared to another; whether it produces sound energy continuously or in a percussive manner, etc. Because our ear-brain system is able to pick up and comprehend these types of information we can extract useful information from data sets via auditory display. Hence, it is important to understand the physics and psychology behind sound and hearing in order to design an appropriate sonification system.

This chapter explains three main properties of sound: loudness, pitch and timbre. The reason to focus on these three features is that they are the key components for the parameter mapping in the sonification system. An introduction to the general listening experience follows, divided into musical listening and everyday listening. Next, the reason that auditory displays have promising potential in data interaction is explained. The final section focuses on sound synthesis methods as they were applied in the sonification system development for the experiments.

3.2 Loudness

Loudness is predominantly dependent on the variations in the intensity of a sound, although other parameters may also affect it, such as background sound, spectrum and duration (Roads, 1996). The sound intensity is measured in *sound pressure level* (SPL), which is described as

$$SPL = 20 \times log_{10}(\frac{P_{measured}}{P_{reference}})$$

where the reference pressure in the air $P_{reference} = 20\mu Pa$, which is the threshold of hearing at 1kHz. The threshold of hearing is 0dB and the threshold of pain is 120dB. If the sound pressure is doubled the amount, the SPL increases 6dB, and SPL increases 20dB if the sound pressure is increased by ten times.

But even with the same SPL, the perceived loudness might be different at different frequencies. For example, a sine wave at 2000Hz will sound louder than one at 200Hz with the same intensity. To explain the perceptual differences in loudness across the frequency spectrum, the Fletcher-Munson curves (or equal loudness contours) are shown in Figure 3.1. The perceived loudness level (phons) is measured with 1kHz as the reference. For example, a sine tone at 1kHz with an SPL of 50dB has the same loudness level as 50phons. But to create the same loudness level for a 100Hz sine tone, it requires 60dB SPL (follow the same contour).

The loudness of hearing multiple sound sources is not equal to the sum of the loudness of each individual source (Kaper and Wiebel, 1999). When one sound is added to another, the increase in loudness is based on the frequency

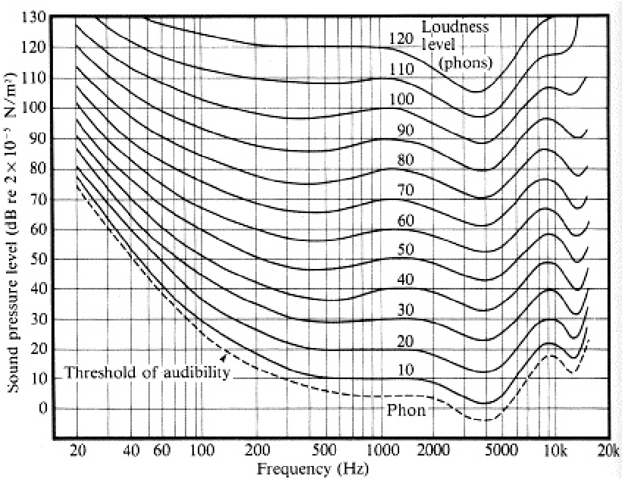


Figure 3.1: Equal loudness contours (Roads, 1996)

relationship of both sounds. For example, if the frequencies of both sounds are very close to each other within a critical band[1], they will 'compete' with each other for the same nerve endings on the basilar membrane of the inner ear. The perceived loudness is slightly greater than either sound alone.

This leads to another important characteristic of hearing: *masking*, which is a phenomenon that a sound is made harder to perceive or inaudible due to the presence of other sounds. For example, a sine tone with the frequency of 1000Hz will be masked by another signal with frequency content near 1000Hz and with enough SPL. This is because these sounds excite the same area on the basilar membrane, and the extent of this area is called the *critical band* (Fletcher, 1940; Moore, 1977). This increases the threshold of audibility of the original signal, and as the masker's volume increases it will eventually become inaudible to the listener. This characteristic is important in sonification especially when multiple streams of data are sonified simultaneously. In frequency mapping, one of the solutions is to spread out the frequency ranges of the sound sources so that there are less spectral overlaps. This is also a common practice in mixing music, to let each instrument occupy its own spectral space to make it clearly audible. Another way to avoid masking is

[1] A frequency range which is perceived as the same pitch by the ear.

to create distinctive timbres for each sonic stream to allow for more effective sound separation.

3.3 Pitch

Pitch is defined by the American National Standards Institute (ANSI) in 1973 as follow:

> "...that attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from high to low. (ANSI, 1973)"

The perception of pitch is mostly dependent on the frequency partial(s) of the sound. A sinusoidal tone (pure tone) has only one frequency element. However, for a harmonic tone such as a square or sawtooth wave, which consists of multiple frequency partials across the spectrum, the perceived pitch is dependent on the fundamental frequency (the lowest frequency of the periodic signal). For inharmonic tones such as a bell, the frequencies of certain partials decide the perceived pitch (Houtsma, 1997).

Normally our hearing range is between 20Hz to 20kHz. It varies between each individual due to the small difference in the ears and nerve structures. As we age, the upper hearing limit reduces. When designing sonic interaction using pitch mapping, the range is very important. The pitch ought to be not only easy to perceive but also comfortable to listen to. Perceived pitch ranged between 20Hz - 40Hz is considered as 'sub-bass'. This range is often described as 'muddy', which is very difficult for us to distinguish the actual pitch and therefore it is not a reliable carrier of information. For a higher pitch range, although our ears are most sensitive to the zone between 2.5kHz - 5kHz (think about the highest octave of a piano), it can cause discomfort and listening fatigue if the data mapping produces sounds predominantly in that frequency range. For frequencies above 5kHz, melodic sense is lost despite the ability to detect the variations in frequency, which is also not ideal for long period of listening. Therefore, the ideal range should lie somewhere above the sub-bass to the lower treble (approximately 40 - 2500Hz).

Our auditory memory is good at storing and recalling pitch relationships (?), which is greatly beneficial to sonification design. Similar to our ability to remember and recognize the melody of a song, a stream of data can be presented by mapping to the frequency of the sound and then be memorized by the perceiver. In a real-time feedback scenario, each segment of input, e.g. a single repetition of a repetitive exercise or each step of running, will create its own pitch variation. The perceiver then can store, and even compare those patterns in order to readjust the action or tactic.

3.4 Timbre

Timbre was defined by the American National Standards Institute (ANSI) as

> "that attribute of auditory sensation in terms of which a listener can judge that two sounds similarly presented and having the same loudness and pitch are dissimilar. (ANSI, 1973)"

This definition summarises our ability to discriminate the sounds of two different instruments even if they are playing the same note with the same loudness. However, this definition is not widely accepted by researchers. Bregman in Auditory Scene Analysis argues that this definition leads to an interpretation that only sound with pitch has timbre, which is not entirely correct because some sounds have no pitch (Bregman, 1994). Hence this definition cannot explain examples such as why we can distinguish the sounds of scratching a wooden floor or a metal plate because they do not have a perceivable pitch.

Timbre is heavily dependent on the spectral content of the sound. For example, a triangle wave and a sine wave have very different frequency contents, which define the tonal difference. In Figure 3.2, the difference between a flute sound and a piano sound in spectral content is presented. Clearly different harmonic structures can be seen from the spectral graphs of the instruments. In additions, there are other physical characteristics which can affect the timbre, such as the amplitude envelope of the sound. The onset (attack) and offset (release) of the sound also have a strong influence on the timbre.

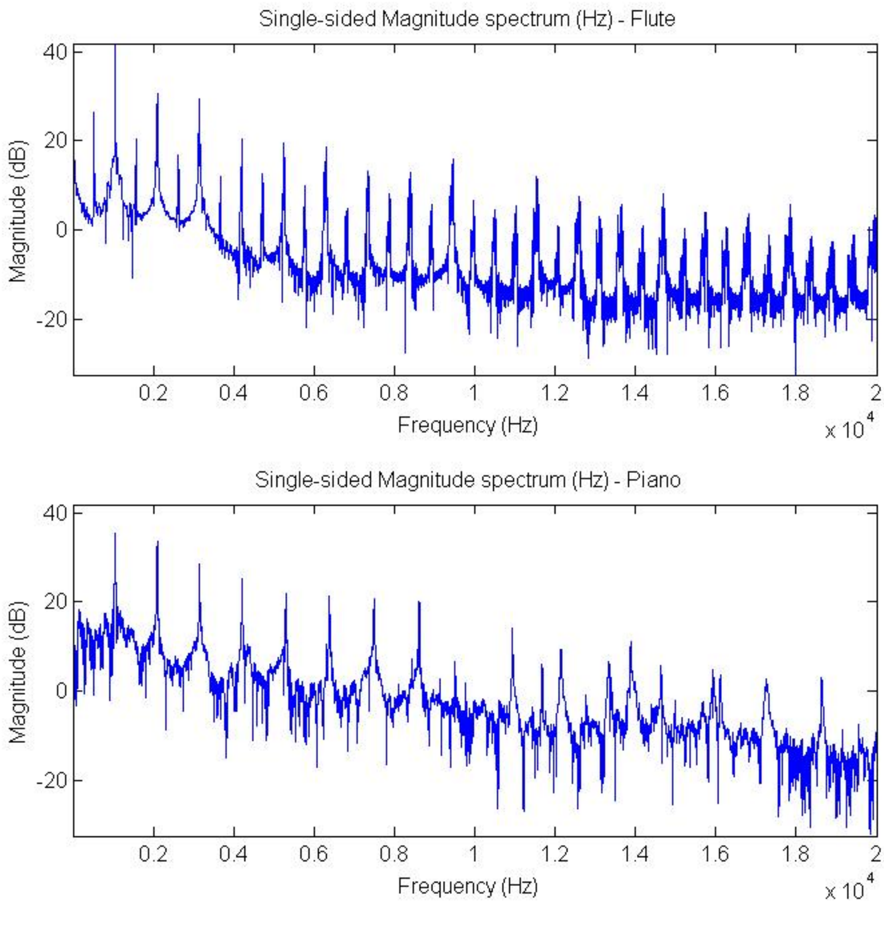


Figure 3.2: Frequency spectrum of flute and piano playing at the same note (C4: 262Hz)

Timbre can also be considered as a perceptual impression of a sound, as we often find musicians describing the sound of an instrument as being ‘mellow’, ‘rich’, ‘dark/bright’, or even abstract words such as ‘noble’, ‘strong’, etc (Berger, 1964). These specific perceptual impressions have many applications in auditory display. For example, a fire alarm sound need to portray urgency, therefore it uses an intensive and piercing sounding rather than something mellow and slow. In this case, a spectrally rich sound such as sawtooth would be a better option than a sine tone.

3.5 Musical Listening and Everyday Listening

We can classify listening to two main types: musical listening and everyday listening. Musical listening relates more to the experience of the sound properties such as melody, rhythm, whilst everyday listening concerns with the experience of events associated with the sound based on its acoustical properties such as the cause, material, action and location (Gaver, 1993). These two types of listening are not independent can be overlapped.

Our abilities to perceive pitch (melody), harmony, loudness and timbre allow sonic interaction designers to facilitate methods such as *Parameter Mapping*, which links the data sets to different acoustic/audio attributes. Musical listening can also trigger emotions, which needs to be considered carefully when using musical content for conveying information. People interpret music differently. Therefore, although a good listening experience is always encouraged in sonification, trying to convey emotionless data based on musical content with emotion may not be as clear as other sonification techniques such as pitch mapping.

Everyday listening is an essential part of our being aware of our surroundings. It strongly indicates to us the sound-producing events. For examples, experienced drivers can often tell whether a car is faulty by noticing that the sound of the car has changed. Occasionally, they can even identity the problem accurately. In such cases their memory has recorded the sound of 'the car working properly'. If the new sound is perceived to be different from the memorised sound, we then can make a judgement that the car might be faulty. In terms of sonification, everyday listening has resonances with *Auditory Icons* (mentioned in Section 2.3.2), which is a method of presenting information via sounds from the physical world. The meaning of information has a natural connection with the everyday sound. This leads to an advantage of auditory icons for being natural and easy to learn.

3.6 Characteristics of Sound and Hearing

Light and sound are received and transferred into neural signals nearly effortlessly and automatically (Neuhoff, 2011). However, if you look away from an object, or your view is blocked, or even if you simply just close your eyes, data from that object cannot reach your brain. On the other hand, sound waves have a much greater ability to bypass obstacles because of diffraction, where sound waves will bend around an object or bounce off surrounding surfaces. As a result the perception of a sound source with a sufficient amount of energy becomes compulsory. This is why audio signals are always the first choice in alarm systems.

The omnidirectional characteristic of auditory displays overcomes the positional limitation of vision so that screen displays are not necessary. According to Leob and Fitch (2002), in an operating room, anaesthetists need to spend time on looking at monitors and at the same time have many other responsibilities. This visual multi-tasking requirement can cause mistakes to be made. The provision of *auditory* monitoring systems in this case could help anaesthetists to reduce their mental workloads and maintain their ability to carry out duties needed during an operation.

Human ears are finely tuned to expect unique and varied sonic events. They are highly sensitive and accurate in perceiving sound, especially towards rhythmic and temporal signals. When time is an important variable, acoustic cues are much more reliable as a reference point compared to visualisation, because of their ability to naturally represent time-based data. Patel et al. implemented an experiment to find out whether people were capable of extracting a beat from visual displayed rhythmic sequences. They provided rhythmic sequences in both visual and acoustic form and asked participants to tap to the beat. The results showed that generally participants were unable to synchronise to rhythms based on visual cues (Patel et al., 2005). Their research indicated that in order to perceive rhythmic perception, auditory cues are still considered to be much more suitable. Relating this to the research in this thesis: repetitive free weight training such as biceps curl can be regarded a rhythmic action, in this case sonification has the potential to help improve the steadiness (rhythm) of the movement.

Auditory perception is also more thorough than visual perception at allowing us to pick up details while still being aware of the ‘whole’. For example, when a specific target is visually selected to focus on, most of us are not good at noticing changes in surrounding objects (a feature used by magicians through the ages, where it is known as ‘misdirection’). On the other hand, most people can focus on a guitar solo in a rock music whilst still being able to perceive and enjoy the whole song. For this phenomenon, sound surpasses vision in terms of picking out useful information from a pool of data whilst still paying attention to the whole. This could lead to a more sophisticated interaction with multivariate data via sonification.

However, there are also some problems associated with sound and hearing, which we should bear in mind. The first is the safety issue. When working with sound, it is vital to keep the sound pressure level within an appropriate range to prevent damage to the listener’s hearing. This issue can be easily avoided through control of the amplitude.

Secondly, prolonged periods of working with sound will cause tiredness.

This will reduce the sensitivity and accuracy of acoustic perception, which directly affects the quality of work as a result. Therefore, it is important to take regular rests when working in a continuous sound situation. For the work in this thesis, repetitive free weight training, this usually involves an action phase (the exercise repetitions) and an resting phase. The resting phase between sets is a good opportunity to 'switch off' the sonification to prevent listening fatigue.

Thirdly, although using *musical* sound as the sonified outcome can improve its aesthetic attractiveness, it is commonly known that different people sense a piece of music differently. This difference in perception towards musical content might introduce ambiguity of understanding the input data stream. Therefore, in a sonification design where musical content is to be used, a designer needs to consider whether the musical outcome can still convey the intended information clearly within an acceptable range of self-interpretation among different people.

3.7 Synthesis Method: Frequency Modulation Synthesis

Although natural sounds are familiar to everyone, they may lack in discernible parameters to be able to fully represent a data set (Kramer et al., 1999). Synthesised sounds, on the other hand, are much more flexible for a sonification design because every parameter and characteristic of the sound is controllable. Furthermore, synthesised sounds have been very popular in modern music, which means that most people, especially younger generations, are nowadays familiar with them.

Frequency Modulation Synthesis allows the frequency of a simple waveform to be modulated by the signals of other waveform(s) as a means to create new sound timbres. The technique was originally developed for radio broadcasting. For musical instrument use, it was first explored by Chowning in 1973 (Chowning, 1973) then quickly evolved into one of the most popular musical synthesis methods.

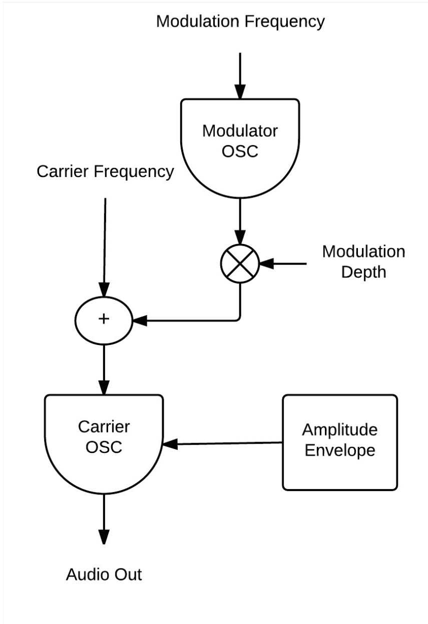


Figure 3.3: A simple FM synthesiser with one carrier and modulation oscillator

In FM synthesis, the signal being modulated is called the carrier and the control signal is called the modulator. It is common to use basic waveforms such as sine, triangular, sawtooth etc. for both the carrier and modulator. Figure 3.3 presents a block diagram of a simple FM synthesis structure. It has one oscillator called *Modulator OSC*. The modulation frequency determines how fast the carrier frequency is altered. The amplitude of the modulating oscillator is multiplied by a parameter called depth, which scales the modulator signal (ranged between -1.0 and 1.0) to a new range of modulation values. By adding that to the carrier frequency, the originally fixed frequency is modulated. If the modulation amount is small enough, it produces a vibrato effect and does not change the carrier oscillator's tonal quality. If the modulation amount is large, it can massively alter the timbre of the original tone.

Based on the basic structure in Figure 3.3, more sophisticated designs can be constructed by expanding to multiple carriers and modulators. A mixture of connections is also possible by using both cascade and parallel layouts. A well-known example of a complex FM synthesis on the market is the FM8 (Fig. 3.4) developed by Native Instruments[2]. It provides 6 oscillator units each of which can function either as a carrier or a modulator. The FM matrix allows the user to use either cascade or parallel connections for those oscillators. This product is capable of creating extensive tonal possibilities, which makes it popular among musicians and sound designers.

Figure 3.4: FM8, a commercial digital FM synthesiser

3.8 Synthesis Method: Subtractive Synthesis

Subtractive Synthesis uses one or more filters to shape the spectral components of a waveform. The filters amplify or decrease the amplitudes of selected ranges of frequencies of a sound. Normally *Subtractive Synthesis* is used to shape waveforms which are rich in frequency contents (such as square waves and sawtooth waves). By using different types of filters (low-pass, high-pass,

[2]http://www.native-instruments.com/

band-pass, notch, etc.) and parameterising them, a wide range of new timbres can be created, which can even mimic natural sounds (Roads, 1996). A block diagram of a basic subtractive synthesiser is shown in Figure 3.5.

Figure 3.5: Signal flow of a subtractive synthesiser

Figure 3.6 is an example of passing a white noise signal through four types of filters with the cut-off frequency of each filter set to 1000Hz. The Low-pass filter allows lower frequencies (below 1000Hz) to pass through and any frequency higher than 1000Hz is attenuated. The High-pass filter behaves in the opposite way, allowing higher frequencies to pass through. The Band-pass filter allows a certain range of frequencies to pass through while attenuating other frequencies, and the Band-stop filter does the opposite.

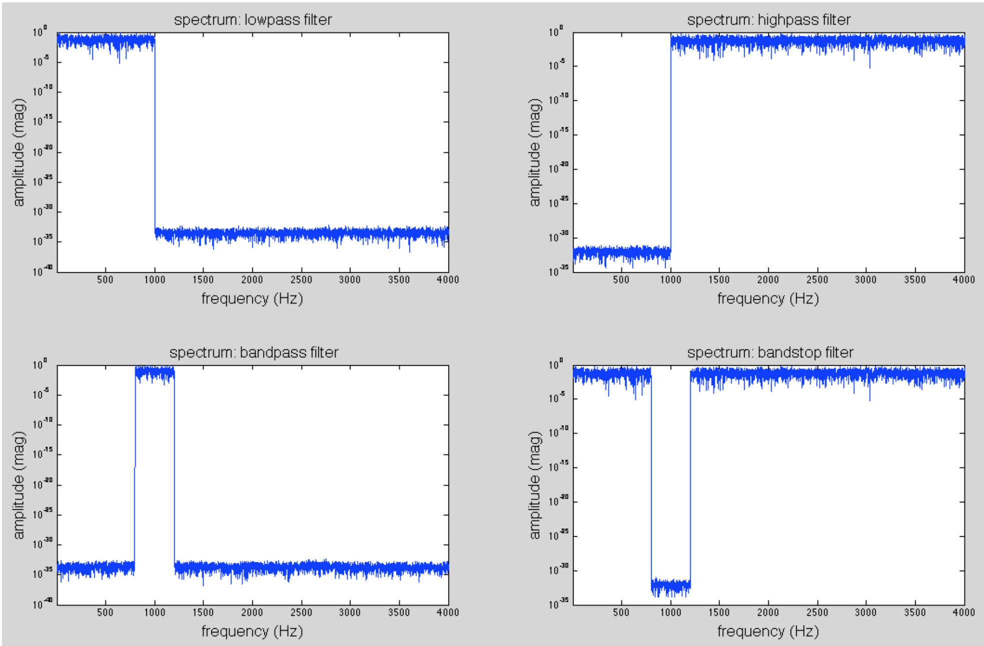


Figure 3.6: Spectrograms of four common filter types, with the centre frequency set to 1000Hz

A commercial product is shown in Figure 3.7, which is a virtual analogue subtractive synthesiser built by Roland[3].

Figure 3.7: Roland Gaia SH-01 virtual analogue subtractive synthesiser

[3]http://www.roland.co.uk/products/details/1074

3.9 Other Popular Synthesis Methods

Subtractive Synthesis and Frequency Modulation Synthesis are used in the sonification for this thesis, hence being explained in detail. There are many other synthesis techniques which are also popular. This section gives a brief introduction to some of these other methods.

Additive Synthesis

The idea of *Additive Synthesis* is based on the fact that any periodic signal can be constructed by adding together a series of sinusoidal functions of various frequencies. The timbre of this synthesis method is determined by adding many sinusoidal signals with different amplitudes and most importantly harmonic frequencies[4] (Moore, 1985).

Granular Synthesis

Granular Synthesis is a sample-based synthesis method that uses one or more small sections from an audio source (usually 1 to 100ms in length), which are called *grains*. A grain is regarded as a short microacoustic event, which is just over the threshold of perception (Roads, 2001). New acoustic events can be constructed by combining and overlapping thousands of these grains (Roads, 1996). This synthesis technique provides much scope for sound design, and has very good potential for creating interesting sonic events that will be useful for representing data. In the early stage of the research, a granular synthesiser was developed (Fig. 3.8). However, it was later removed because the method required more processing power than the others.

[4]Integer multiples of the fundamental frequency.

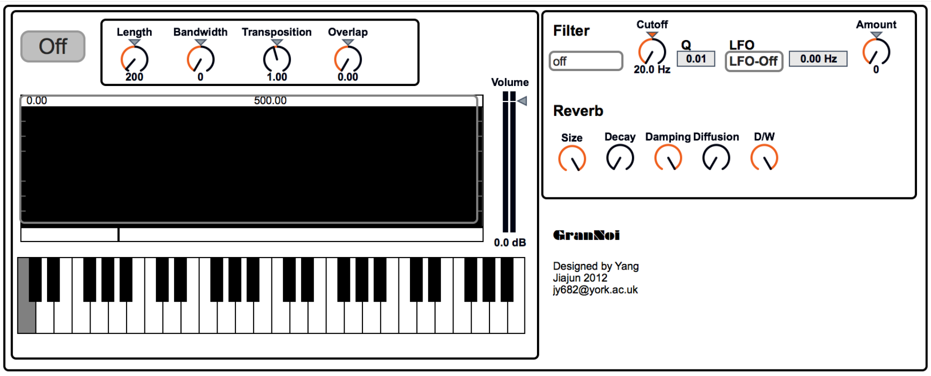


Figure 3.8: GranNoi: A granular synthesizer developed using Max

Others

There are many other techniques such as physical modelling synthesis, formant synthesis, etc. They all have their own advantages and disadvantages. Here, there are not presented individually.

Design Consideration

The decision to choose FM and Subtractive synthesises for the sound design is based on the following considerations:

- They are relatively easy to design yet still provide a wide range of sonic outcomes.
- They provide sufficient accessibility to synthesis control parameter, to be used for parameter mapping.
- The programming language, Max, provides a wide range of filters for subtractive synthesis design.
- Max's graphical programming style makes suitable for designing FM synthesis, as it creates a visually clear interconnections between carriers and modulators.

- FM synthesis is capable of generating a huge range of tonal quality. Yet its tonal outcome may be hard to predict. Therefore, this method was used only for the sound design but not for parameter mapping. Subtractive synthesis on the other hand is more predictable.

- Some other synthesises methods demand more computing power.

This is not to claim that FM and Subtractive synthesises are the only good options. Kleiman-Weiner and Berger (2006) applied formant synthesis to sonify golf swing movement. The use of vowel-like tones is responsive to the small variation in movements. This has the advantage of highlighting small variations in movement in order for the user to make minor adjustments which are crucial the quality of the golf swing. The same synthesis method was also used in sonifying hyperspectral colon tissue in (Cassidy et al., 2004). Physical based sound synthesis was used in the rolling ball experiment in (Rath and Rocchesso, 2005). Granular synthesis was applied in the sonification of time-varying probabilistic information (Williamson and Murray-Smith, 2005).

3.10 Chapter Summary

This chapter explains the fundamental knowledge of psychoacoustics and its connection with sonification. Three main acoustic attributes (loudness, pitch and timbre) are detailed. General listening is explained based on both musical listening and everyday listening. The final part of the chapter introduces the FM Synthesis and Subtractive Synthesis methods, used in this thesis, as well as some other synthesis methods which were not chosen in this research. Chapters 2 and 3 have presented some background knowledge of sonification and general hearing. The next chapter describes the second part of the research background, which is physical exercise and biofeedback.

Chapter 4

Physical Exercise and Biofeedback

4.1 Introduction

This chapter presents the knowledge of physiology in the context of physical exercise and biofeedback. At the beginning of the chapter, the concern of lack of physical activity in the general public is raised with statistical facts from various governmental health reports. In Section 4.3, the example of the biceps curl exercise is explained. Following is the biofeedback section, which is separated into *muscular activity* and *kinematics*. The hardware used for this research is explained along with a brief introduction to several other sensory devices. In Section 4.8, examples of using biofeedback in physical exercise and rehabilitation are presented.

4.2 General Health and Physical Activity

Modern life styles are potentially affecting our health around the globe. More specifically, there is a lack of physical activity among people, and this problem is more severe in more developed cities. Physical activity is defined by the World Health Organization (WHO) as

> "... any bodily movement produced by skeletal muscles that requires energy expenditure (World Health Organization, 2014)."

The definition of physical activity is broad, covering light activity such as walking and carrying goods to intense activity such as intense sports and bodybuilding. The most direct way to improve general health is to maintain a decent amount of physical activity on a regular basis. The suggested intensity is 30 minutes of moderate/intense physical activity a day and 5 times a week (Department of Health, 2004). This will help prevent cardiovascular disease, obesity, musculoskeletal health, cancer, diabetes and mental illness. Even lower intensity activity, such as general housework, shows a positive effect on body glucose. It reduces the required insulin produced from the pancreas to process the glucose in the blood, which leads to a better control of blood sugar (**?**Braith and Stewart, 2006).

Physical inactivity means failing to meet the recommended amount of physical activity. It has become a great threat to public health. In 2014, WHO (2014) reports that 6% of global mortality can be traced back to physical inactivity, which does not affect humans instantly but slowly. It insidiously leads to a series of issues such as obesity, stroke, diabetes, heart disease and osteoporosis.

The number of overweight adults in the UK between 1993 to 2012 increased from 57.6% to 66.6% in men and from 48.6% to 57.2% in women (Health & Social Care Information Centre, 2014). In another study, it is estimated that 37% of coronary heart disease in the UK is due to physical inactivity

(Department of Health, 2004). Allender et al. (2006) studied the statistics of the UK's morbidity and mortality in 2003-4, identifying and analysing different diseases to discern the effect of physical inactivity. Results showed that 3.1% of morbidity and mortality were caused by physical inactivity and this led to a cost of more than £1 billion directly to the National Health Service (NHS). Allender et al. also suggested that one third of all diseases causing deaths could be partly reduced if there was an improvement in physical activity. This study sounds a warning bell that it is highly urgent to improve our social health situation and encourage more people to get involved in increased physical activity.

According to UK's health profiles in 2012, bigger cities in England, such as Birmingham, Leeds, and Manchester, have significantly worse adult lifestyles than smaller towns such as Scarborough and Malton (Public Health England, 2013). One of the reasons is that generally people are living in a more stressful environment in bigger cities with more sedentary work. They don't have enough regular exercise because of their busy lives. However, in small towns people tend to be more relaxed, and to get more day-to-day exercise. In New York, only 20% of the population regularly exercises as recommended by the American Heart Association. This data is gathered from the Department of Health New York website[1]. In Australia, the 2011-2012 national health survey also indicated a similar trend of physical inactivity (Australian Institute of Health and Welfare, 2014). Among young people (5 - 17), there is an increase in screen-based activity and a decrease in physical activities. Only 45% of the adults reported that they met the minimum required amount of physical activity, which is at least 30 minutes per day.

Although this section cannot include the statistics of general health in every country, the presented examples are enough to pinpoint the severity of physical inactivity in modern societies. There are many factors that can lead to this trend, including economics, long hours of office work, unhealthy diet, stressful life, technology and so on. Allender et al. (2006) conclude

[1]Department of Health New York: http://www.health.ny.gov/

with some of the difficulties that adults encounter with participation in sport and physical activity. Some adults find themselves not confident enough to do exercise in a gym environment surrounded by unfamiliar (and often intimidatingly fit) people. A lack of role models and poor self-perception is another factor discouraging adult participation in sport and physical activity. What makes it worse is that physical inactivity and physical well-being tend to form a negative loop, in that people with many health problems and low self-esteem tend to be less physically active (Hardy and Grogan, 2009).

Modern technology has been making our lives increasingly ‘easier’, yet that also means we spend less effort completing daily tasks. Now people can sit in front of a computer and complete most of their daily work. Meetings can be arranged through the internet. Heavy work can be done by machines. There are countless numbers of new technologies such as gaming consoles, which also affect the amount of physical activity expended in leisure hours. In short, it is now technologically possible to work and play while sitting all day and barely moving the body’s major muscle groups.

With the problem presented, the next stage concerns finding a solution. This research aims to provide a sonification assistive tool, which has the potential to improve the quality of physical exercise with real-time auditory feedback, as well as interesting people in exercising more. As shown above, there is a strong demand to encourage people to engage in more physical activity.

4.3 Fitness Training and Biceps Curl

The purpose of fitness training is to improve overall health and well-being. Generally, it can be classified into 3 types: aerobic, anaerobic and specific training (Figure 4.1). Aerobic training leads to an increase of maximum oxygen uptake ($V0_{2max}$) through light physical activities, while anaerobic training targets the ability to improve the rate of producing force. Specific training selects and isolates particular muscles to focus on the development on muscle strength, speed endurance and flexibility (Bangsbo et al., 2006).

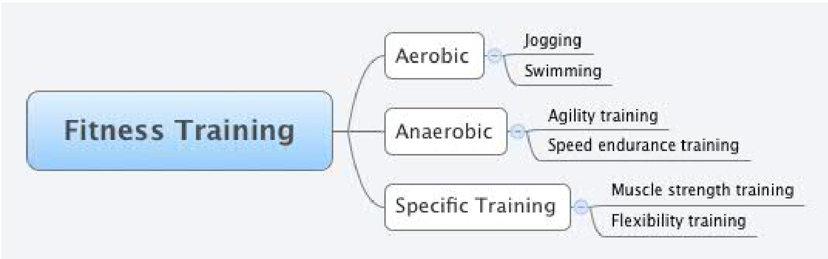


Figure 4.1: Diagram of fitness training with examples

Another way of classifying physical exercise is to split it into 2 types based on muscular behaviour: static exercise (isometric), locomotory exercise (isotonic).

- *Isometric* means that the active muscle volume is unchanged during muscular contraction and therefore it will not result in any physical movement. A typical example is the static contraction training by holding a steady weight. Planking is another popular isometric exercise, which involves maintaining the push-up position by resting both forearms on the ground.
- *Isotonic* exercise involves changes in muscle volume and movement. There are two types of isotonic contraction, which reflect the direction of the change in muscle volume. *Eccentric* contraction means the muscle is lengthened, whilst concentric means the muscle is shortened. Take biceps curling as an example. Lifting the dumbbell from a straight arm position to a fully bent position, the biceps shorten in order to move the dumbbell against gravity, which is a *concentric* contraction. The reverse movement, straightening the arm downwards, lengthens the biceps to move the dumbbell in the direction of gravity, which is an eccentric contraction.

Both concentric and eccentric contraction exercises can improve muscle strength. Many exercises, such as biceps curl, consist of both concentric and eccentric contractions of the muscle, an example of which is shown in Figure 4.2.

Despite the fact that many exercises involve both contractions, it is common that many people do not achieve a balanced workout. Less experimental attention has been paid on eccentric contractions comparing to concentric contractions (LaStayo et al., 2014). For example, in biceps curl, some people tend to only focus on lifting the dumbbell but let the dumbbell lower quickly. In a push-up or sit-up exercise, commonly more effort was on rising phase (concentric) rather than lowering down (eccentric) (Borten, 2015).

Studies have found many benefits of eccentric training, such as more muscle strength, faster metabolic rate and quicker muscle repair (Bubbico and Kravitz, 2010). Eccentric contraction can generate a greater amount of power, which means that people can bear greater weight resistance compared to concentric contraction. Focused eccentric training can help prevent injury and increase performance in sporting activities and physical therapy (LaStayo et al., 2003; Gerber et al., 2009; Marcus et al., 2011). Colliander and Tesch conducted a 12-week resistance training test to compare the difference between concentric focused and balanced concentric-eccentric training regimens on quadriceps muscles (Colliander and Tesch, 1990). The results showed a better improvement in peak torque and strength-related performance with a balanced training consisting of concentric and eccentric contractions than concentric only training method.

It is beneficial to pay attention to both concentric and eccentric contractions in resistance training. However, for average exercisers, most people do not pay too much attention on the physiology of exercising and it could lead to inefficient result. The next section discusses about how biofeedback can help exerciser achieve an effective training through sensory technology.

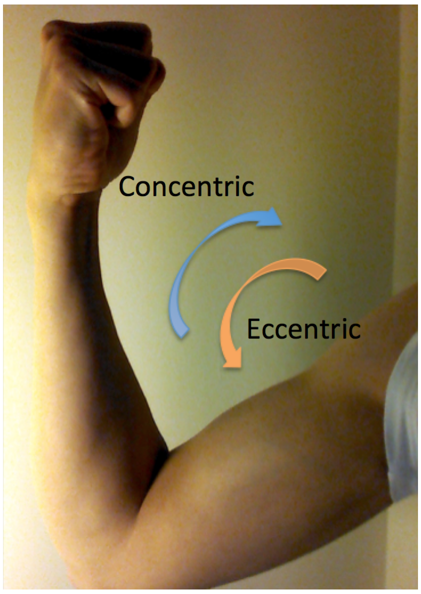


Figure 4.2: Pictorial explanation of concentric and eccentric contraction during a biceps curl repetition

4.4 Biofeedback: Muscular Activity

This section focuses on the insight of extracting muscular activity via electromyography (EMG) sensors.

4.4.1 The Benefits of Biofeedback

The traditional 'feedback' in physical exercise is verbal information given by observers such as coaches or therapists. Feedback is usually given based on the observer's judgement of the visible attributes of the human body movements, e.g. velocity, coordination, and movement precision. However, there are a few disadvantages with this conventional feedback:

- In order to receive feedback, an observer (e.g. sport coach or therapist) is required to be present, which can be inconvenient and costly.
- The 'quality' of the feedback relies on the ability of the observer. Hence

there is always a risk of inaccurate judgement. It is subjective to some extent due to the involvement of a human.

- The process takes time to finish. There is a delay between the occurrence of the action and the occurrence of the feedback.
- There are attributes which are not directly visible such as the internal muscular activity. Yet these attributes are highly important. They reflect the strength, dynamic, and fatigue of the actions, which inform of the quality of the action and can also indicate possible injury.

Biofeedback, on the other hand, is an objective representation of the physical attributes generated by the person during the exercise. These attributes can be quantified and presented continuously. Appropriate algorithms can also be developed to analyse the attributes and present the results of the analysis in real-time to the user. According to the definition of biofeedback approved by Association for Applied Psychophysiology and Biofeedback, biofeedback is measured by instruments to immediately and accurately feed back information such as heart function, breathing, muscle activity, skin temperature and brain waves (Association for Applied Psychophysiology and Biofeedback (AAPB), 2014). The same article also explains that the purpose of receiving biofeedback is to adjust physiological activity in order to improve health and performance. The benefits of biofeedback have been well supported over the years. Supportive evidence has been found in areas such as human body movement and sport (Gerard et al., 2002), chronic stroke rehabilitation (Wolf and Binder-Marcleod, 1983), and musical learning (LeVine and Irvine, 1984; Fujii and Moritani, 2012).

Motor control may seem completely natural to most people, yet for patients in pathological conditions, regaining control is difficult due to the damage or loss of sensory control. In these circumstances, by reinforcing sensory information through other media (mostly visual or auditory) patients can regain awareness of their motor control and gradually become capable of controlling the movement independently. The long-term potential of the work described in this thesis may well applicable to auditory feedback to enhance movement recovery in such people as stroke patients. However, the focus of the experiments described in the following chapters is purely on able-bodied subjects.

Gottlieb et al. suggested that improvement of motor control can be achieved with *all* ranges of movement complexity (Gottlieb et al., 1988). Hence, it is always beneficial to aim for a better quality of simple physical exercise. In the long term, the person exercising will gain much better results than ignoring the quality while training.

The research described in this thesis investigates the provision of auditory biofeedback of physical exercise attributes. The attributes are separated into muscular activity and kinematic information. The next section provides insight of the kinetic energy, which is the muscular activity measured via electromyography (EMG) sensors.

4.4.2 Definition and Characteristics of EMG

Early experiments on detecting myoelectric signals can be traced back to the 1600s (Bonner and Devleschoward, 1995), where experiments showed the change in shape of frog muscle while nerves were stimulated mechanically. Yet, it wasn't until the 1940s that a measurement technique named electromyography (EMG) was developed for studying muscle activity. Quoted from (Konrad, 2005), the definition of electromyography is as follows:

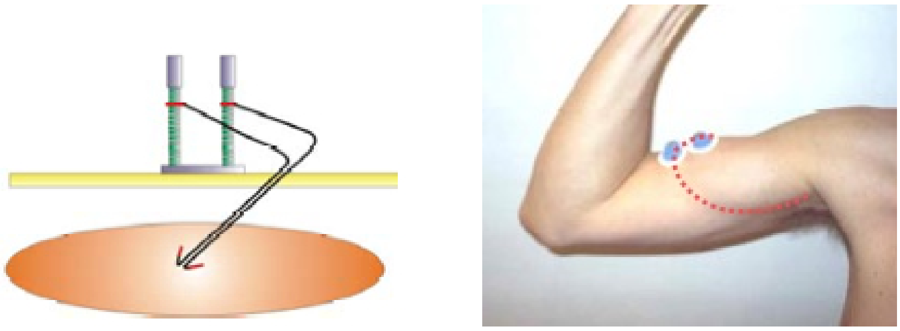
> "Electromyography is an experimental technique concerned with the development, recording and analysis of myoelectric signals. Myoelectric signals are formed by physiological variations in the state of muscle fibre membranes."

When a muscle is activated, muscle cells produce electrical potential. The electrical signal resulting from many muscle cells can be recorded through sensors. Walton, in his paper (Walton, 1952), stated that in the resting phase the muscle stays electrically silent, yet extremely complex interference activities will be produced with any form of muscle activation, even with weak muscles. Regarding the signal, un-amplified EMG signals at the skin's surface typically have a potential difference of between a few microvolts to a few millivolts. The signal is generally amplified by a factor of 500 to 1000 (Konrad, 2005).

There are many advantages of using EMG. It helps us to gain understanding of muscle activities, which are normally impossible to observe. In recent years, an increasing number of positive results have been found showing that the use of EMG feedback from dedicated muscles can enhance the condition of that muscle, such as increasing muscle mass through exercise (**?**). Detailed demonstration of the home use EMG feedback device invented by Church and Hassel is presented in Section 4.8. Also, EMG feedback can help healthy individuals to maximise and prolong a voluntary contraction with better quality in a little used muscle (Middaugh, 1978; Fernando and Basmajian, 1978). Also, continuous real-time EMG biofeedback is able to provide an awareness of the user's muscular activity patterns, which is beneficial in maintaining the quality of action and also in injury prevention (Vedsted et al., 2011).

4.4.3 Surface EMG

Two main types of EMG are currently used in practice: Intramuscular EMG and Surface EMG (Fig. 4.3). Intramuscular EMG uses a fine-wire electrode (a needle) inserted into the subject's muscle to record the myoelectric signal directly from inside the muscle. Although this invasive application is more accurate, it also causes pain and discomfort to the subject.



(a) Fine-wire electrode connection (b) Surface electrode connection

Figure 4.3: Illustration of the two types of EMG measurement. Pictures are taken from (Konrad, 2005)

A surface EMG sensor is non-invasive. It commonly uses silver/silver chloride electrodes (Ag/AgCI) which are placed on the skin close to the active muscles. An example is shown in Figure 4.4. Surface EMG sensors provide a more flexible and easy method for kinesiological study, as they are much more comfortable in use compared to intramuscular detection, and can be attached by non-professionals. Therefore these sensors were chosen as the main detection method for the work described in this thesis. Soderberg and Cook suggest that the use of surface EMG enables standardized methods to be developed with zero discomfort (Soderberg and Cook, 2012).

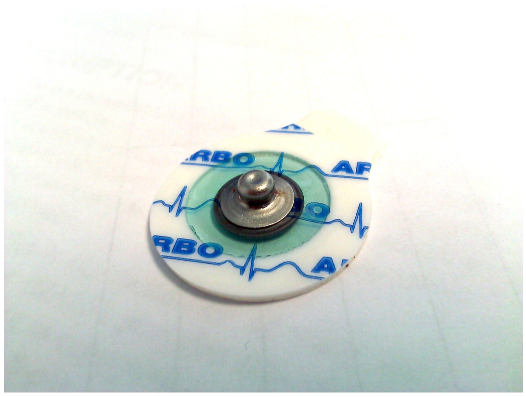


Figure 4.4: An example of EMG electrodes used in this research

The electrodes pick up myoelectric signals at two different positions of the muscle (usually the middle and the end of the muscle). Then the sensor uses a differential amplification circuit to calculate the difference in myoelectric potentials of the two positions as the EMG signal. The EMG signal is then amplified and filtered (using a low-pass filter to smooth the signal). Usually, a rectification is also used so that both concentric and eccentric contraction produce positive EMG values. Overall, the amplitude of the EMG signal is related to the net motor unit activity, which is the 'recruitment and the discharge rates of the active muscle units' (Farina et al., 2004).

Several issues affect the performance of surface EMG:

- During a contraction, neighbouring muscles may produce a certain amount of myoelectric signal as well, which will be picked up by the local electrode. This is called cross-talk. Cross-talk signals are considered to be extra noise added to the signal. In surface EMG, the area of electrode also has influence on the cross-talk (De-Luca, 2002).
- It is possible for one to produce a larger force than another yet generate lower surface EMG signals. This is mainly because of subcutaneous fat layers. Figure 4.5 shows the structural cross-section of a limb. The thickness of the fat layer reduces the amplitude of surface EMG amplitude and also increases cross-talk from other muscles (Kuiken et al., 2003). Therefore, EMG can also help to measure the reduction of subcutaneous fat in physical exercise by measuring the improvement of EMG amplitude (Konrad, 2005).
- Other noise signals, such as equipment induced noise from cables and connections, internal amplifier noise and external noise will also affect the output.

4.5 Kinematics Information

Kinematics is described by Sewell et al. as the 'spatial and timing characteristics' of human body movement (Sewell et al., 2005). During sport movements

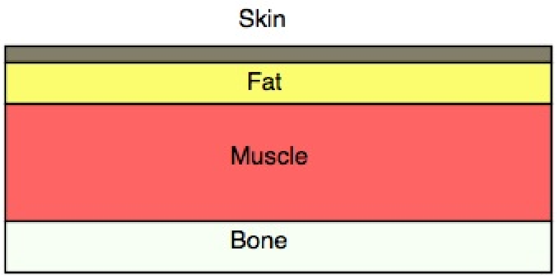


Figure 4.5: Cross-section of a limb

and rehabilitation, this information can be observed visually as it is concerned with the position change, velocity and acceleration of movement. Tracking algorithms can be used to acquire kinematic information. In this section, a motion tracking device called *Kinect* is introduced. Kinect was originally designed to be used on a Microsoft XBOX360 gaming console. Because of its versatility and accuracy in 3D motion capture and recognition, it has been used in various interactive projects such as visual rehabilitation, graphical interaction and virtual reality. In (Chang et al., 2011), Kinect was used in physical rehabilitation by tracking and determining the movement accuracy of a patient's therapeutic movements as an alternative to a human observer (therapist). Huang (2011) developed a Kinect-based rehabilitation system in 2011, which detects the user's joint movements and determines whether the movements reach the quality standard based on spatial movement accuracy.

4.6 Other Types of Sensory Device

Sections 4.4 and 4.5 introduced two sensory devices to acquire bio-information, namely the EMG sensor for muscular activity and Kinect camera for kinematic information. Apart from these two, there are many other sensors available for human body movement and bio-information detection. This section introduces several alternative options.

Movement detection sensors can be mainly split into vision-based and non-vision-based according to their operating principles. This section mainly concerns sensory devices for human body movement tracking and muscle activity only, hence other biofeedback devices such as electroencephalography (EEG) sensors for detecting brainwaves are not included.

Vision-based devices use cameras and sources such as optical beams to detect movement. For example, VICON[2] is a commercial tracking system, which has been widely used in film making, virtual reality, biomechanics and many other areas. It uses a camera array for multiple angle tracking, allowing virtual 3D reconstruction of the recorded movements. However, the advanced technology of the system also makes it very expensive, which makes in impractical for use in this project as the target group is the general public. A simpler option is to use a computer webcam combined with tracking software. However webcams are typically limited in quality, which makes it hard to achieve quality real-time tracking.

Non-vision-based sensors often require direct physical contact with the user. For example, a gyroscope can measure orientation. An accelerometer can measure acceleration forces such as g-force. This can lead to measurements such as rotation, angle, velocity, vibration and so on. A dynamometer can measure force, torque or power. These types of sensor are usually very compact and suitable for use in a wearable device. A potential alternative for movement tracking to using a Kinect camera would be to develop a wearable device using a combination of accelerometers and angular sensors. Limb movement, such as joint moving angle, position changes and speed of movement could all be acquired. Another example is the popular gaming system Nintendo Wii[3]. This was first released in 2006 equipped with a handheld controller and a receiver to achieve three dimensional motion tracking. However, the Wii was not a practical option for this research because the requirement to use a handheld controller makes holding a dumbbell impossible.

[2]http://www.vicon.com/
[3]https://www.nintendo.co.uk/

Apart from EMG sensor, the muscular activity can also be measured by acoustic myography (AMG) and mechanmyography (MMG). Instead of measuring myoelectric signals produced from muscle contractions, an AMG sensor uses a specially designed microphone placed close to the surface of the active muscle (Barry et al., 1985). Because muscle contraction produces low frequency vibration, which is usually below 50Hz, the microphone picks up the "sound" of the muscle contraction. Similarly, a MMG sensor also measures the vibrations produced by the muscle (Evetovich et al., 2007).

4.7 Final Choice of Sensor System

In the final system design, the main reason for choosing the EMG sensor is that the physical exercise is directly linked to muscle activity, which can be quantified using an EMG sensor. Kinect is inexpensive comparing to some of the professional visual tracking systems such as VICON. It has a resolution of 640 x 480 at 30fps, making it sufficient and responsive for body tracking. However, for further development, a wearable device is considered to be a more accessible option.

4.8 Examples of Biofeedback used in Physical Exercise and Rehabilitation

Pauletto and Hunt in 2006 carried out a project to sonify EMG data from leg muscles. Traditionally, physiotherapists need to analyse a large amount of data collected from EMG sensors, based on graphical displays. This leads to a problem that the analyst can either focus on the screen monitor or the patient, which means it is highly difficult to compare the data with the real motion simultaneously in order to carry out a more comprehensive study and produce diagnosis (Pauletto and Hunt, 2006). It also distracts the therapist from maintaining eye-contact with the patient an important action to watch out for signs of pain or distress. Therefore, this project looked into an alternative way of portraying the data from EMG sensors using sonification instead of a visual display. Planned future work involved the patient being able to hear the sonic feedback of their muscle activities as well. The experiment discovered that there was a perceivable difference in the quality of sound produced by EMG recordings from participants of different ages and medical conditions. This project showed the potential that using sonification in rehabilitation or diagnostics can set the observers eyes free to focus more on patients and their limb movements rather than looking at the monitor.

In 1994, Church and Hassel argued that most clinical EMG devices for rehabilitation required skilled supervision, which reduced the amount of training that was possible for a particular patient (**?**). In order to let patients do high quality physical rehabilitation at home, they developed an EMG feedback device for home physical rehabilitation without the presence of therapists. First of all, an in-clinical evaluation was carried out on the patient with electrodes attached over the indicated muscles. The therapist then optimised the system regarding operating parameters and electrode placement. After the device was set up properly for home-use, patients were instructed how to use the system, and then home physical rehabilitation using the device could be implemented. In further assessments, the therapist could evaluate the recorded data from the device to adjust the therapy and the dedicated operating parameters until no further use was required.

EMG biofeedback has also been used in footballer training programs. Musclelab[4] is a portable device that provides on-line biofeedback to coaches. It records real-time EMG and other bio-information such as kicking force to evaluate the quality of exercise, and it gives verbal feedback to suggest how coaches can make adjustments. A screenshot is shown in Figure 4.6. Musclelab is a commercial product that has been used widely in athlete training and one of most famous football clubs, FC Barcelona, is among the

[4]Ergotest Innovation http://www.ergotest.com/

users.

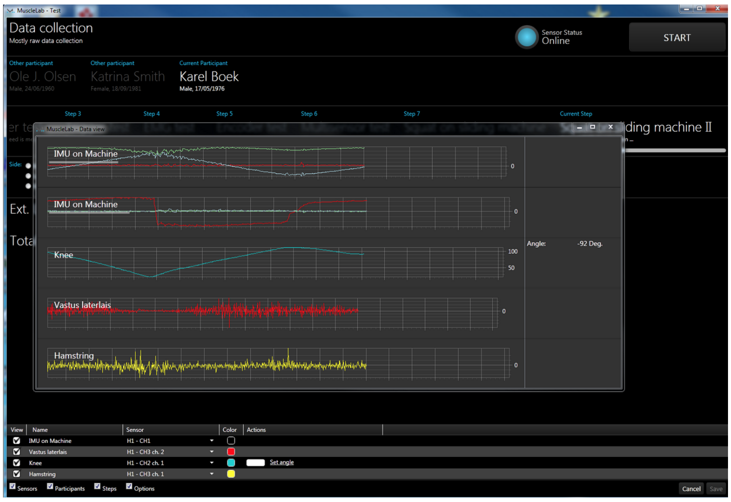


Figure 4.6: Screenshot of the Musclelab software for real-time data monitoring. Picture is taken from its official website: http://www.ergotest.com/

Residual limb recovery is essential for people with amputation to retrain the control of gait with a prosthesis. Due to the loss of limb, the lack of proprioception makes learning to walk with a prosthesis difficult. If the weight-bearing to the residual limb is under-loaded the balance cannot be maintained, and if over-loaded can cause injury and affect the circulation. (Chow and Cheng, 2000) conducted an experiment and asked six persons with limb amputation to do weight-bearing training with auditory biofeedback (Fig. 4.7). The biofeedback informed the participants when an appropriate amount of load was achieved. The experimental result showed that the audio biofeedback significantly improved the quality of training. A more well-balanced gait cycle was achieved compared to training without the audio feedback.

Visual and auditory biofeedback of surface EMG of the quadriceps muscle group was studied in (Croce, 1986). In the study, participants joined a 5-week *Cybex Isokinetic Exercise Machine* training program (leg extension exercise). The results showed a better improvement of muscle strength in the biofeedback group (with audiovisual feedback of the EMG of the active

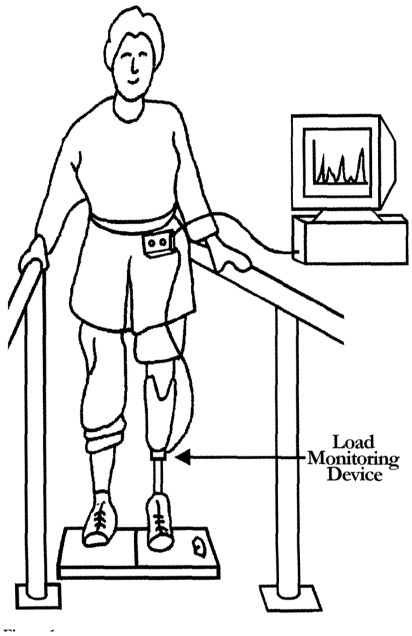


Figure 4.7: The load monitor is equipped on the prosthesis. Load information is sent to a computer to produce auditory feedback. Picture is taken from (Chow and Cheng, 2000).

muscles) than the control group (no feedback given). Higher peak torque values and integrated EMG[5] values were also found in the biofeedback group.

Brooks et al. (2002) created a virtual reality room utilising audiovisual feedback as a game-like environment (Figure 4.8) to improve the experience of rehabilitation for children with severe disability. The system used infrared sensory devices (Dbeam[6] and a custom-made device) to capture children's movement to control visual and audio signals. Overall, the system creates an immersive environment to let children do more physical activities.

Intiso et al. (1994) studied the effect of audiovisual EMG biofeedback in walking therapy. In the study, sixteen ischemic stroke patients participated and were split into two groups (experimental and control). In addition to EMG

[5]Integrated EMG (iEMG) refers to to the total amount of EMG signal.
[6]Dbeam: A device for human computer interaction via infrared light. It was originally developed by Interactive Light, and is currently owned by Roland and used as a non-contact controller in many of their keyboard synthesisers.

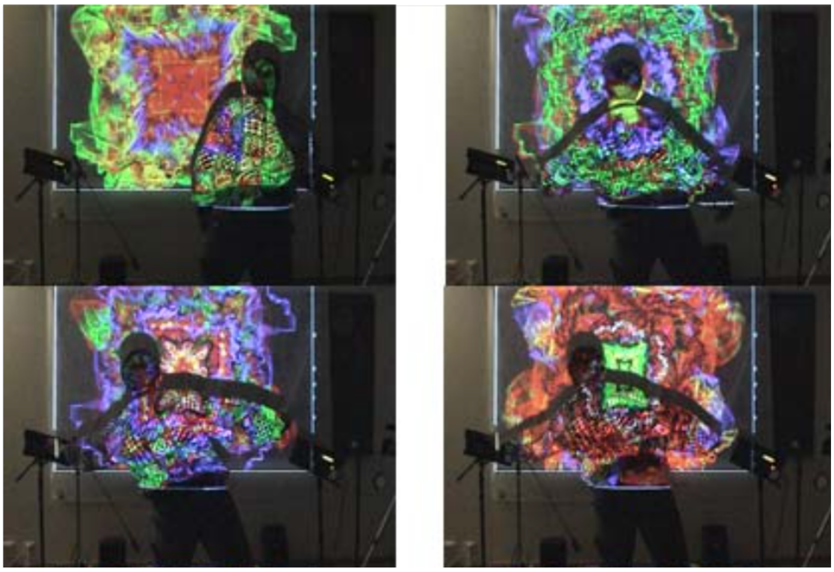


Figure 4.8: An example of a person using the audiovisual feedback system. Picture is taken from (Brooks et al., 2002).

biofeedback, the kinematic information such as speed and length of steps were measured using the ELITE system, which tracks movement information based on the interference of light sources by attaching marks on the user's body. The auditory feedback is given based on the participant's anterior tibial muscle (location of the muscle is shown in Figure 4.9) contraction. The results report better increases in muscle recruitments and improved locomotion recovery of foot-drop in the experimental group (with biofeedback) than the control group (traditional physical therapy without biofeedback).

In (Chang et al., 2011), the Kinect was used in physical rehabilitation to track and determine the accuracy of patients' therapeutic movements. Chang et al. studied the exercise results of two young adult participants with motor impairment. The exercise mainly involved several types of arm lifting. The system is a game-like device which generates interesting audio and graphical results based on the participants' movements. Results indicate both participants' motivation and performance have improvement greatly.

Iguchi et al. (2013) conducted an experiment to study the effectiveness of

Figure 4.9: Anterior Tibial

auditory EMG biofeedback of the gripping action. An example of the set-up is shown in Figure 4.10. The study compared sighted and blind participants on their difference of gripping a dynamometer at 20% of their maximum voluntary contraction (MVC). The amplitude of muscle contraction was mapped to the amplitude of a fixed 460Hz sine tone. The blind participants found it was more difficult at contract muscles at the required MVC level than when receiving the sonification. The auditory EMG biofeedback significantly reduced the error. The qualitative study also found that subjects much preferred using the biofeedback than without. However, the effect of auditory feedback is not as strong in the sighted group. Iguchi et al. suspected that blind people's auditory system is more sensitive and trained than sighted people, which led to the result.

4.9 Chapter Summary

This chapter highlights the urgency for encouraging the general public to become more physically active. The use of biofeedback has been mostly applied in fields such as medical science, elite sport training and has not been applied much for the general public. Yet, nowadays technology allows assistive tools to be designed at low cost. This gives a great opportunity for the development of biofeedback assistive devices. This research facilitates the

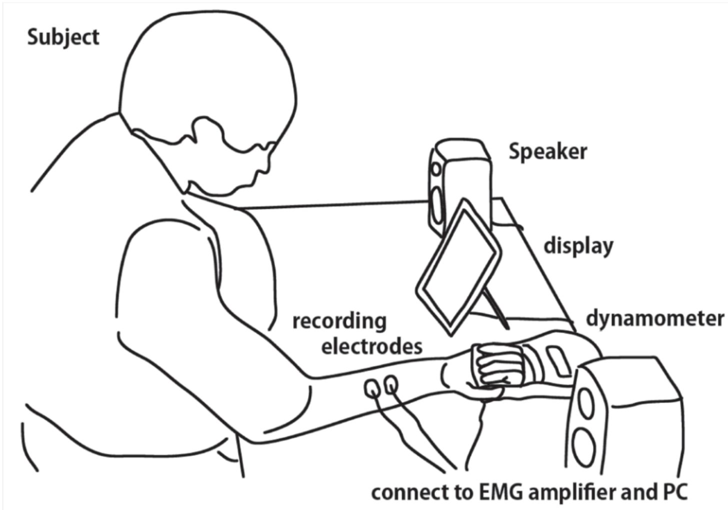


Figure 4.10: The experimental set-up for the gripping session. Picture is taken from (Iguchi et al., 2013).

biofeedback of both muscular activity and kinematic information from the user during physical exercise. The biofeedback aims to improve the quality of the exercise.

Chapter 5

Research Methodology

5.1 Chapter Structure

The structure of this chapter is as follows. Section 5.2 summarizes the examples presented in Chapters 2 and 4. It highlights the current trend of applying real-time auditory feedback to physical exercise and comments on the novelty of this research.

Section 5.3 explains the high-level research objectives in terms of system development and hypothesis testing.

Section 5.4 provides an overview of the experimental design and the purpose of each experiment.

Section 5.5 explains the quantitative and qualitative data to be analysed, along with the statistical methods used in the analysis.

5.2 Summary of the Literature Study

To re-emphasize the research hypothesis, this research aims to explore the use of real-time auditory feedback of the subject's physical exercise as an approach to improve training quality and motivation.

Chapter 2 delivers an insight of the strengths and advantages of sonification as an alternative data display method, and Chapter 4 emphasizes the importance of encouraging the general public to do more physical exercise. From the past examples of real-time auditory feedback in biofeedback and physical activities, a few issues are highlighted:

1. Sonification as a way to convey information for movement-based activity has been well supported by many examples. It is capable of delivering useful cue for the sake of improving exercise quality. In some cases, the effectiveness was appeared to be less effective than visualisation, yet the overall result was still encouraging. And adding to the advantage of being screen free, sonification make biofeedback more suitable for many types of physical activity where visual attention needs to be focused on elsewhere.
2. For sonification in sports, the research focus has been mainly landed on professional athlete training. There are not many examples which seek ways to benefit the general public.
3. The use of biofeedback has been also applied to professional athletes or medical applications. This was partly due to the high cost of biofeedback devices in previous years. Nowadays these devices are not longer that expensive, and indeed there is somewhat a revolution taking place at the time of writing concerning the widespread monitoring of public health data.
4. The sound designs of some sonification projects have tended to be relatively simple. Although they are capable of conveying information,

more effort can be put in the design of the sounds for specific uses and for individuals.

5. Several sonification projects offer a simple type of mapping, which leads to simple and predictable sonic outcomes. Although in theory this would seem to be a good way of reliably portraying data, the lack of options and variation can in practice cause listening fatigue.

To target those issues, this research project developed a real-time sonification system and examined its use in general physical exercise for healthy subjects. Affordable sensory devices were used in the system development. In terms of the auditory feedback design, the system provided multiple sound options for users to choose from.

5.3 Research Objectives

This research achieved two core objectives:

1. Sonification system development. The system can provide sufficient technical capability to generate auditory feedback from the user's physical movement in real-time.

2. Develop a series of experiments to evaluate the sonification and test the hypothesis.

The sonification system comprises both hardware and software components. Sensory devices are required to extract biceps curl information such as position change and muscular activity in real-time. Then a software platform sonifies the movement information to create auditory feedback. The sonification design criteria are as follows:

1. The sonification should *reflect* the movement so that the user can perceive information of their movement from the sound directly and in real-time. For example, the user should be able to hear the change of muscular activity of the biceps during the contractions.

2. The sound should be *suggestive* enough to remind the user about the quality of the exercise. Users should be able to realise whether changes are required purely based on their perception of the sound.

3. The *listening experience* in long-term use should be taken into account. Hence, the design should involve a careful tailoring of the sound aesthetics and variations.

The details of the system design are explained in Chapter 6.

5.4 Experimental Design

The experimental design followed Bordens and Abbotts' research design procedure described in *Research Design and Methods* (Bordens and Abbott, 2008). The procedure includes: deciding types of experiments, choosing subject population, deciding measurable variables and analysing data. The procedure is now presented.

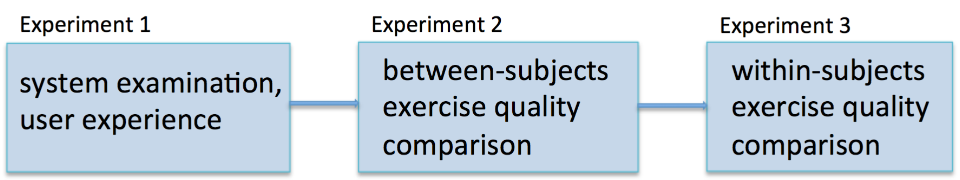


Figure 5.1: Diagram of the experimental structure

There are three main experiments: Pilot Study, Between-Subjects Experiment and Crossover Trial. All three experiments investigated the effect of using real-time sonification in physical exercise but from different aspects (Fig. 5.1). All three experiments used biceps curls as the training programme. This is because the biceps curl is one of the most common exercises for the general population. However, despite being a well-known exercise, the quality is not always satisfactory (discussed in detail in Section 4.3). If supportive evidence on the effect of sonification could be found for this exercise, it could be deduced that sonification has the potential to be applied in a wide range of other types of exercise.

The first experiment (*pilot study*) examines the system and gathers suggestions for improvement. Through the testing procedure, an initial impression is gathered of whether the sonification could potentially lead to a good quality of exercise.

The second experiment compares the exercise quality with and without sonification. The experiment is categorized as a *between-subjects* design (Bordens and Abbott, 2008). Subjects were randomly assigned to two equally sized groups, one with the sonic feedback and the other without. The exercise data and results were recorded for comparison.

The final experiment is the crossover trial (*within-subjects*), which takes place over a longer time-scale than the previous experiment. This type of experimental set-up can help to eliminate the factor of individual differences between participants. Another advantage is that a smaller sample size is required than between-subjects design. It, however, has a disadvantage for causing a 'carryover effect', which appears as the new treatment is affected by the previous treatment (Bordens and Abbott, 2008). To minimize this effect, the crossover trial used a AB-BA method, where the population was separated into two groups with different treatment orders. The purpose of this experiment is to examine the difference in exercise quality (with and without real-time auditory feedback) for all subjects.

The reason for conducting both the between-subjects and within-subjects experiment is because it is difficult to recruit a large number of participants to take part in an extended longitudinal test. Physical exercise quality cannot be defined in a single session. With the between-subjects test, we could recruit a larger amount of subjects for a shorter time-scale, whereas the crossover trial required a longer training time-scale with fewer participants.

The experiments were ethically approved by the Physical Sciences Ethics Committee of the University of York. The sonification device did not cause any discomfort to the user and the auditory feedback was played at the normal volume. All participants were advised not to choose an overly challenging weight of the dumbbell. In addition, the participants were given the choice stop the experiment at any point if they experienced any form of discomfort or pain. The experiments were monitored by the author of the thesis to ensure safety.

5.5 What Data to Analyse?

The analytic approach is based on the concept of triangulation, which is a research method using a combination of qualitative and quantitative data analysis (Jick, 1979). It offers a holistic investigation of the hypothesis by examining both objective experimental data and subjective comments from the test participants.

A quantitative study can objectively calculate a purely technical problem, for example improving the speed of a particular computer processor. Human activity, in contrast, has certain level of subjectivity, which can be hard to gather from quantitative data alone. By including a significant contribution from qualitative data, the analysis covers both the objective and subjective perspectives, which is a better way of evaluating the potential of sonification. It is important to see whether sonification can improve the quantifiable exercise results, but people's subjective motivation is also an important factor.

In this research, three main attributes were studied for the analysis:

- Repetition Time,
- Movement Range, and
- Total Effort.

The repetition time and movement range were measured using the Kinect camera with the sampling rate of 30Hz. The Kinect camera outputs hand coordinates that are related to the user's center of mass, this measurement was more stable, unlike some other tracking systems that required calibrations (such as fixed camera placement and standing spot). All three attributes have the same polarity as the higher value represent better quality of exercise. Both SPSS[1] and R[2] were used as the analytical tools.

5.5.1 Repetition Time

Figure 5.2 demonstrates the change of the hand's vertical position in a set of biceps curls. The repetition time is the difference between the starting and ending times of the repetition. The smallest variation of the measurement is $0.033s$ (1/30Hz), whilst the repetition time is approximated to $\pm 0.1s$.

[1] http://www-01.ibm.com/software/uk/analytics/spss/
[2] http://www.r-project.org

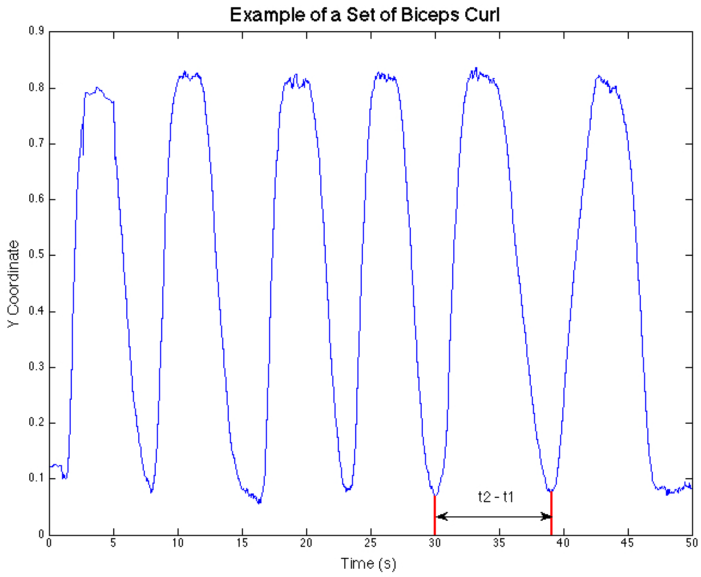


Figure 5.2: An example of finding the repetition time

5.5.2 Movement Range

The movement range is the distance between the hand's vertical position at the beginning of the lifting phase (concentric contraction) and the beginning of the lowering phase (eccentric contraction) in a repetition (see Fig. 5.3). It scaled between straight-arm position (0) and head height (1.0), where 0.8 represents the approximate shoulder height. This variable has a resolution of 1000, meaning the smallest variation of of this variable is ±0.001.

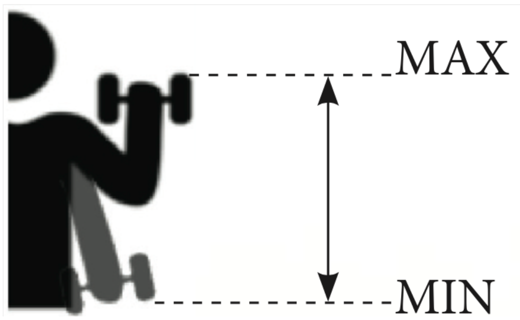


Figure 5.3: An example of finding the movement range

5.5.3 Effort

Because different people may choose different dumbbell weights, the effort expended is dependent on both the weight of the dumbbell and the number of repetitions carried out. Hence, the variable 'effort' is defined as the combination of both, which is calculated by the equation below,

$$effort = weight \cdot repetition$$

The total effort is the product of the dumbbell weight and repetition amount, which are recorded manually by the facilitator. Therefore it would not be affected by any system error.

5.5.4 Exercise Quality Criteria

We defined and explained to the participants that a good quality of exercise should consist of the following two criteria:

1. Participants should aim for a large movement range. This means trying to fully bend the forearm in the concentric phase and lower to the straight position in the eccentric phase, while the upper part of the arm remains still.
2. The contractions should be executed at a steady and relatively slow speed, preferably at least 4 seconds per repetition.

The predefined criteria aimed to introduce a degree difficulty and restriction to the exercise. While it is common to maximise the number of repetitions for an effective workout, there are other types of training method which suggest a different attitude to the speed of repetition. Slow pace weight training can effectively increase muscle strength (Atha, 1981; Newton et al., 1996). Fast pace training (moving the load as rapidly as possible), also known as explosive training, can be more effective in developing explosive strength (Newton et al., 1996; Behm and Sale, 1993). However, explosive training is not used in this research and thus a fast repetition is not considered as good quality in this particular context.

5.5.5 Quantitative Data Analysis

The following statistical tests were used in this research:

Paired Sample T-test

The paired sample t-test looks at the difference of mean variables of the same population under two different conditions/treatments. It was applied in the crossover trial where all subjects exercised both with and without the real-time feedback.

Independent-Samples T-test

An independent-samples t-test compares the means of the dependent variable of two sample groups to find out whether there is a significant difference between two groups. The test was applied in the comparative experiment. The test examined the difference (between groups) of the three abovementioned dependent variables.

Multivariate Analysis of Variance (MANOVA)

Multivariate analysis of variance (MANOVA) compares the differences in the means of multiple dependent variables, and outputs both the combined effect and the separated effect among groups to see whether there are significant differences (Pallant, 2010). This was applied in the comparative experiment to study the composite impact of the exercise quality variables. By combining the three variables as a general exercise quality factor, we could investigate whether the use of sonification could lead to a better exercise quality from a more holistic perspective rather than by each individual dependent variable.

5.5.6 Survey Data Analysis

The survey data involved gathering survey questions (rating) and comments. The questions were presented as a rating on an ordinal scale to collect the participants' subjective opinions of the sonification and exercise experience.

Regarding participants' comments, a content analysis method was applied (Weber, 1996), which makes inferences from the comments. The comments are presented in matrix format, which is a tabular format to display arranged data (Miles et al., 2014). It includes the categorised comments regarding their types (e.g. sound feedback related, physical condition related), and evaluation (positive or negative).

5.6 Summary

This chapter presents the researcher's opinion of the examples presented in the literature chapters, which leads to the objectives of the research. An overview of the experimental design and analytic methods are presented. The next part of the thesis presents the main contents of the research including the sonification system development and experimental results.

Chapter 6

SonicTrainer - Real-time sonification system

6.1 Chapter Introduction

This chapter presents a detailed description of the sonification system. It gives specifications of hardware components and software to provide insight to the system construction.

6.2 Hardware

Two types of sensory devices are used to capture arm movement and muscular activity separately. The first is an EMG device, which is capable of measuring muscular activity. The technical background of EMG was provided in Chapter 4. The second captures movement information, such as the change of limb position, using the Microsoft Kinect camera.

6.2.1 Electromyography (EMG) Sensor

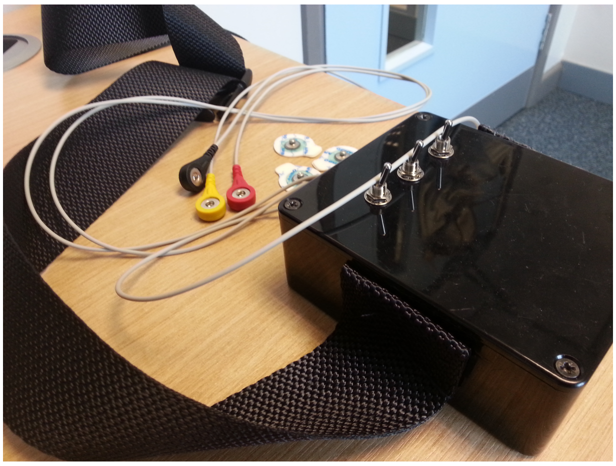


Figure 6.1: The EMG belt

Figure 6.1 shows the EMG belt developed to measure the myo-electric signal generated from the biceps activations (both concentric and eccentric contractions). The belt comprises two EMG sensors designed and manufactured by Advancer Technologies[1], an Arduino Duemilanove microprocessor[2] and a Bluetooth modem that provides wireless data transmission to the computer at 9600baud. The Arduino is a microprocessor for converting analogue electronic signals from the EMG signal to digital signal, which can be received with a computer for the use of sonification. The layout of the belt is presented in Figure 6.2. The EMG signal and its pin layout is shown in Figure 6.3.

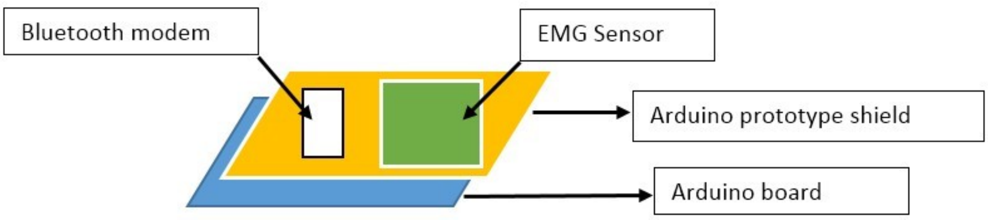
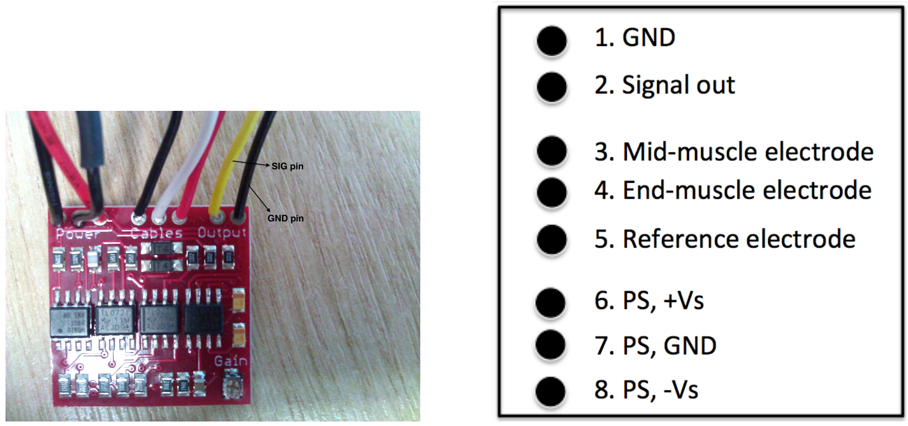


Figure 6.2: Layout of the EMG sensory belt

[1]http://www.advancertechnologies.com/
[2]http://arduino.cc/



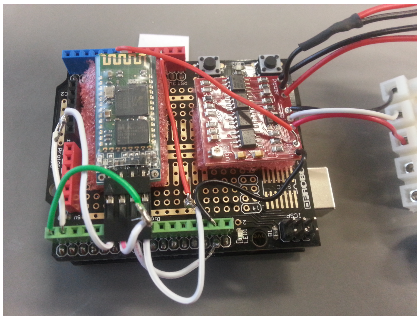
(a) Muscle sensor developed by Advancer Technologies.

(b) Muscle sensor's pin layout

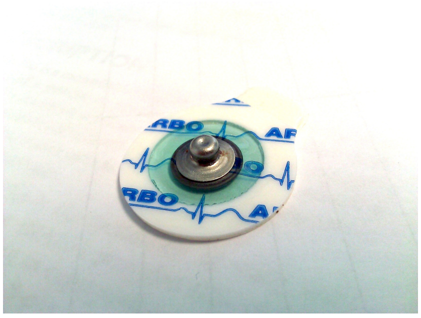
Figure 6.3: The EMG sensor and its layout

The EMG sensor consists of one INA106 differential amplifier and three TL072 operational amplifiers powered by two 9v batteries. The sensor collects electric activity of one muscle through the three cables shown in Figure 6.4a. For skin contact, pre-gelled surface EMG electrodes (Figure 6.4b) need to be connected to the metal end of each cable. The red and white cables connect to the active muscle's middle part and end part (as shown in Figure 6.5). The black cable is connected to an inactive part of the body as a reference point; the usual choices are bony parts or other muscles which will not be active while the main muscle is in action. The microprocessor converts the analogue signals (0 to 5.0 volts) into digital signals (data range 0 to 1023). The data transmission between the belt and the computer uses wireless Bluetooth serial communication.

The EMG belt consists of two sensors sensors, allowing electrode attachments on both arms simultaneously. For this research, it was decided to concentrate on sonifying one arm at a time. Even though it is feasible to sonify both simultaneously. Most of the participants will be newcomers to sonification and could be potentially confused when trying to decode two streams of sound. However, adjustment can be easily made in the future if two EMG sensors are required to be used at the same time.



(a) The actual construction inside the EMG belt



(b) Kendall/Tyco ARBO* Ag/AgCI EMG Electrode

Figure 6.4: EMG Sensor and Electrode

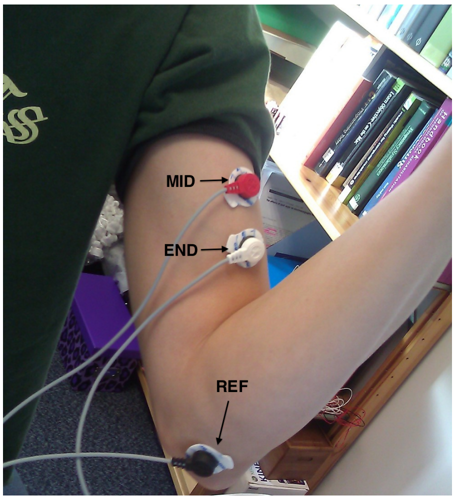
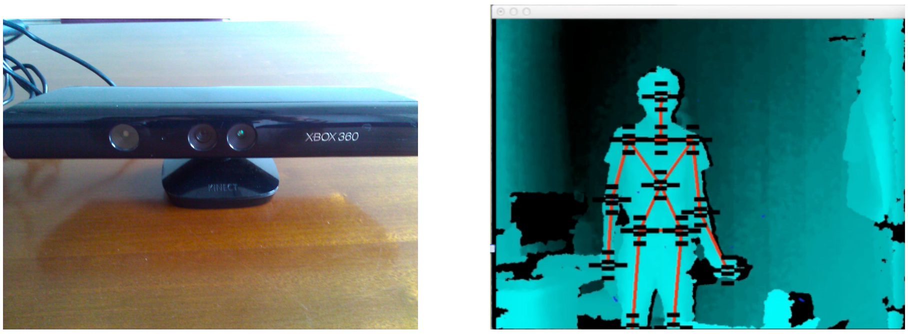


Figure 6.5: Electrode placement for biceps

6.2.2 Microsoft Kinect Camera

Another sensory device used in this research is Microsoft's *Kinect* motion sensor. In this study, the Kinect (Figure 6.6a) is used in addition to the EMG sensor in order to provide additional kinesiological information by capturing the subject's real-time gestural information. To communicate with the sonification system, an open-source program named Synapse[3] is used to obtain positions of up to 15 body joints (hands, elbows, shoulders, neck, head, etc.). A screenshot of Synapse for tracking multiple body joints is shown in

[3] http://synapsekinect.tumblr.com/



(a) Miscrosoft Kinect Camera (b) Screenshot of the Synapse Tracking

Figure 6.6: Joints tracking using Synapse and Kinect camera

Figure 6.6b. The data transmission is based on Open Sound Control (OSC) protocol[4]. Each joint contains the horizontal, vertical and depth coordinates relative to the centre of a person's torso. These coordinates are encrypted with a specific identifier and can be received via other programs on the computer.

6.2.3 Section Summary

The abovementioned sensory devices enable measurements of both the kinesiological information (visible information such as arm movement) and the kinematic information (muscular activity). They provide essential attributes of the biceps curl for sonification and analysis.

6.3 Sonification Software

This section presents the design of the sonification software. It contains the design consideration and descriptions of the main functions. The sonification software was developed using Max[5]. Max is a graphical programming software that is often used for multimedia and interaction designs.

[4]http://opensoundcontrol.org/
[5]https://cycling74.com

6.3.1 Top-Level Design Overview

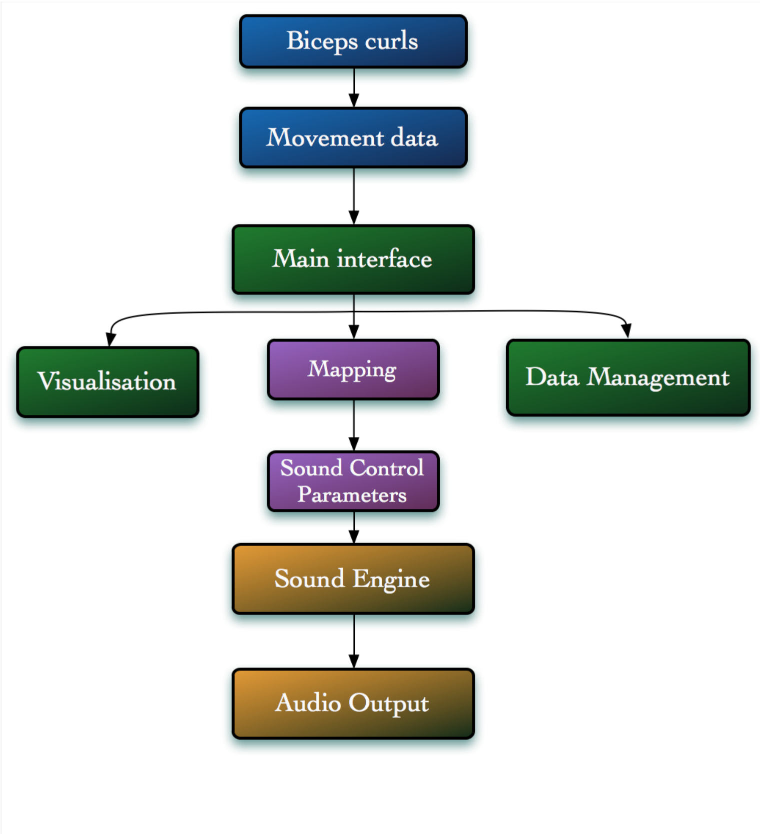


Figure 6.7: The sonification process

Figure 6.7 presents the top-level workflow of the software. The top section of the diagram (in blue) is the input section. The exercise movement information is captured by the sensory devices and sent to the computer software via the Arduino microprocessor. The sonification software consists of three main parts: Main Interface, Mapping, and Sound Engine.

The main interface (shown in green) handles basic data management such as file saving and visualisation. The Mapping section (shown in purple) is responsible for converting the input data to sound control parameters, which is used to drive a Sound Engine (shown in yellow) which produces the audio heard by the user.

The following section explains the detailed software design. Since the software development took place on Max, this thesis adopts the common terminology of referring to a block of Max function(s) interface as a '*patch*'. The software consists of presented patches in the form of Graphical User Interfaces (GUIs) and background patches (functions that are hidden from the GUIs). The next section covers all the essential functions and interfaces of the software.

6.3.2 Software Part 1: Main Interface Section

(1) Overview

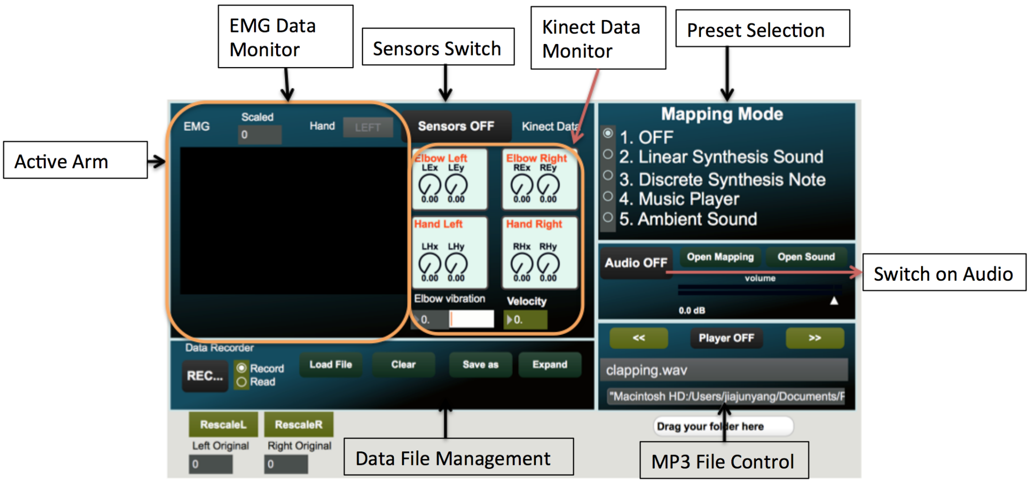


Figure 6.8: Main interface of the sonification software

This interface allows the user to complete all the essential operations of the sonification process. It handles EMG data and Kinect data acquisition through serial communication and the Open Sound Control (OSC) protocol. The user can select and activate the sonification and record the movement information. Different mapping options for various sonic outcomes are also available here. A data recorder is used to store all the bioinformation into a text file for later analysis. Hence, bioinformation can be studied either in real time or offline. Figure 6.8 shows the main GUI, annotated with the key functions. Additionally, the interface also provides visualisation of both the Kinect and EMG data.

(2) EMG Data Acquisition

This is a function to receive EMG data via serial communication. The code in Figure 6.9 was compiled to the Arduino board. This enables data reading of pin A0 and A3 on the Arduino which are linked to the EMG sensors' output cables. Because there are two EMG sensors connected to the Arduino, identifiers are added to separate the channels. Pin a0 is assigned with the name '*analog0*' and pin a3 with '*analog3*'. They are separated by a newline command ('*Serial.println()*'), which acts as channel separation between a0 and a3 in Max. For example, one data frame will look like:

analog0.700 analog3.850

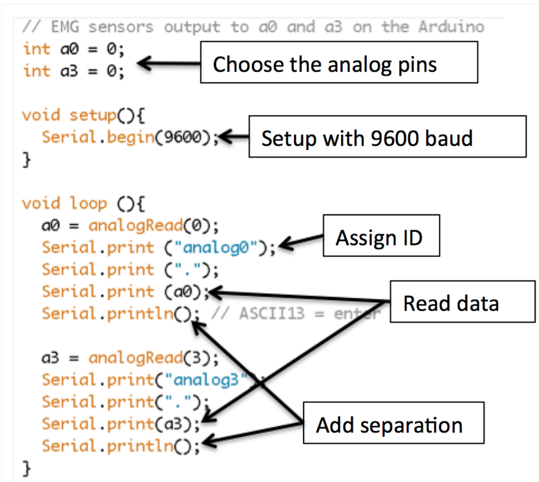
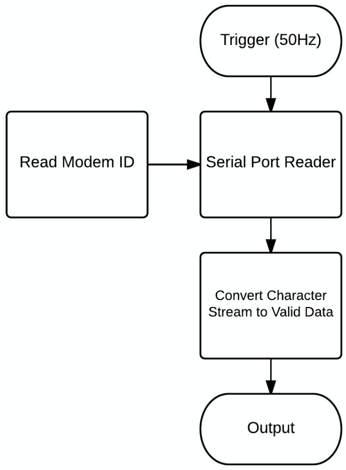
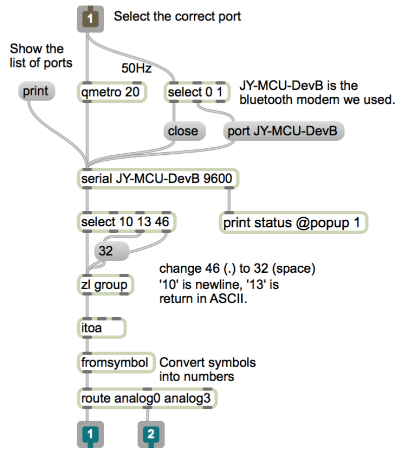


Figure 6.9: Script for acquiring Arduino analogue pins values

On Max, a serial communication patch was created to receive data from the Arduino. Figures 6.10a and 6.10b show the details and structure of the EMG data acquisition on Max. Firstly, the serial port reader ([serial] object) points at the ID of the Bluetooth modem. Then the data is output at a



(a) EMG acquisition diagram



(b) EMG acquisition patch

Figure 6.10: EMG acquisition via serial communication

sample rate of $50Hz$ (using the [metro] object to trigger the [serial] object every $20ms$). Since the data is originally in ASCII (characters) format, it is converted to numbers using the [fromsymbol] object.

The value of the captured EMG signal ranges between 0 and 1023 (equivalent to 0 to 5.0 volts from the sensor circuit). This will be used to control sonic parameters such as filter frequency.

Signal normalisation is applied at this point. The overall idea is to let user listen to the changes in EMG signal from the rest stage to the maximum voluntary contraction (MVC) during biceps curls. MVC refers to the maximal force generated by a muscle in an isometric condition (Bigland and Lippold, 1954). This is usually measured by letting the subject to contract the muscle as hard as possible at a stationary condition. In this research, the participants were asked to move their forearm to a fully bended position then contract the biceps brachii as hard as they could. The maximum value was measured and used as the maximum range of the EMG signal. Normalisation of EMG signal was applied by rescaling the user's rest stage signal and the MVC. Therefore, individual participant could generate clear sound variation from the contraction regardless the muscle strength. The normalisation process avoids two potential issues: 1) A subject is weak and can only generate lower quality of sound even though the subject is working hard. 2) Due to the characteristics of EMG signal, some people can only generate low range of EMG even though they are strong (Section 4.4.3).

The scaling algorithm is presented below, where v is the raw EMG signal.

$$v_{scaled} = \frac{v - v_{min}}{v_{max} - v_{min}} \cdot 1023 \tag{6.1}$$

(3) Kinect Data Acquisition

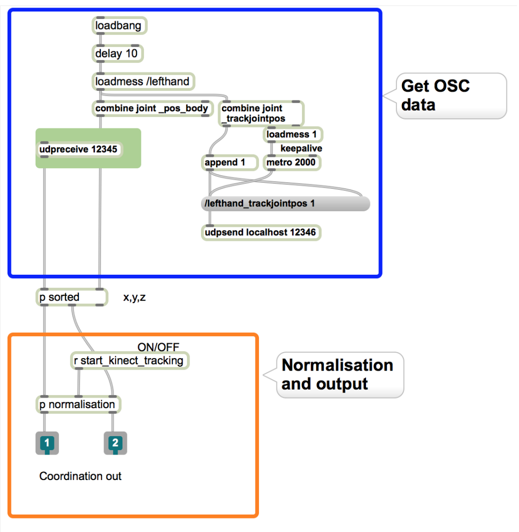
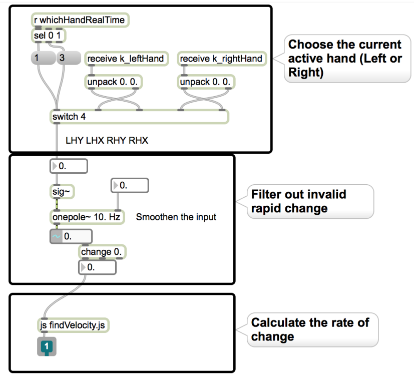


Figure 6.11: Kinect data acquisition patch

The Kinect data was transmitted via OSC with a frame rate of 30fps. It is capable of outputting the coordinates of up to 15 body joints simultaneously. Since the study only concerns arm movement, only the hand coordinates are collected and sonified. Each joint has three coordinates: x (horizontal), y (vertical) and z (depth), however the depth is not needed in this research. This is because the z coordinate is the distance between the user to the Kinect, which is irrelevant to the exercise. Each body joint was pre-assigned with a unique ID, for example the left elbow has the ID of '*/leftelbow_pos_body*'.



(a) Velocity calculation patch

```
// Calculate the rate of change,
// inlets and outlets
inlets = 1;
outlets = 1;

// global variables
var length = 1;  // Current interval is one sample
var counter = 0; // Initialise counter
var xVars = new Array(length); //declear variance

// float -- run the equation once
function msg_float(a)
{
    outlet(0, a - xVars[counter]);
    xVars[counter++] = a;
    counter = counter % length; //  Modulus of the interval
}
```

(b) Javascript for calculating the movement velocity

Figure 6.12: Velocity calculation patch and Javascript

In Max, the [udpreceive] object is capable of receiving OSC data via User Datagram Protocol (UDP), which is a network communication protocol allowing sending/receiving OSC data. The data is then normalised to a range between 0 and 1.0. The demonstration is shown in Figure 6.11. The other elbow and hand joints use the same patch but with different OSC IDs.

(4) Hand Vertical Movement Velocity

A function called '*velocityCalculator*' (Fig 6.12a) was developed to detect the rate of change of the movement. This parameter reflects the speed of the movement.

The top section of the patch selects the exercise hand. In the middle part of the patch, an one-pole low-pass filter is used to filter out invalid rapid change caused by the occasional invalid Kinect tracking, which may occur if something blocks the sight of the joint. This is due to the skeletal algorithm used for the human body tracking, which means if an object is overlapped with the body it will also be considered as part of the body, resulting in a sudden change of the recognised 'body shape'.

The final part of patch is a differentiator written in Javascript. The

Javascript is listed in Figure 6.12b. The variable *length* decides the interval of two samples. In this example, the length was set to 1. Therefore, the rate of change is the difference between the previous rate of change and the current coordinate.

(5) Hand Vertical Movement Range

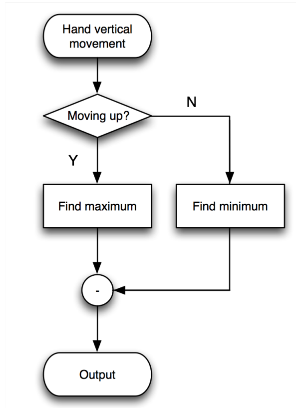


Figure 6.13: Repetition range calculation

Another attribute that strongly relates to the exercise quality is the vertical movement range of the hand. Figures 6.14 and 6.13 present this process. This movement range is the difference between the lowest and highest hand positions in one repetition. The repetition range calculation was developed to record the maximum and minimum y-coordinates of each repetition and output their differences.

(6) Elbow Vibration

This patch calculates the vibration in elbow movement. The original idea was to observe the steadiness of the biceps curls. By looking at the elbow movement, we can find out the amount of movements in the upper arm during the exercise. The initial idea was to define a better quality biceps curl should involve the least amount of movements in the upper arm. However, this

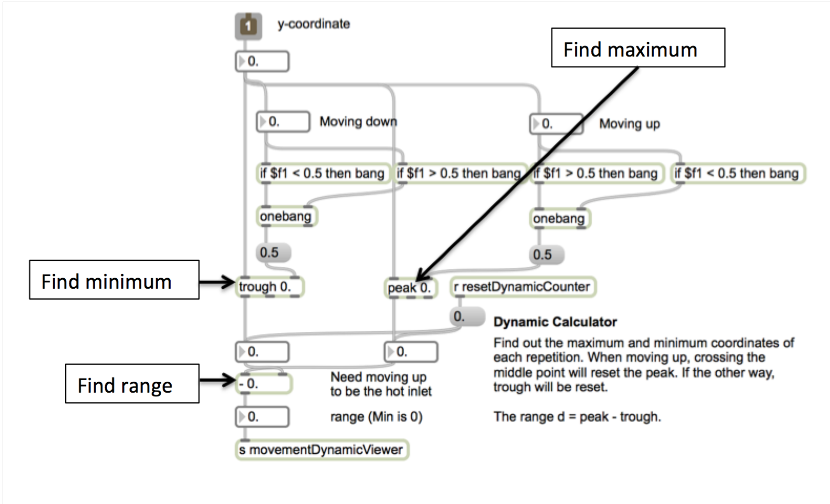


Figure 6.14: Patch view of the repetition range calculation

variable was decided not to put into the sonification despite the factor that it functions properly. The reason is because we do not want to overcomplicate the sonification. The additional information can be useful but also increase the difficulty in understanding the auditory feedback in real-time.

The patch for calculating the elbow vibration is shown on Figure 6.15. The first part of the patch selects the elbow coordinates of the active arm. Then in the second part, it calculates the difference between the current coordinates the delayed coordinate, which is 3 samples behind. Then the vibration is the sum of the absolute values of both directions. The algorithm for the elbow vibration *vib* is shown below

$$vib = |x(n) - x(n-3)| + |x(n) - x(n-3)| \tag{6.2}$$

Because the Kinect tracking may occasionally causes the lost of tracking or sudden change of body shape, which can lead to a sudden jump in the coordinates. To prevent this invalid coordinates being counted as part of the elbow vibration, a [split] object and an if statement are used to in combination to selectively filter out the vibration values which are higher than a threshold

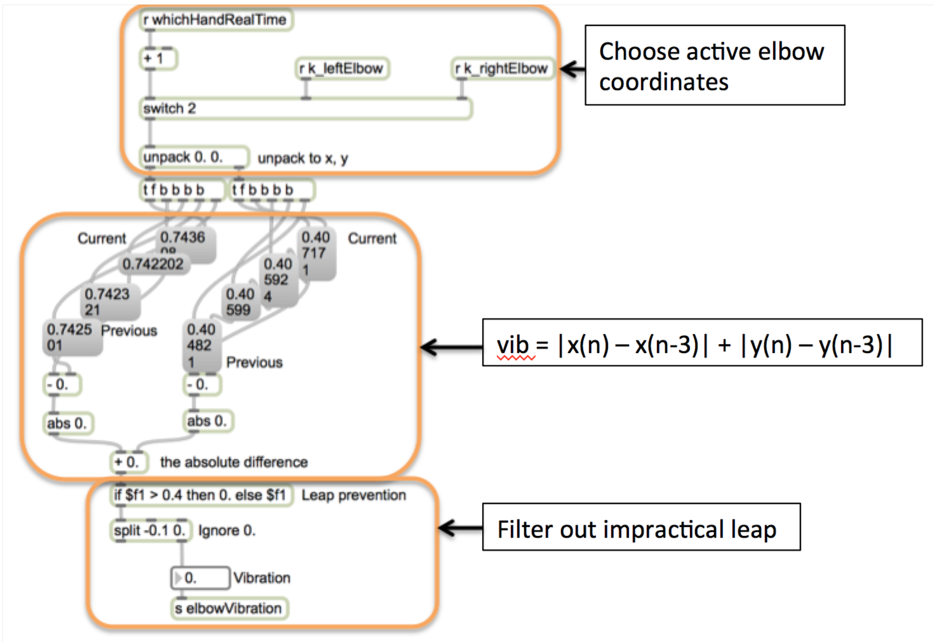


Figure 6.15: Patch for calculating elbow's 2-dimensional total vibration

value, which is considered to be physical practical for a slow pace biceps curl.

(7) Data Recorder and Reader

(2) to (6) explained the attributes to be used for either sonification or analysis. A data recorder is needed to store these attributes during the exercise. The data recorder captures the raw data (EMG and coordinates) and analysed information (velocity and dynamic) before they are sent to the mapping section. It allows exercise information to be stored for analysis and allows the analyst to play back pre-recorded files for off-line sonification (when the exercising user is no longer present).

The data recorder has a sample rate of 50Hz. As the two streams of sensory data have different sample rate, this section of the patch provides a unified sample rate of 50Hz. This is taken as the data rate of the fastest sensory input (EMG), whereas the Kinect data, which has the sample rate of 30Hz, is put into a buffer and resampled at 50Hz. The recorded data is stored in a [coll] object, which can output the data as a text file. Recorded files can be reloaded and replayed at the same sample rate.

The [pack] object (shown in Fig 6.16) combines all the data as a list and assigns a specific sample index for each frame. This list of data is sent to the [coll] object for storage. The data reader is the reversed process of the recorder.

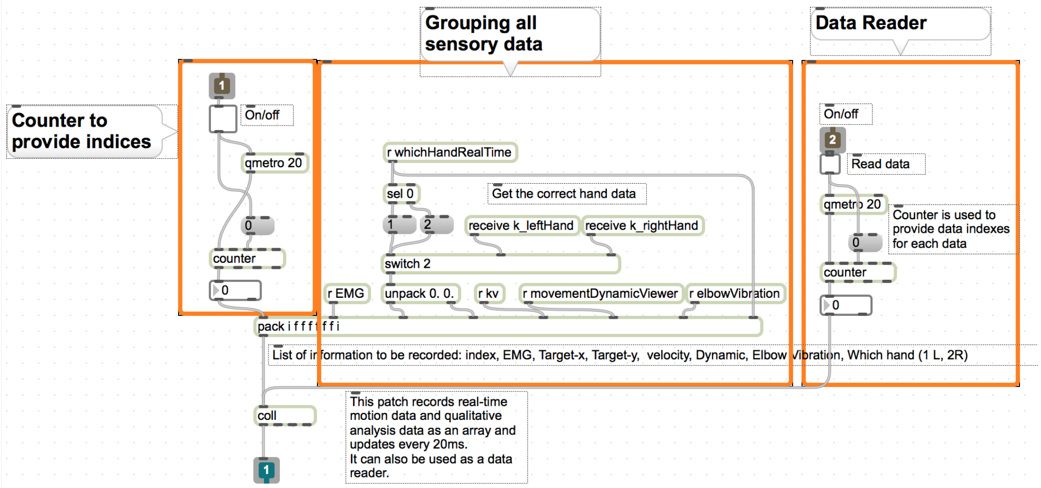


Figure 6.16: The inside structure of the data recorder

The list of recorded data includes: EMG signal, hand x/y coordinates, vertical movement speed, vertical moment range, elbow vibration and hand code (1 for left and 2 for right)[6].

In summary, the main interface provides full functions for operation, input data acquisition and data storage. It also contains functions that pre-analyses the input data such as finding the movement range of a biceps curl repetition and the hand movement speed. Section 6.3.3 explains the mapping process, which connects the input data and the sound parameters together.

[6]In the final experiment, participants were asked to exercise both arms (one at a time). Therefore, it is necessary to put an identify so that the analyst can see which hand was recorded in the particular sets.

6.3.3 Software Part 2: Parameter Mapping Section

The Mapping is the second main part of the software, which can be accessed by clicking [mapping] on the main interface. This patch (Fig 6.17) maps the rescaled EMG data, hand vertical movement and hand velocity to various sound parameters. In this research, we provided four different types of sonic outputs. Hence there are four types of presets to be recalled, each with a unique mapping scheme. The available sound parameters are synthesiser pitch, sound volume, filter cut-off frequency, alter sound and noise trigger.

This research uses One-to-One Parameter Mapping method is to create a perceptually clear sonic outcome. For instance, a user should be able to easily perceive that the high and low pitch of the sound results from the high and low of the hand position.

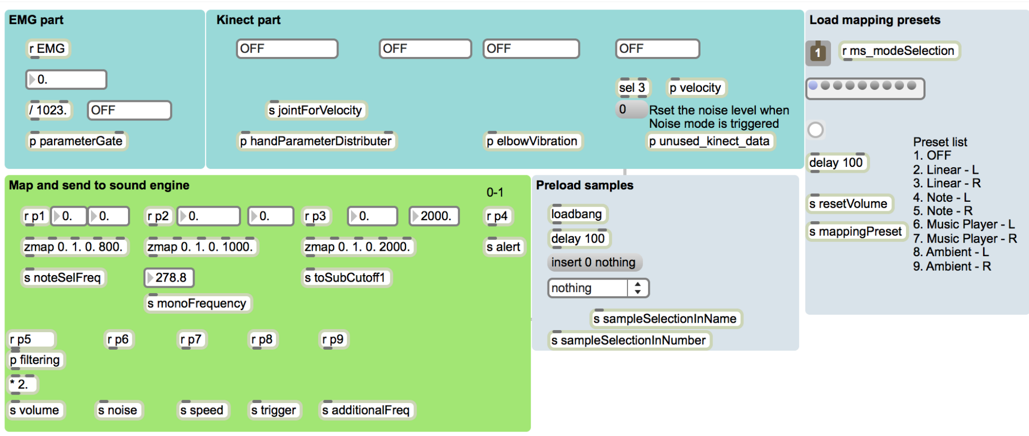


Figure 6.17: Mapping patch

6.3.4 Software Part 3: Audio Synthesis Engine Section

The third part of the software is the sound engine. This consists of a *Frequency Modulation/Subtractive Synthesizer* and two *audio samplers* for playing back audio files such as music files and ambient samples (Fig. 6.18). This patch can be run as a separate virtual instrument. The top level signal flow of the

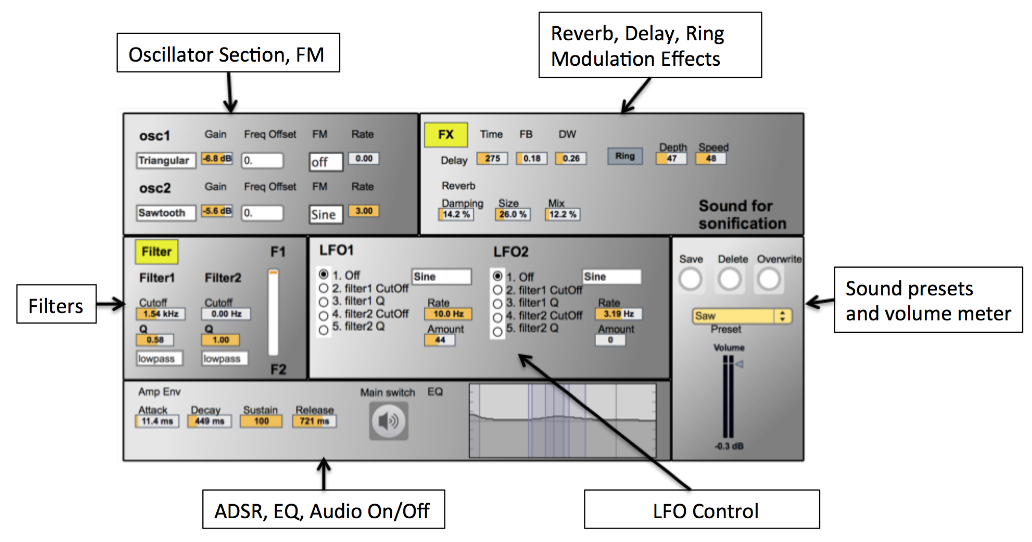


Figure 6.18: Audio synthesizer and sampler

Synthesis Engine is presented in Figure. 6.19.

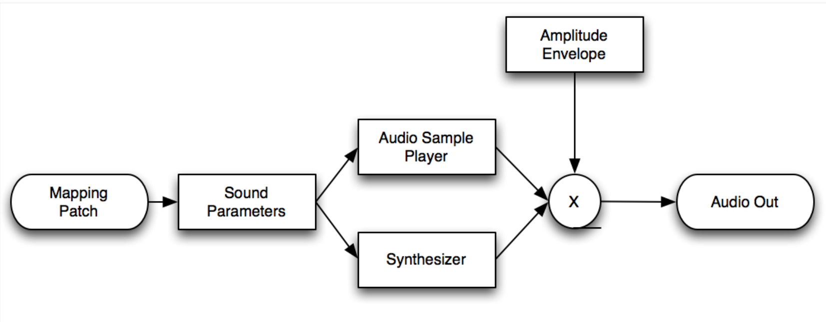


Figure 6.19: Sound generation flowchart

(1) Synthesizer

Figure 6.20 shows the synthesis design block diagram. At the beginning of the signal flow, an FM synthesis block is used with a modulator connected to each carrier oscillator. In total, there are two carrier oscillators and two modulator oscillators. Each oscillator has a wavetable lookup, allowing the selection of four different wave types: sine, triangular, sawtooth and rectangle

(Fig. 6.21). These waveforms are pre-constructed using Matlab and stored in four different buffers.

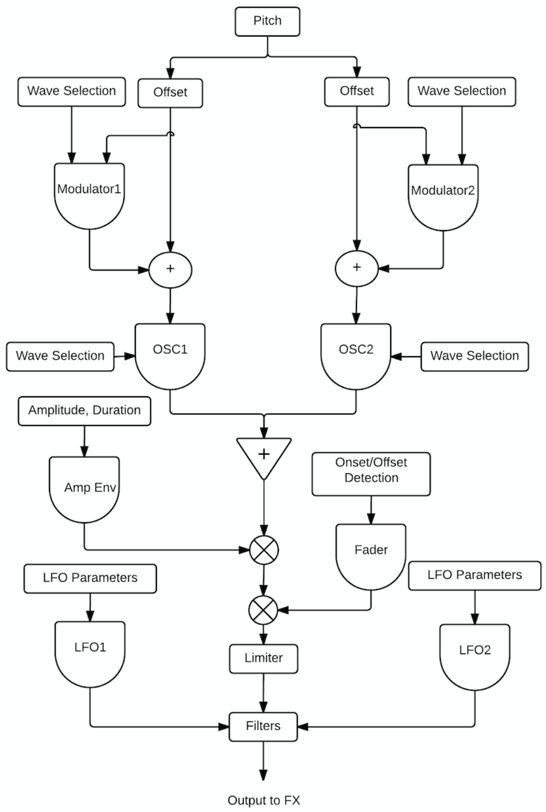
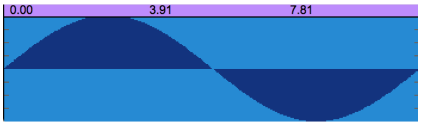
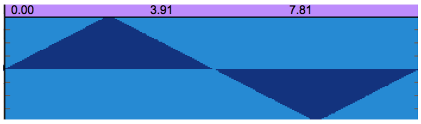


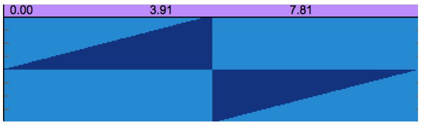
Figure 6.20: Signal flow of the synthesizer



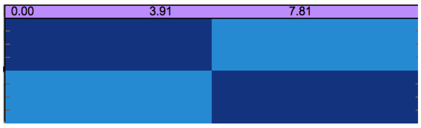
(a) Sine Wave



(b) Triangular Wave



(c) Sawtooth Wave



(d) Rectangle Wave

Figure 6.21: Four waveforms for selection

The two carriers signals (OSC1 and OSC2) are combined and shaped by an amplitude envelope and a fader. The amplitude envelope can modify the onset, sustain and offset of the signal amplitude. The fader detects signal onset and offset, and ramps their transients to prevent from sudden signal level changes, which would cause a clicking noise. Then, a limiter is connected afterwards to prevent distortion. Finally, the spectrum of the signal can be shaped by a combination of two filters. Four types of filters are available: low-pass, high-pass, band-pass and notch. Low-frequency oscillation (LFO) is used to provide modulation to the sound by controlling the parameters such as filter cut-off frequency and resonance (Q).

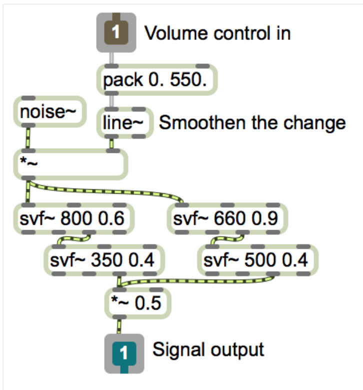


Figure 6.22: White noise generator

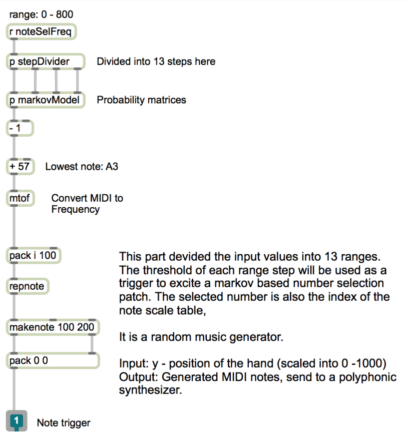
In addition to the synthesiser sound, there is a white noise unit (Fig 6.22) called [noise˜], which is used as a warning to the user that a certain parameter is being exceeded. The noise signal passes through four band-pass filters ([svf] object) as shown in Figure 6.22. The use of four filters allows the sound to be less harsh, which means that it can be alerting but not too uncomfortable to listen to. This noise unit only has one parameter as the control, which is the volume.

(2) Synthesiser Control Methods

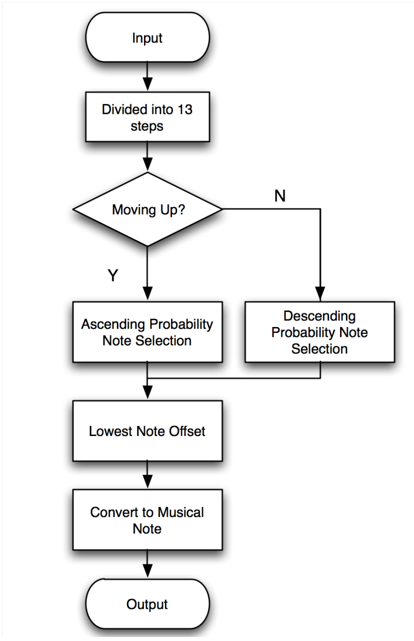
There are two ways of controlling the synthesiser. The first is a linear change of fundamental frequency. Hence, a monophonic version of the synthesiser is sufficient for this requirement.

The second way is more complex as it generates polyphonic outputs. This method triggers musical notes (between C4 and E5) instead of a linear progression of the fundamental frequency. The amplitude envelope provides a clear amplitude attack and decay to each note. It allows multiple notes to be played simultaneously or one overlaps with the other. This requires the synthesiser to become polyphonic instead of mono.

To achieve the polyphonic functionality, the [poly˜] object is used, which encapsulates a patch and creates multiple instances of it for triggering more than one note simultaneously.



(a) Patch View



(b) Diagram View

Figure 6.23: Note selection

To trigger the musical notes, a probability-based note selection algorithm was designed. Figure 6.23 shows the note selection process. At the beginning, the input data is sent from the mapping patch with the name [noteSelFreq] (range between 0 and 800). It then passes into a subpatch named [stepDivder], which divides the data into 13 equal sections. This function is shown in Figure 6.24. When the data moves from one section to another, it triggers a new message and outputs to Outlet2[7] ('Hit note' on the graph). Outlet1 sends out a message to select the ascending or descending probability tables according to the movement direction. If the input value reaches the top range, it will switch to the descending move and vice versa. This is because Outlets 3 and 4 send out messages to initialise the landmark notes indicating that the hand has reached its lowest or highest position. Fixed lowest and highest notes will be triggered respectively as a reference tone.

[7]Inlets and outlets are the inputs and outputs of a patch, which can be connected with either a message or an audio signal.

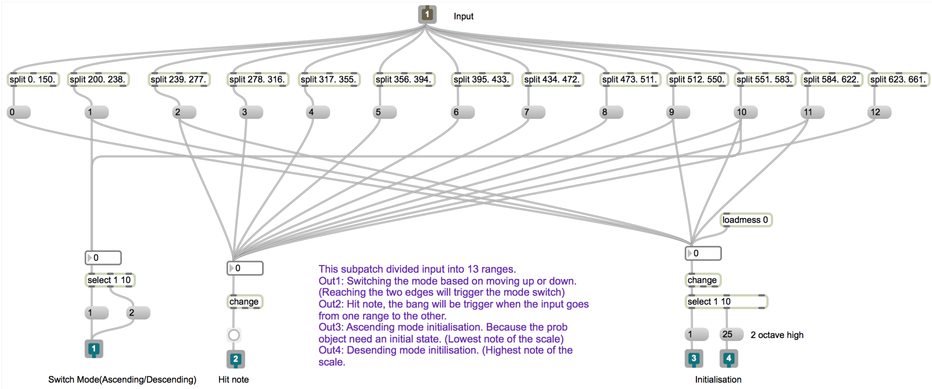


Figure 6.24: Range division process

The probability model is shown in Figure 6.25. The [prob] object is used to select output values based on the predefined weighted probability matrices. For example, Table 6.1 demonstrates how this works. If the input value is 1, it has a 5/22 chance of resulting in 4 (The total weight is $5 + 2 + 15 = 22$), a 2/22 chance of a 3 and a 15/22 chance of a 5. Based on the movement direction (up or down), there are two different probability tables provided for the ascending and descending directions of progression. In the final step, the selected output is in MIDI message format. It is then translated into frequency to drive the polyphonic synthesiser.

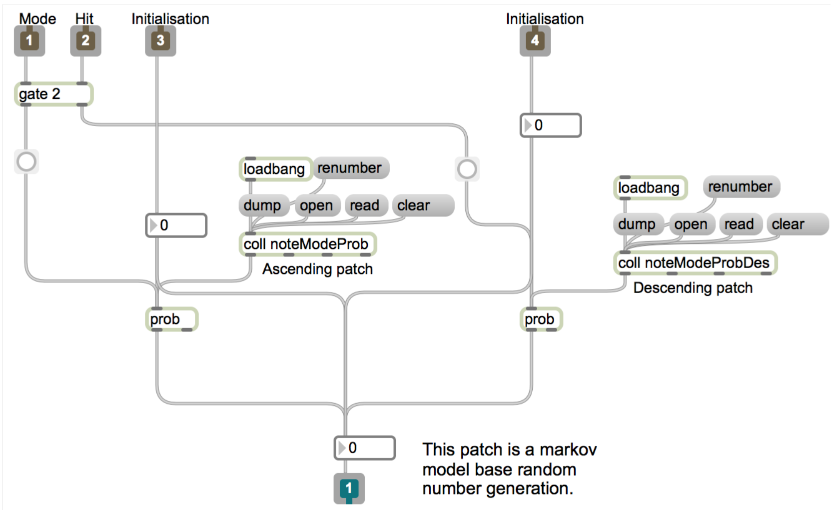


Figure 6.25: Note selection using probability matrices

Current Value	Destination	Weight (possibility)
1	4	5
1	3	2
1	5	15

Table 6.1: Weighted probability matrix example

(3) Audio File Player 1 - Music Player

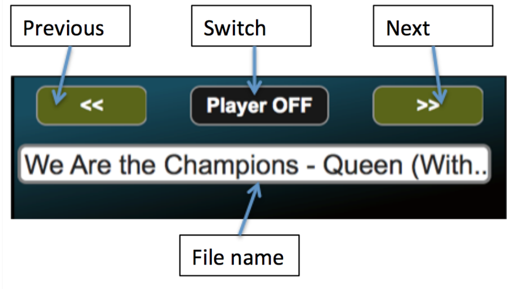


Figure 6.26: Music Player

The music player can be controlled at the bottom-right of the main interface (Fig. 6.26). In the sound engine patch, the construction of the music player is shown in Figure 6.27. First of all, the object [groove˜] is used to enable audio file playback. When an audio file is loaded, it is stored in a buffer named 'yourMusic'. The on/off switch of the music player has a ramping effect resulting in a 'turntable effect' (imagine switching a vinyl disc player on and off) when the music player is switched on or off.

A frequency domain pitch-shifter called [gizmo˜] is connected to the output of the music player, which is one of the pre-built functions available in Max. When the speed of the hand's vertical movement is larger than a threshold value, the right channel will be altered to a higher pitch than the original. As a result, the left and right channels will sound differently in pitch to warn the user that their movement is too fast. But this sound effect will only last for one biceps curl repetition. When the user's forearm returns to its straightened position, the right channel returns to its normal pitch.

At the bottom left of Figure 6.27, the block allows the [groove˜] object to play the next song whenever the current song has reached the end, which can prevent the situation that a song finishes when the user is still exercising.

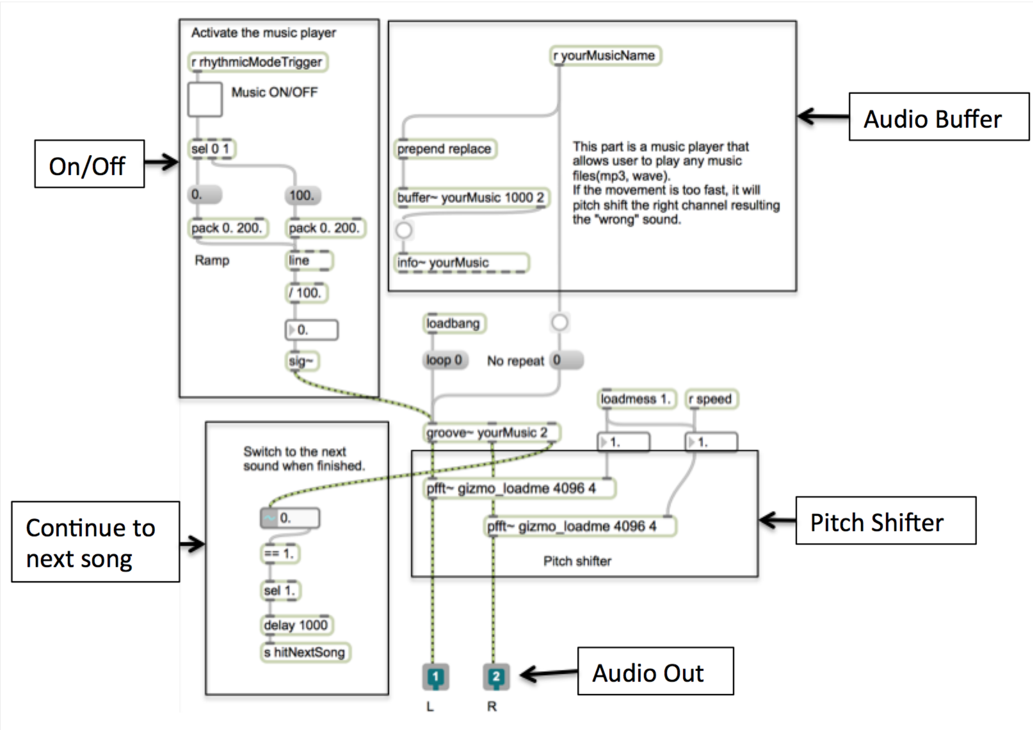


Figure 6.27: Music file playback function

(4) Audio File Player 2 - Sample File Playback

There is another audio sample playback function that works in parallel with the music player described above. This playback function is mainly for ambient samples or other non-musical files. Samples loaded for this player will be played repeatedly. The patch, in Figure 6.28, consists of three main functional blocks. The top-left of the patch works as an on/off switch. The switch is controlled by the hand movement. The audio player is switched on when a biceps curl is initiated, then switched off when the user's forearm returns to the natural straightened position. The [line] function is used to create a smooth transition between on (0.0) and off (1.0) to prevent a sudden

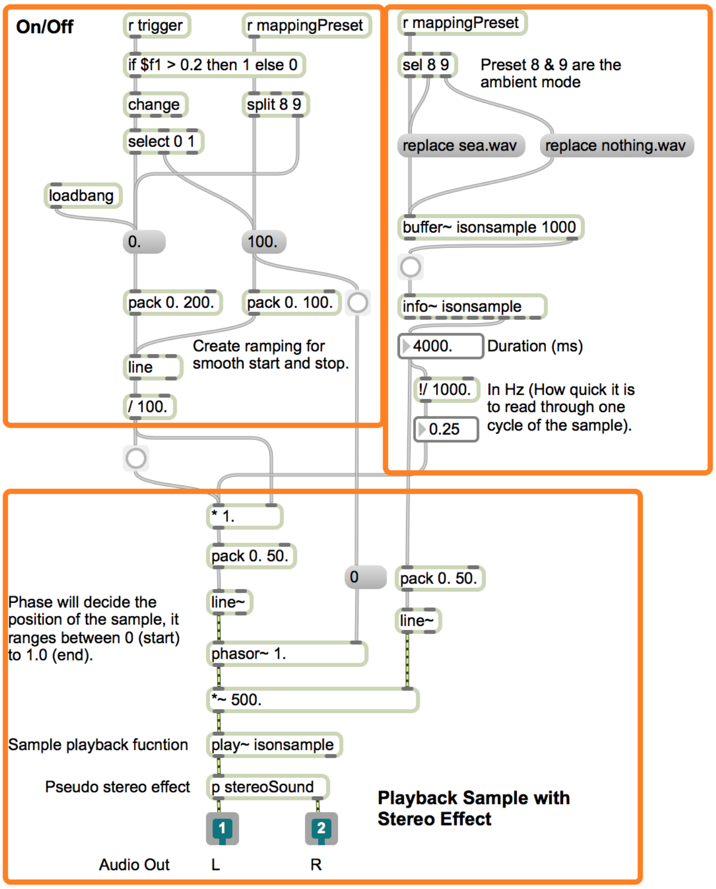


Figure 6.28: Audio sample playback function with looping and stereo effect

change in signal level.

The top-right block of Figure 6.28 loads the sample file to a buffer named 'isonsample'. An [info˜] object outputs the duration in milliseconds of the file, and this information is used to loop the sample. The bottom block of the figure is the actual sample playback function using [play˜]. It reads the sample from start ($0ms$) to the end (the full sample length in ms) repeatedly. Before the audio signal is sent to the effect unit, a stereo effect is connected to the signal chain to provide a stereo sense to the sound. This effect is detailed in Figure 6.29. Essentially, it creates a small amount of delay to each channel, resulting in a perceptually different sound in each ear.

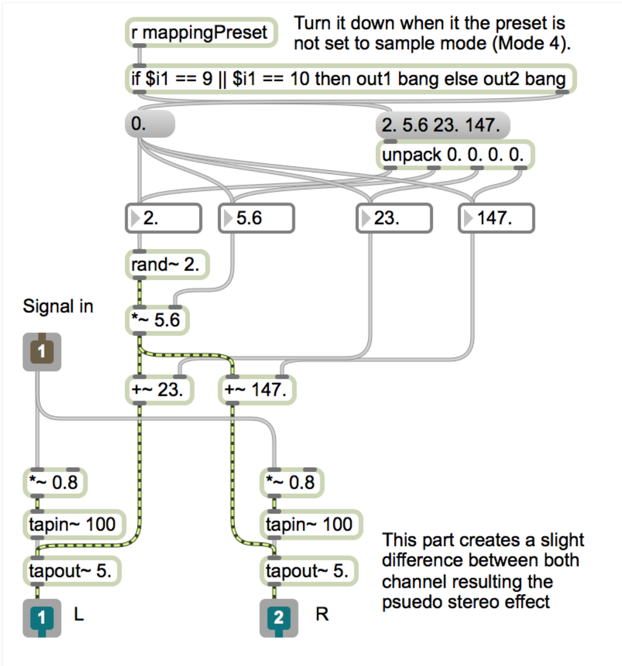


Figure 6.29: Stereo effect emulation

(6) Audio Effects

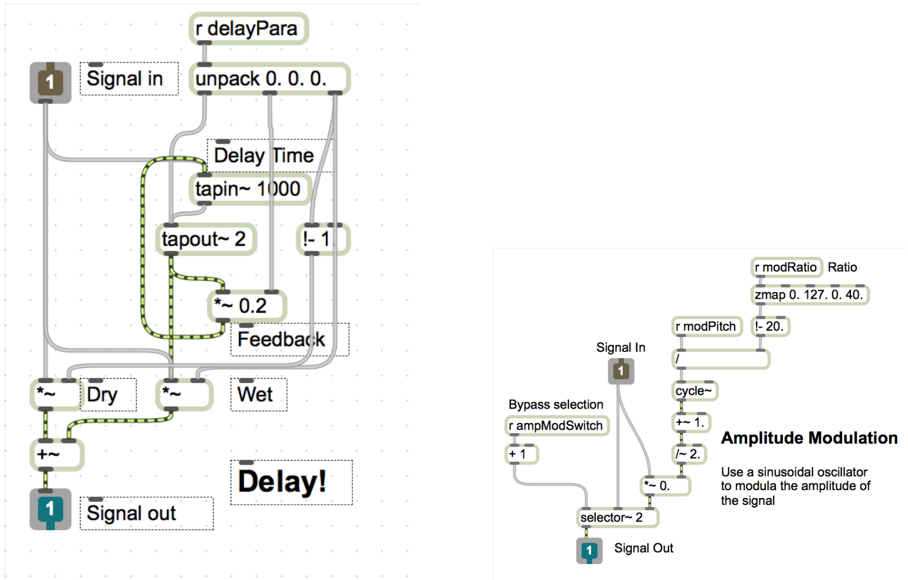
Both the synthesised signal and the audio from the file players pass through four cascading audio effect units. The user can switch on the effects by clicking the [FX] button on the sound engine interface.

The first is a delay unit (Fig 6.30a), which provides controls such as delay time (0 to 4000 ms), feedback (0 to 0.9) and mix (0 to 1.0).

The second effect is a ring modulation (amplitude modulation) unit (Fig 6.30b), which uses a sinusoidal oscillator to generate modulated numbers between 0 and 1.0. The audio signal is multiplied by these numbers resulting in an amplitude modulation effect (or 'tremolo').

Thirdly, a graphical 4-band EQ is available at the end of the signal chain.

The last effect is a plate reverberation emulation. It was inspired by a plate-class reverberation design known as the Griesinger Reverb (Dattorro, 1997).



(a) Delay Effect

(b) Ring Modulation Effect

Figure 6.30: FX details

The patch is shown in Figure 6.31. It consists of 4 diffusers using all-pass filters to decorrelate the incoming signal to simulate the initial reverberation process. Then the reverberation tank is used to emulate the acoustic bouncing which would occur inside a physical tank by randomising the delay and phase change of the signal.

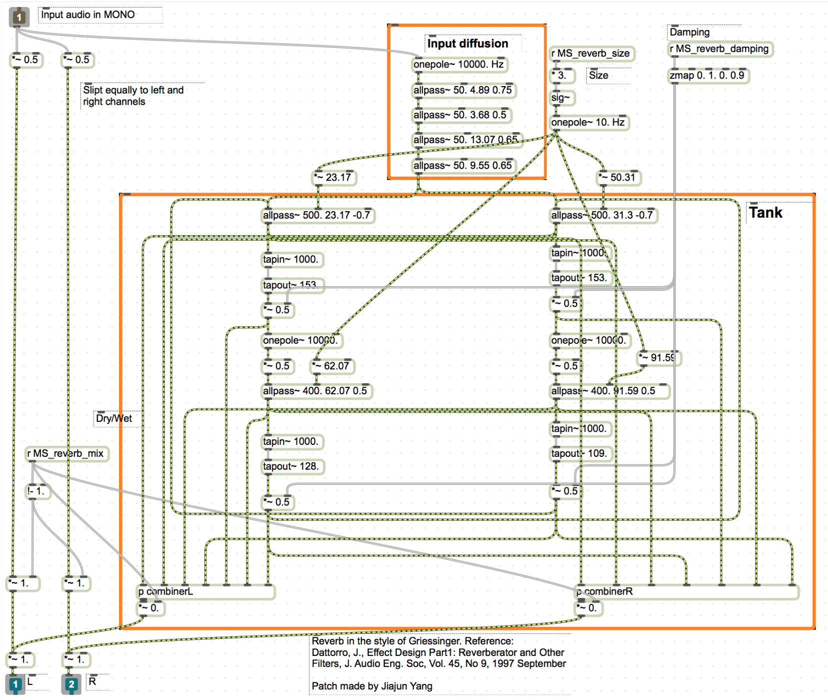


Figure 6.31: Griesinger style reverberator

(7) Storing and Recalling Presets

The preset function (Fig. 6.32) allows the storage and recall of predefined parameter values. Thus multiple sound effects can be created. [pattrstorage] can store all variables in the patch as a preset. Then basic controls such as saving, deleting and overwriting the current presets are available.

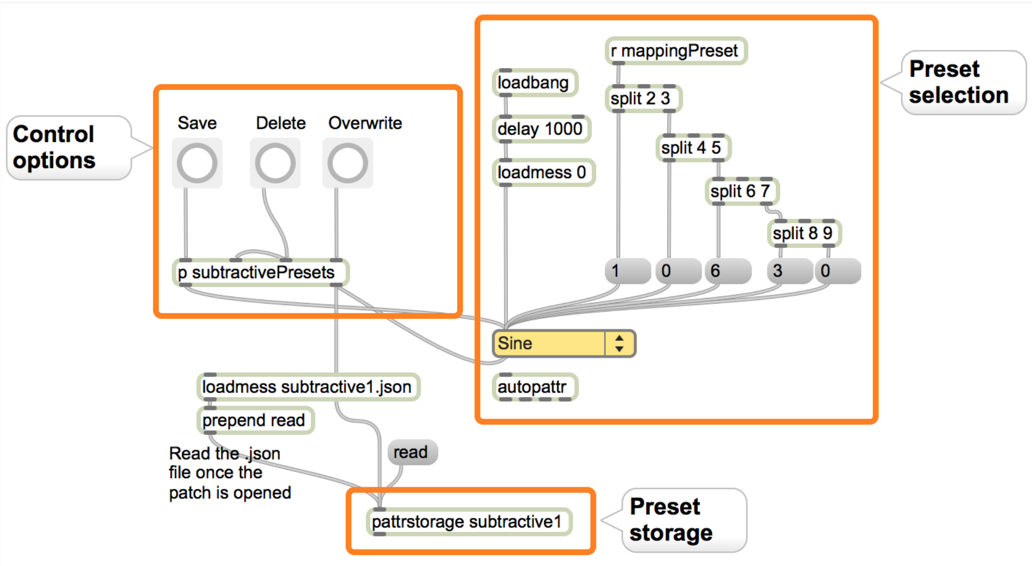


Figure 6.32: Patch for managing sound engine presets

6.4 4 Types of Sound Outputs

Four types of sounds are designed, which can be selected from the "Mapping Mode" located on the top right side of the main interface (Fig. 6.33).

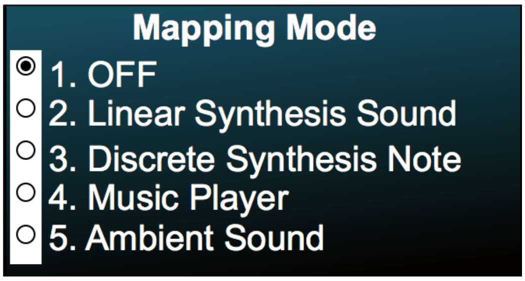


Figure 6.33: Mapping mode

The four different modes provide a good range of options to the users based on their own preference. Each mode sounds distinctively different from the other. Details are presented in the following sections:

6.4.1 Linear Frequency Synthesis Mode

This mode produces a sound with rich spectral content using a combination of triangular (Oscillator 1) and sawtooth (Oscillator 2) waves. The timbre of this mode was described as 'sci-fi like' by some participants during the experiments.

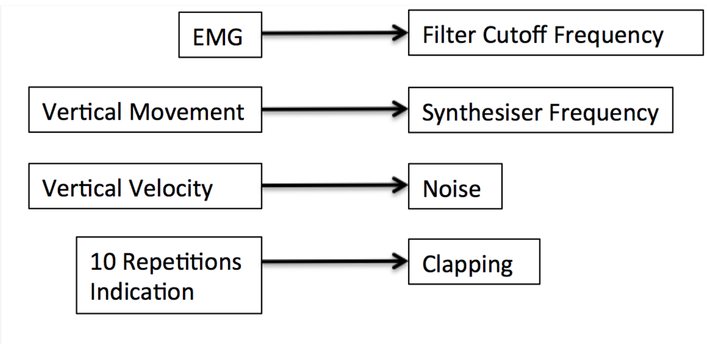


Figure 6.34: Linear frequency mapping scheme

The mapping scheme is presented in Figure 6.34. In this mode, the vertical coordinate of the hand holding the dumbbell is mapped to a linear scale of frequency with values between 0 and 620Hz. The reason for setting this range is to let the frequency drop to near zero when the arm is lowered and straightened, and to reach approximately 600Hz at the fully bent forearm position. The vertical movement velocity is set to trigger the noise patch when it exceeds a threshold value, which notifies users that their movement is too fast. The noise sound easily distinguishes the speeding indication from the synthesiser sound used for regular motion. The EMG signal is mapped to the cut-off frequency of a band-pass filter. As a result, the EMG signal affects the brightness of the sound. Increased muscle power leads to a brighter and clearer tonal quality.

6.4.2 'MIDI Note' Synthesis Mode

The second option uses discrete MIDI notes rather than continuous linear frequency. The mechanism of this mode is explained in Section 6.3.4. The same timbre is used as for the linear frequency method. The amplitude envelope results in a short attack time (10ms) and a release time of 214ms, which makes the sounds decay naturally yet without a long tail to overlap with the next note.

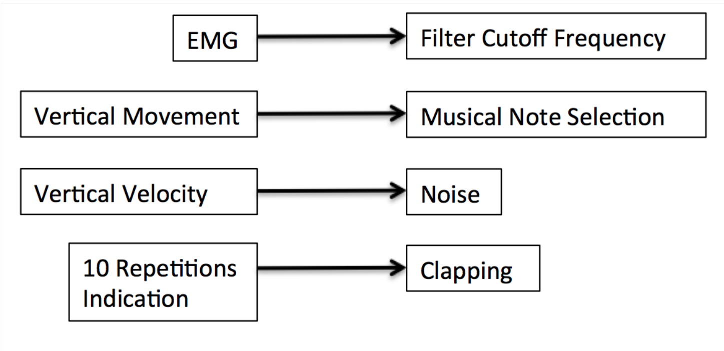


Figure 6.35: MIDI note synthesis mapping scheme

The mapping scheme is shown in Figure 6.35. This is similar to the linear frequency except that the vertical movement is mapped to discrete note selection. With customised probability tables, the user is able to generate different patterns of melody for each repetition. Biceps contraction results in an ascending melody while extension generates a descending pattern. There are reference tones for the highest and lower hand positions. So, even though the melody varies slightly each time, the user will always hear the same MIDI note when the hand reaches either the highest (E5: 659Hz) or lowest (C4: 262Hz) position.

6.4.3 Music Player Mode

Initially, another type of sound called the Rhythmic Sound Mode was developed using a fixed arpeggiator loop. The idea was to play a fixed rhythmic cue to let the users scale their movement according to the timing of the loop. However, negative comments were collected in the pilot study. Therefore, a new mode - called the Music Player Mode - was developed to replace its predecessor.

In this mode, users can store and use their own music files, which are played back during exercise. In this mapping strategy (Fig. 6.36), the hand's vertical position is not linked to any of the sound parameters. The EMG is set to control the cut-off frequency of a low-pass filter. Therefore, the more muscle activity is generated, the greater the clarity and brightness of the music. This mapping aims to encourage users to work hard to hear good quality music. At the resting stage, users can only hear a very 'muddy' and unclear version of the music. If the user moves his/her arm too quickly, the pitch of the right channel will be altered so that the music does not sound 'correct'. This is used as a warning or a penalty if the user is moving too quickly. The incorrect effect only lasts for one repetition and will then be reset to normal pitch once the forearm has returned to the straight position.

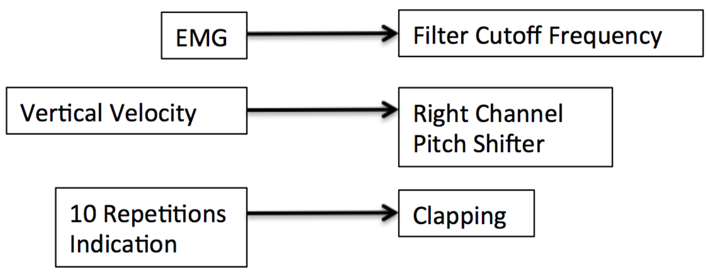


Figure 6.36: Music player mapping scheme

6.4.4 Ambient Sound Mode

The last mode plays back an ambient sample, which was the sound of ocean waves. It aims to create a relaxing sensation for the user rather than giving precise feedback of the movement. The audio samples were downloaded from

SoundBible[8].

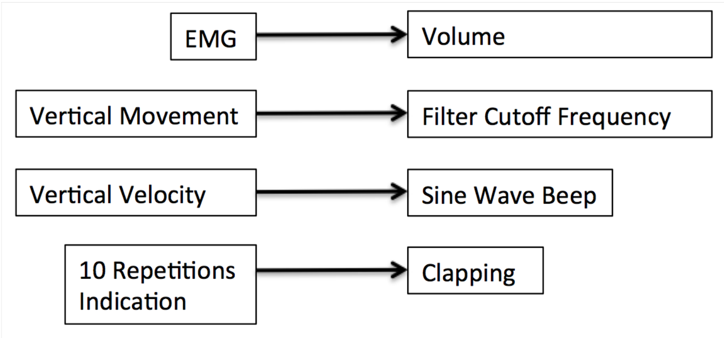


Figure 6.37: Ambient sound mapping scheme

In this mode, as shown in Figure 6.37, the EMG is used to control the volume of the sample and the vertical hand movement controls the cut-off frequency of a low-pass filter. So the sample sounds 'harsher' when more effort is put in. Similar to the music player, the user is notified that they are moving too fast using a sine wave beep instead of noise. Because the sample itself is noise-based, the use of white noise for a notification would not be easily distinguishable.

6.5 How to Use the System

This section provides a brief description of how to use the system. Figure 6.38 shows a user wearing the EMG belt with the two signal electrodes directly placed on the skin over the dedicated muscle, and the ground electrode placed on the skin over the elbow position. The Kinect is placed in front of the user and facing toward them. An adjustable dumbbell was provided, and participants could adjust the weight by adding or removing plates either side of the dumbbell. The participant was then fitted with the EMG device and positioned to stand in front of the Kinect sensor.

Once the sensors are connected and the software is activated, both the

[8]http://soundbible.com/

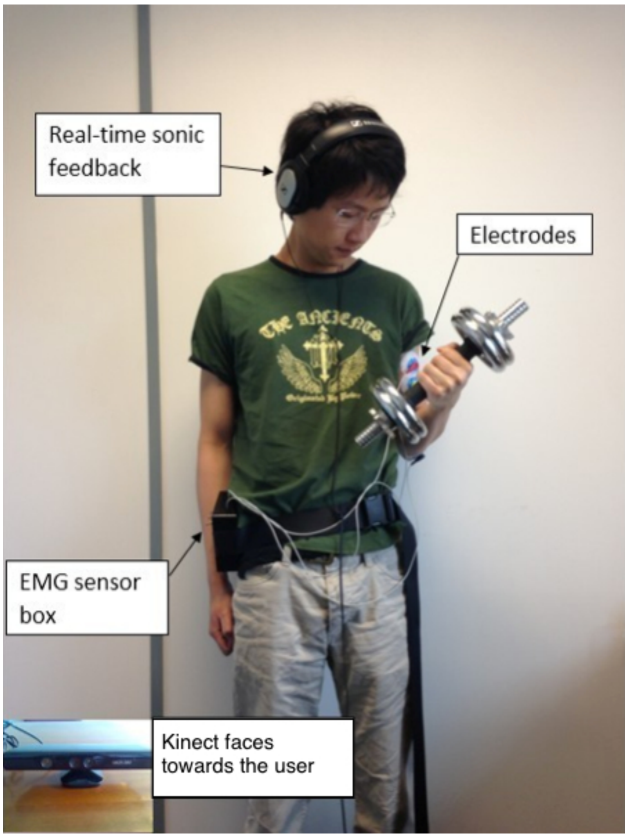


Figure 6.38: Example of using the device

EMG signal and joint coordinates will be extracted in real-time. The user can view the bioinformation on the screen, as shown in Figure 6.39. The user can listen to the sonification via a pair of headphones or speakers.

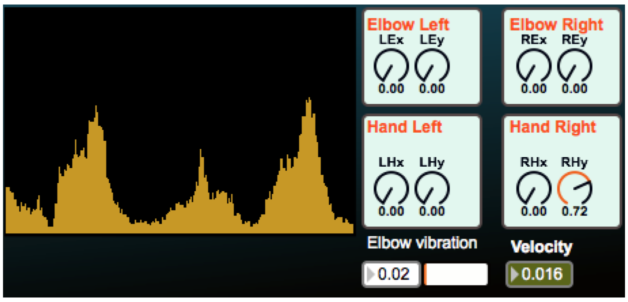


Figure 6.39: An example of the data monitoring. The EMG signal is shown in the left. The limb coordinates are displayed in the right.

Figure 6.40 presents an example of the exercise data recorded from a regular trainer (male) for demonstration purposes. This is an example of a set of high-quality biceps curl as it achieved a large movement range for each repetition because 0.8 is approximately the shoulder position (see the upper graph). The hand's vertical position changed steadily and slowly, which was approximately 8 seconds per repetition. The lower figure represents the EMG signals generated in the same set of movement. In the concentric contraction, the EMG signal rose and peaked at roughly the highest vertical position. Notice that there were small drops in the middle before reaching the peak value. That is because to raise the dumbbell, we generally produce a burst of power to create an acceleration of the forearm. The action then required less power before it needed another burst of power. In the eccentric contraction, the action required less power due to the natural falling of the dumbbell. However, there is another small EMG peak indicating the subject tried to prevent the dumbbell from falling too quickly.

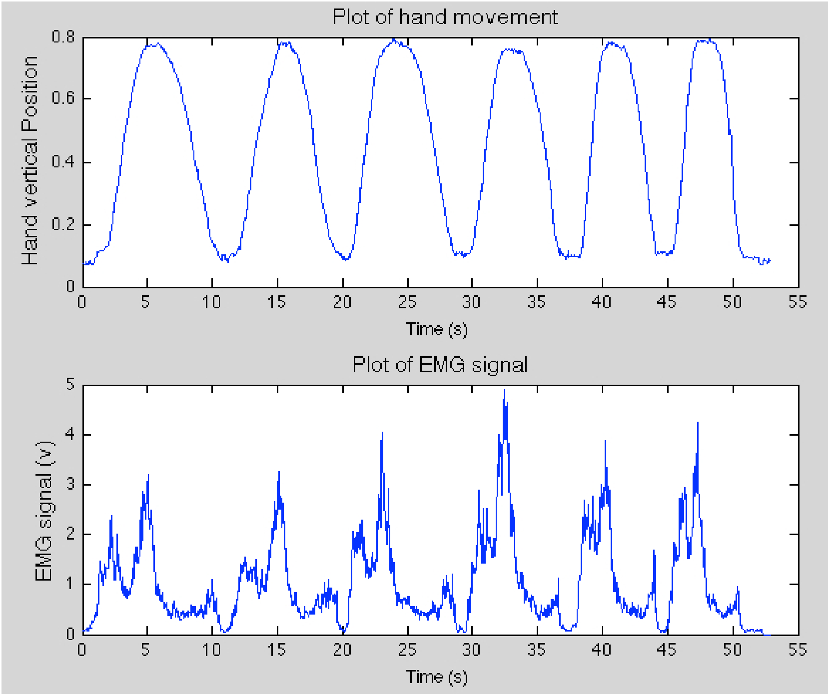


Figure 6.40: An example of a set of biceps curl recorded from a regular gym trainer

6.6 Chapter Summary

This chapter describes the hardware and software structures of the sonification system including the sensory devices and the algorithms used to create auditory output. This system was used in all of the experiments conducted for this research, which are described in the following three chapters.

Chapter 7

Pilot Study

7.1 Introduction

The pilot study was conducted after the initial development of the sonification system. The main objectives were to assess the system and gather initial user experience, gather suggestions for adjustments and find out which mode was the best sonification method.

Through this study, an initial impression was gained on how the sonification system influenced the user's movement during biceps curls. The analysis involved both objective exercise results and a subjective survey. The users' impressions of the four types of sounds, both in terms of the sound's comprehensibility and preference, were collected.

During the pilot test, the sonification software was different from the latest version, which was presented in Chapter 6. One of the main differences is that the Rhythmic Sound mode was used rather than the Music Play mode, which is presented in Section 6.4.3. The Rhythmic Sound Mode triggered a 4-bar arpeggiator loop when the user started raising the forearm. The music of the loop is notated in Figure 7.1. This sample played back continuously until the user's forearm returned to the straight-arm position. The EMG signal was mapped to the cut-off frequency of the bandpass filter, which affected the brightness of the sound. Similar to the synthesis sound, a white noise unit was used as an indication that the user's arm was moving too quickly.

Figure 7.1: Notation of the rhythmic loop

7.2 Implementation

In this study, nine healthy people (all male, age 25.8 ± 3.0) participated in the test, which took place in the University of York's Audio Lab. A consent form (Appendix D) was given to each participant prior to the test. The instructions are as follow:

1. The purpose of the study.
2. The usage of the sonification system.
3. The experimental procedures.
4. The exercise movement was demonstrated by the researcher. The exercise criteria from Section 5.5.4 were explained.
5. The participants were informed that they needed to do at least 5 repetitions in each set with no upper limit. 1-2 minutes rest was given between each set.
6. During the main test, participants were requested to do four sets of exercises, each with a different sound mapping. The *sequence* was:

Linear Frequency Synthesis – 'MIDI Note' Synthesis – Rhythmic Sound Mode – Ambient Sound.

7. Privacy protection. Participants had the freedom to terminate the experiment at any point (all participants completed the experiment).

The study consisted of two sessions. In each session, participants were asked to do four sets of dumbbell curls on one arm with one of the four sonification modes played in each set. Participants listened to the sonic feedback through a pair of Sennheiser SD-201 headphones during the exercise. The participants experienced all four sonification modes. Post-session interviews were conducted to study their experience of using the sonification system.

Prior to the exercise, participants were given a trial to gain familiarity with the exercise and the auditory feedback. The researcher demonstrated the usage of the device to the participants. The auditory feedback was explained in detail regarding how the sound is generated in relation to the movement. During this trial, participants could move their arm freely without the dumbbell and listen to the sound feedback.

After the session, participants filled in a questionnaire to rate each sonification mode in terms of its comprehensibility and preference on a scale between 1 to 5 (very poor, poor, moderate, good, excellent). The comprehensibility metric indicates how much the participant felt that the sonic feedback reflected their exercise movement, whereas the preference shows how much the participants enjoyed the sound. They were also asked to comment on the experience of using the device with each type of sound. Comments were recorded either in audio or written format. The pilot study questionnaire is included in Appendix D.

The participants came back on another day (within 7 days) for the second session, where they repeated the same training but without the trial. No additional instruction was given in this session. The same sonification modes were again used in the same sequence. After the session, participants again rated the sonification modes. By conducting an identical second session, participants would become more familiar with the sonic feedback, which let them have a better understanding of the sonification system in order to provide more comprehensive opinions. In addition, the difference in exercise quality could be studied between sessions.

7.3 Experimental Results

This section consists of two parts. The first part analyses the exercise results recorded using the sonification software. Data of the repetition time and movement range is presented. The second part reports the qualitative results collected from the questionnaires. Participants' comments and their rating for each sound in terms of its comprehensibility and preference were reported.

7.3.1 Exercise Measurements

The repetition time and movement range are analysed.

Average Repetition Time

The first attribute is the average repetition time in seconds. According to Table 7.1, participants on average performed well (met the speed criterion) in all modes and both sessions. The rhythmic sound seems to be able to contribute to a better result at achieving a slow pace of repetition in the second session ($M = 7.103s$). However, it has the highest standard deviation of $2.906s$, which underlines an uneven performance among the participants. The result of the Linear mode is satisfactory even though it sits at the bottom of the table. It is suspected that the sequence of the modes caused the lower performance of this mode. This mode was used first at both sessions. During the sessions, the researcher observed that a few participants (No. 2, 3 and 6) started the exercise quickly in the first 2-3 repetitions, and then gradually slowed down.

Mode	**Session 1**		**Session 2**	
	Mean	SD	Mean	SD
Linear Frequency	4.605	1.608	5.138	1.400
MIDI Notes	4.861	1.942	6.844	2.097
Rhythmic Sound	4.756	2.162	7.103	2.906
Ambient Sound	4.931	1.569	6.583	1.801

Table 7.1: Average repetition time (s) of four types of sound

The blue boxplots in Figure 7.2 show that the performances of the four different sounds were similar in the first session. A correlation analysis has confirmed the similarity (Table. 7.2). Significant correlations are shown in the other modes apart from the correlation between the Linear mode and MIDI mode, which is not statistically significant ($r = 0.644$, $p = 0.061$). In the second session (green boxplots in Fig. 7.2), different levels of improvement were recorded. The other modes show greater improvements than the Linear Frequency Synthesis sound.

		S1Linear	S1MIDI	S1Rhythmic	S1Ambient
S1Linear	Pearson Correlation	1	.644	.717*	.726*
	p (2-tailed)		.061	.030	.027
	N	9	9	9	9
S1MIDI	Pearson Correlation	.644	1	.821**	.838**
	p (2-tailed)	.061		.007	.005
	N	9	9	9	9
S1Rhythmic	Pearson Correlation	.717**	.821**	1	.706*
	p (2-tailed)	.030	.007		.034
	N	9	9	9	9
S1Ambient	Pearson Correlation	.726*	.838**	.914**	1
	p (2-tailed)	.027	.005	.002	
	N	9	9	8	9

**. Correlation is significant at the 0.01 level (2-tailed)
**. Correlation is significant at the 0.05 level (2-tailed)

Table 7.2: Correlations of the average repetition time in the first session

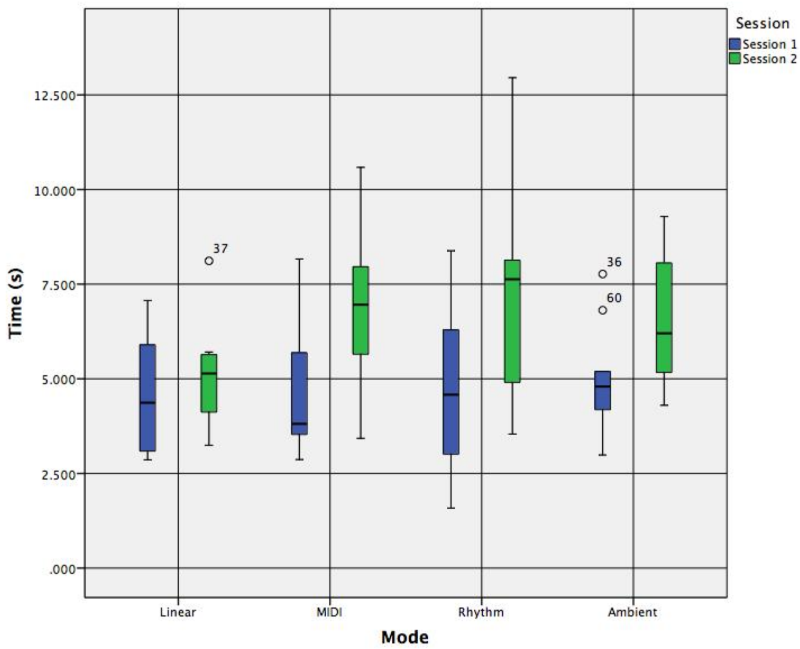


Figure 7.2: Boxplots of the average repetition time for the four types of sound

Overall, the repetition speed was improved in the second session regardless of what type of sound was used. The paired samples t-test shows a significant difference between session 1 ($M = 4.788$, $SD = 1.76$) and session 2 ($M = 6.417$, $SD = 2.173$), $t(35) = 6.025$, $p < 0.001$. This encouraging result indicates that participants had become more familiar with the sonic feedback and utilised the feedback to improve their quality. All participants were told at the trial that a slow speed meant better in quality, yet no further instruction was given in the actual exercise sessions. Thus no other factor could potentially affect their action and lead to the improvement in the 2nd session.

Movement Range

Mode	Session 1		Session 2	
	Mean	SD	Mean	SD
Linear Frequency	0.638	0.064	0.659	0.037
MIDI Notes	0.651	0.060	0.699	0.052
Rhythmic Sound	0.659	0.086	0.683	0.054
Ambient Sound	0.653	0.054	0.706	0.049

Table 7.3: Average movement range of four types of sound

The second attribute is the average repetition range, scaled between 0 and 1.0 (where 0.8 represents the approximate shoulder height). The movement coordinates file of participant No. 2 in session 1 (Rhythmic Sound) was damaged and thus could not be used in the analysis. Table 7.3 shows the movement range of the four types of sound in both sessions. In comparison, the linear frequency synthesis has a lower performance than the other three. A larger average movement range was recorded in the second session.

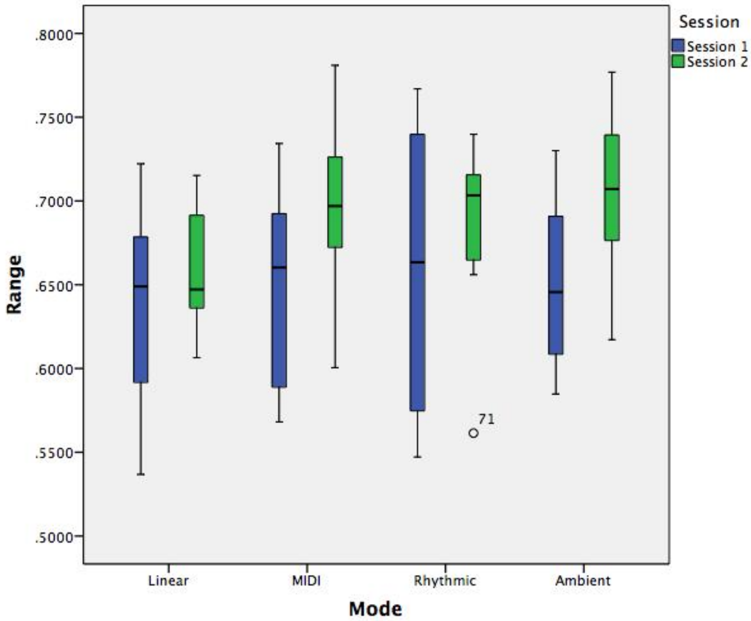


Figure 7.3: Boxplots of the average repetition range between four types of sound

As shown in Figure 7.3, the performances between four types of sound are very similar in the first session (high correlations are shown in Table

7.4), except for the rhythmic sound which has a wider spread. Noticeable improvements are shown in the second session. The linear frequency synthesis has a similar upper 50% between sessions but a more obvious improvement in the lower 50% mark. It is also noticed that, in the second session, the range between the upper quartile and lower quartile became narrower, indicating a more balanced performance.

		S1Linear	S1MIDI	S1Rhythmic	S1Ambient
S1Linear	Pearson Correlation	1	.929**	.895**	.720*
	p (2-tailed)		.000	.003	.029
	N	9	9	8	9
S1MIDI	Pearson Correlation	.929**	1	.962**	.827**
	p (2-tailed)	.000		.000	.006
	N	9	9	8	9
S1Rhythmic	Pearson Correlation	.895**	.962**	1	.914**
	p (2-tailed)	.003	.000		.002
	N	8	8	8	8
S1Ambient	Pearson Correlation	.720*	.827**	.914**	1
	p (2-tailed)	.029	.006	.002	
	N	9	9	8	9

**. Correlation is significant at the 0.01 level (2-tailed)
**. Correlation is significant at the 0.05 level (2-tailed)

Table 7.4: Correlations of the participants' average movement range in the first session

When comparing the average range between two sessions, a larger average movement range is reported in the second session regardless of what the type of sound was used. The paired samples t-test shows a significant improvement between session 1 ($M = 0.650$, $SD = 0.064$) and session 2 ($M = 0.684$, $SD = 0.048$), $t(34) = 9.89$, $p < 0.001$.

7.3.2 Survey Results

The survey analysis involved a survey rating of the comprehensibility and preference of each type of sound, and post-session comments.

Comprehensibility and Preference Ratings

Section 7.3.1 provided an initial impression of how the sonification affected the movement range and repetition time. However, due to the small sample size, the results could not statistically support the hypothesis. The qualitative study held the main purpose of the pilot study - to collect subjective suggestions from the users. Participants rated each sound mode in terms of the comprehensibility and preference on a scale from 1(highly disliked) to 5 (highly favoured).

	Comprehensibility		Preference	
Mode	Mean	Std	Mean	Std
Linear frequency	4.2	1.3	3.6	1.6
MIDI note	3.6	1.0	3.3	1.1
Rhythmic loop	3.3	1.1	3.7	1.1
Ambient sound	3.8	1.1	3.1	1.4

Table 7.5: Mean rating and standard deviation of four sound types

Table 7.5 shows the mean ratings of each mode. Overall, above average ratings of all four modes were recorded in comprehensibility ($M = 3.7$, $SD = 0.4$) and preference ($M = 3.4$, $SD = 0.3$) of both sessions.

According to the table, participants found the linear frequency mapping most informative, with a mean value of 4.2 ($SD = 1.3$). All participants rated this mode either 4 or 5 except one who rated it as 1 ('very confusing'). This indicates that in general participants found that this simple linear frequency mapping delivers a better sonic representation of the exercise movement than other modes.

The ambient sound rated second in this catalogue while the rhythmic loop is considered the least informative among all four. The ambient sound created an atmospheric soundscape that responded to the muscle activity sensibly letting user feels like 'the sound of the muscle'. This mapping emphasised more of the variation of the muscle activity during contractions compared to the other modes, thus being informative.

The rhythmic loop was a fixed sample, the internal timing of which was not generated by the exercise movement. The hand's vertical position merely triggered the sample, and once triggered the sound played independently until the arm was returned to its straightened position. The only real-time variation of the sound was the brightness of the sample using a bandpass filter, which was controlled by the EMG signal. This mapping however did not represent much of the actual movement. Therefore, participants felt not as in control as the other three. A bar chart is presented in Figure 7.4, which graphically presents the rating differences.

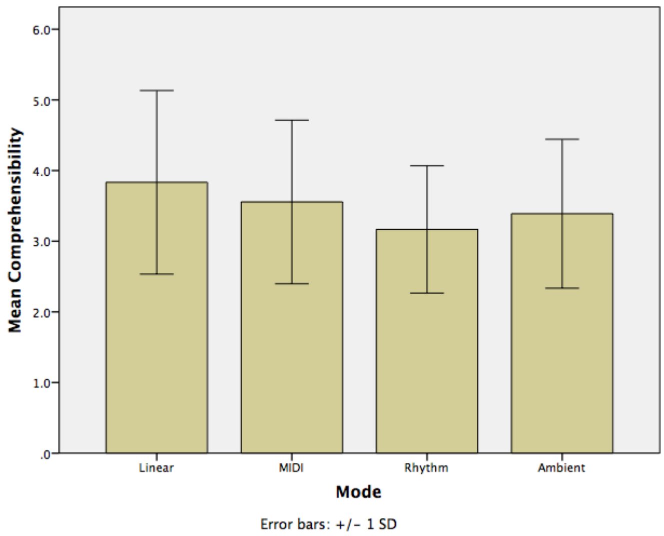


Figure 7.4: Comprehensibility rating

In terms of the personal preference rating, participants found the rhythmic loop most enjoyable to listen to, which could be due to its highly musical characteristic. People often exercise to rhythmic music so this could have been closest to their previous experiences with listening to audio when exercising. The linear frequency mode also received a similar score. The MIDI note mode again received a moderate score. The ambient sound seems to be the least preferred with a mean score of 3.1 ($SD = 1.4$). The graphical representation of the preference rating comparison is shown in Figure 7.5.

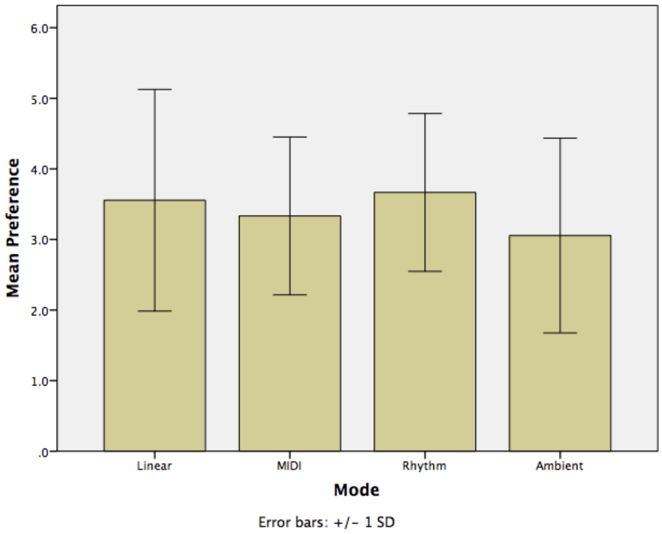


Figure 7.5: Preference rating

Participants' Comments

Subjective opinions were gathered on each mode. Tables 7.6, 7.7, 7.8 and 7.9 show the collective comments made by each participant for each sound.

1. Linear Frequency Synthesis Mode

Assessment	Type	Comment	No.
Positive	1. Functionality	1. Straightforward	2, 6, 8
		2. Most raw presentation	3
		3. Clear logic	6, 7
		4. Very helpful	1, 4
	2. Aesthetics	1. Satisfying	3, 5
		2. Like electronic music	8
Negative	1. Functionality	Difficult to distinguish the noise from the synthesis sound	9
	2. Aesthetics	1. Not good enough	1
		2. Not musical content	2

Table 7.6: Comments of Mode 1: linear frequency synthesis

According to Table 7.6, most participants (8 out of 9) thought this sound could deliver sufficient information reflecting the quality of the exercise in terms of the functionality of the feedback. It terms of the aesthetics, three positive and two negative comments were collected. Notice that No.8 liked the sound because it sounds comparable to electronic music and No.2 disliked it for similar reasons. This indicates that the personal musical taste may have a strong influence on the preference rating. This also means it is impossible to use one single type of sound to satisfy all participants, and thus it is a good idea to provide a selection of sounds for the user to choose from.

2. MIDI Note Synthesis Mode

Assessment	**Type**	**Comment**	**No.**
Positive	1. Functionality	1. It was good and clear	2
		2. Similar to the linear sound (logical)	6
		3. Most interactive	8
	2. Aesthetics	1. Generating music	8
Negative	1. Functionality	1. Not as good as the linear mode	1
		2. Big leap of sound due to fast movement	3
		3. Suitable for more complex exercises	4
		4. Feedback felt a little random	5
		5. Difficult to distinguish	9
	2. Aesthetics	1. It was ok.	1

Table 7.7: Comments of Mode 2: MIDI note synthesis sound

According to Table 7.7, this mode received more negative responses (5) than positive (3). People generally found it not as informative as the Linear mode. It was, however, the favourite sound expressed by No.8 because this mode turned biceps curl into an interactive music generating process.

Also, a participant reported an operational error that the notes would change too quickly, which made the melody progression much quicker than the actual movement. This was described as a ‘big leap’ by the participant. This happened sparingly due to the occasional loss of tracking due to the confusion of visual input. The Kinect tracking uses a skeletal tracking algorithm, which tries to recognise a human body shape. The dumbbell is an extra object which is occasionally mistakenly recognised as part of the limb, and this causes a sudden change of hand coordinates. The change in coordinates then caused the quick melody progression.

3. Rhythmic Sample Mode

Assessment	Type	Comment	No.
Positive	1. Functionality	1. Motivated me to get the right sound	1
		2. Sound and movement are both periodic	6
	2. Aesthetics	1. Enjoyed the progression	3, 8
		2. Comfortable to listen to	9
		3. Interesting	6
Negative	1. Functionality	1. Didn't do much help	2
		2. Not continuous	3, 7
		3. Confusing	4
		4. Too passive	8
	2. Aesthetics	1. Least like of all	1

Table 7.8: Comments of Mode 3: Rhythmic sample

Some criticisms are shown in Table 7.8 reflecting this mode's lowest rank in comprehensibility rating. In terms of its functionality, it has the disadvantage for lacking in continuity, as the sound would be switched off when the arm position was lower down. However, the sound has more musical characteristic. Four participants said they enjoyed listening to the sound because it felt more like the conventional way of exercising while listening to music.

An interesting suggestion was made by No.6 and 8, which was adapted for the subsequent experiments. They suggested that the rhythmic sample was over periodic, which lead to boredom. Hence, it could be developed into a music player, which would allow users to exercise with their own music. During the exercise, the music would sound 'right' if the exercise reached the appropriate standard and 'wrong' otherwise. This could be a good alternative to the other three sonification modes, and might especially be useful for people who simply prefer listening to music while working out but at the same time requiring feedback. The idea of *working hard* in order to hear the '*correct*' music could be a good motivational factor.

4. Ambient Sound Mode

   In terms of its functionality, this mode received more negative responses than positive. From the comments in Table 7.9, the main problem is its lack of sonic variation to represent the movement; hence participants felt less in control. However, this was expected due to the design of this mode. The purpose of using the ambient sound was not to comprehensively portray every aspect of the exercise movement, but rather to create a relaxing sound which represented the muscular activity.

Assessment	**Type**	**Comment**	**No.**
Positive	1. Functionality	1. Most natural 2. Comprehensible	1 3, 5, 9
	2. Aesthetics	1. Pleasant to listen to 2. Sound special	1, 7 8
Negative	1. Functionality	1. Too distracting/relaxing 2. Less in control 3. Not sensitive 4. Not enough information	2, 3 4 6 8
	2. Aesthetics	1. Can be boring in lengthy exercise 2. Not as good as synthesis sound	2 5

Table 7.9: Comments of Mode 4: Ambient sound

7.4 Discussion of the Experimental Results

The pilot study evaluated the effect of the sonification system using a combination of quantitative and qualitative analysis. When comparing the repetition time and movement range between sessions, significant results ($p < 0.001$) were found, showing different extents of improvement in the second session. When comparing the same attributes between the types of sound, we found similar performance and improvement in all modes but the Linear one.

Although the Linear mode led to the least improvement, it was favoured by the most in the survey. In general, participants thought it was the most informative because the frequency progression was directly linked with the hand's vertical position, and the roughness of the sound reflected the muscular activity. This mode also sits second in preference rating.

Another ambiguous mode is the rhythmic loop. Despite having the lowest rating in comprehensibility, participants on average improved the most with this sound in both repetition time and range. After consideration, this mode was modified into a music player, which allows users to upload their own music files for the exercise to provide more variations of the sound rather than using a fixed short sample. The other two sounds also performed well.

From participants' ratings and comments, we found:

1. The *Linear* mode is considered the most informative and straightforward. Yet due to its lack of musical content, some participants disliked it.
2. The MIDI note synthesis sound received moderate responses. It has a known problem for causing quick note changes, which made the melody hard to distinguish. The skeletal tracking algorithm for the Kinect tracking sometime caused this.
3. The rhythmic mode did not provide as much information as the previous two. It is hard to interpret the contradiction between the negative comments and its outstanding exercise results. It is possible that despite its imperfection in interaction, the rhythmic sound itself provided a slow speed reference that affected participants' action. Its musical characteristic also seems to be more familiar to the participants, which is similar to exercising with background music.
4. The ambient sound was relatively informative. The sound created a sonic metaphor of the muscle activity, which let people feel like listening to the muscle during contraction. Yet some felt less in control with the sound as the arm movement was not clearly represented. Its lowest preference rating indicates that the sound aesthetics is a concern.

In summary, the four modes show different strengths and weaknesses.

The Linear mode provides the most raw and comprehensive sonic image of the exercise movement. The MIDI mode aimed to provide more musical characteristic with variation. The Rhythmic mode is closer to the conventional way of listening to music in workout. And lastly the Ambient mode creates an immersive sense which was supposed to work as a relaxing background sound.

The study supports the decision of using multiple types of sonification as options to accommodate the issue of personal preference. From the ratings, participants have at least one preferred sound that was both informative and enjoyable. However, in order to provide a better using experience, further improvement of the sound designs was required before the subsequent experiments.

7.5 Software Adjustments

After this experiment, the following adjustments were made:

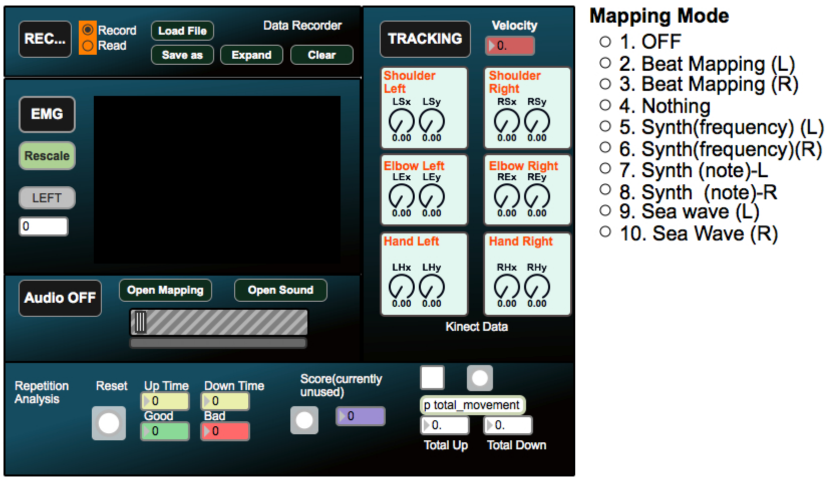


Figure 7.6: The graphical interface of the *old* version of the sonification software

1. The main interface was improved and simplified. The old graphical

interface is shown in Figure 7.6.

2. The repetition analysis section (shown at the bottom of Figure 7.6) was removed. Initially, this section was designed to calculate the time of each repetition, and the total movement, which was the integral of vertical coordinates. These two parameters were designed for a score system, which produced a quality score to encourage people to aim for a higher score in the next session. However, it created an extra factor which had no connection with the sonification and could potentially affect the results, thus it was removed.

3. The rhythmic mode was replaced by the Music Player Mode.

4. The MIDI note mode was optimised. Firstly, the probability tables were optimised for aesthetic purpose. Secondly, the range of notes was increased to two octaves instead of one. This led to a wide range of melodic progression.

5. A plate-reverb effect unit was developed adding extra spatial characteristics, useful for the ambient sound.

6. Various other small optimisations made to made the software design more concise.

7.6 Summary

In summary, we gained an impression that the sonification worked well in a biceps curl training routine. When participants became more familiar with the system, their exercise quality improved greatly. Due to small sample size, the results gave us the motivation to carry on the research yet they did not have enough statistical power to be used to support the research hypothesis. Besides, the design of this experiment did not include a control group; hence it could not provide a comparative result to study the difference between exercising with the sonification and without. However, the results show great potential for the sonification system.

More importantly, this experiment helped to pinpoint the problems of the system and users' opinions of the sound so that adjustments could be made before the subsequent experiments. For that reason, this experiment served a useful purpose.

Chapter 8

Between-Subjects Comparative Experiment

8.1 Overview

In the second experiment, the hypothesis is that the quality of biceps curls will be better for people who exercise *with* real-time auditory feedback of their muscular activity along with kinesiological data, compared to those who do the same exercise but *without* the auditory feedback.

To examine this hypothesis, a comparative experiment was conducted. This experiment analysed the exercise quality of two groups of participants: an effect group and a control group. This chapter describes the details of the experimental implementation and data analysis, and concludes with a discussion of the results.

8.2 Implementation

The experiment took place in the Audio Lab, University of York, UK. 22 healthy adults participated the test: 3 females and 19 males. 15 aged between 18 - 25, 7 aged between 26 - 35. Participants were randomly assigned to one of two different groups- the 'Sonification' group and the 'Control' group. Only the Sonification group participants received the auditory feedback. Both the EMG belt and the Kinect camera were in use to collect exercise information for all subjects.

Prior to the experiment, the participants signed a consent form (Appendix E) explaining the procedures and data privacy measures. All participants agreed to complete the test. Participants were then asked to choose the weight of the dumbbell, which was to be relatively challenging but not overly heavy. A trial was given before the main experiment, allowing the participants to become familiar with the exercise. Also, the Sonification group participants tried out the four different sound modes and could then decide on their preferred mode. The facilitator explained - for each mode - how the sounds were mapped in relation to the exercise movement. Thereafter, these participants chose a mode to use throughout the experiment (9 Linear mode, 2 Music Player).

The experiment consisted of three identical sessions, which required the participants to attend on three different days with a gap no longer than a week between each session. The participants had full control of the quantity of repetitions as a way of understanding their progression and motivation of exercise.

Three criteria were defined and explained to the test subjects:

1. Participants should aim for a slow and steady pace of movement with each repetition to be completed in no less than 4 seconds.
2. Participants should aim for a large movement range. This means raising

the forearm as high as possible in the concentric contraction while the upper arm remains still, then lowering the dumbbell to the natural straight-arm position in the eccentric contraction.

3. Participants were encouraged to do as many repetitions as possible. The minimum amount was 2 sets of 5 repetitions for analysis purposes.

8.3 Experimental Measurements

This section presents the analysis of three dependent variables; average repetition time, movement range and effort.

8.3.1 Average Repetition Time

The repetition time is the time taken in seconds to complete a full repetition (concentric and eccentric). The participants' mean repetition time in each session is plotted in Figure 8.1. Notice that the progress in the Control group does not vary much from session to session, with only three participants showing improvements. By contrast, more improvements are shown in the Sonification group (7 out of 11). While the range of results in the Control group is somewhat concentrated, the Sonification group seems to have yielded a larger range of repetition times, and with more high-value results.

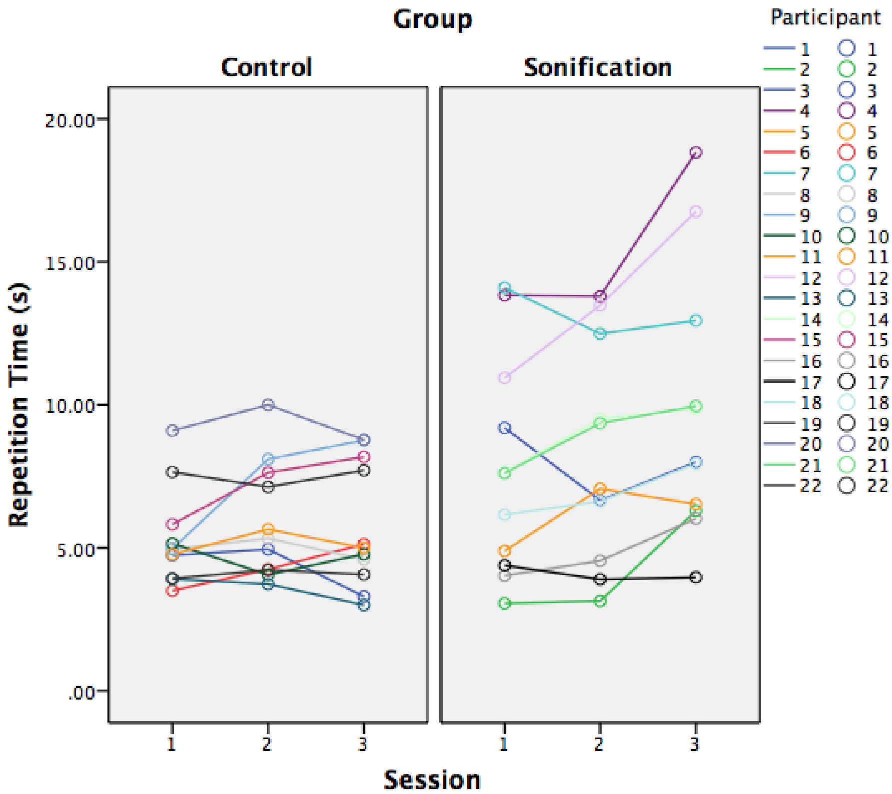


Figure 8.1: Progress of repetition time for each participant over 3 sessions

The individuals in the Sonification group seem to have displayed a better performance and improvement.

The next part analyses the average result on a group level. The boxplots in Figure 8.2 compare the progress of the two groups. In all three sessions, the Sonification group had far better result than the Control group. This difference became statistically significant in the final session. An independent t-test (equal variance assumed) was conducted, showing a significant difference of the mean variable between the Sonification group ($M = 9.74$, $SD = 4.67$) and Control group ($M = 5.76$, $SD = 2.18$), $t(20) = 2.564$, $p = 0.018$ (95% CI: 0.74 to 7.22).

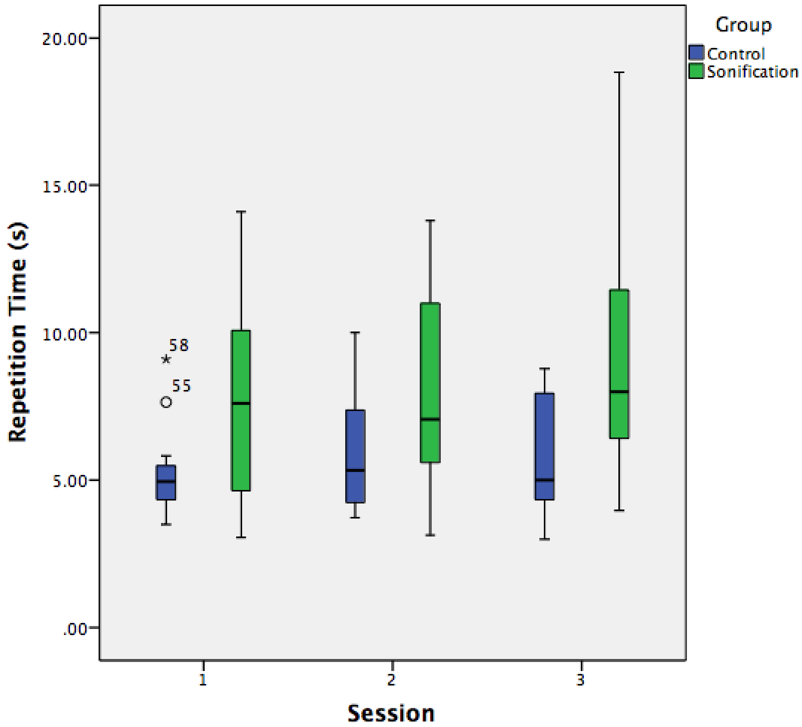


Figure 8.2: Boxplots of the group repetition time across the 3 sessions

The values of the group mean repetition time are displayed in Table 8.1. We can see that on average the Sonification group performed consistently better than the Control group in all sessions.

Session	**Group**	**Mean**	**SD**
1	Sonification	7.8	3.84
	Control	5.32	1.68
2	Sonification	8.24	3.8
	Control	5.91	2.03
3	Sonification	9.74	4.67
	Control	5.76	2.18

Table 8.1: Mean repetition time

8.3.2 Movement Range

The next variable is the movement range of the biceps curl repetition. From Figure 8.3, a bunching effect can be seen in the Control group and conversely a slightly expanding trend in the Sonification group. In the Control group, only two participants improved throughout the sessions. Three participants' movement range decreased. In the Sonification group, five participants' movement range increased and two decreased.

The development in the Sonification group could indicate that, in the long-term, the use of sonification could work in two distinctive directions when it comes to range of movement. It could produce positive outcomes for people who enjoy using the system, but could also make quality worse if the users found it unpleasant to use.

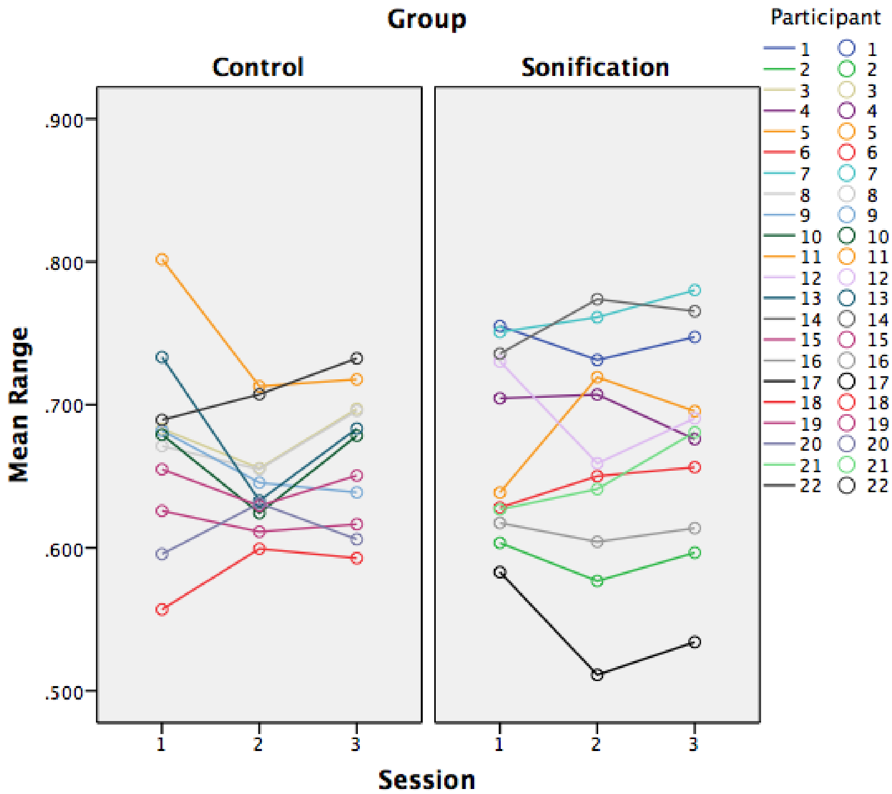


Figure 8.3: Progress of the movement range for each participant

For the group performance, both groups performed similarly with no apparent difference. In the final session, the mean movement range is 0.676 ± 0.074 (Sonification) and 0.668 ± 0.050 (Control) respectively. The independent t-test shows no significant difference ($p > 0.05$) between the two groups. Table 8.2 displays the mean movement range between groups. The two groups performed equally in the first session. The second and third sessions have a marginal difference between groups.

Session	**Group**	**Mean**	**SD**
1	Sonification	0.670	0.065
	Control	0.669	0.065
2	Sonification	0.667	0.081
	Control	0.645	0.036
3	Sonification	0.676	0.074
	Control	0.668	0.050

Table 8.2: Mean movement range

During the experiment, the researcher noticed that three sonification subjects (all using the Linear mode) exercised with a very narrow range of movement. They appeared to either start the eccentric contraction too early without reaching the top or to begin a new repetition without completely lowering the forearm. However, the pitch mapping merely presented the height of the hand. The sound did not actively deliver a message to remind them that they should improve the range of movement.

8.3.3 Effort

The mean dumbbell weights of the two groups (remembering that weight were chosen by each participant) were compared before the experiment. The Sonification group mean was 5.0kg and the Control group mean was 4.7kg. The difference is 6%, therefore they are treated as approximately equal. The total effort is the product of the dumbbell weight and the number of repetitions.

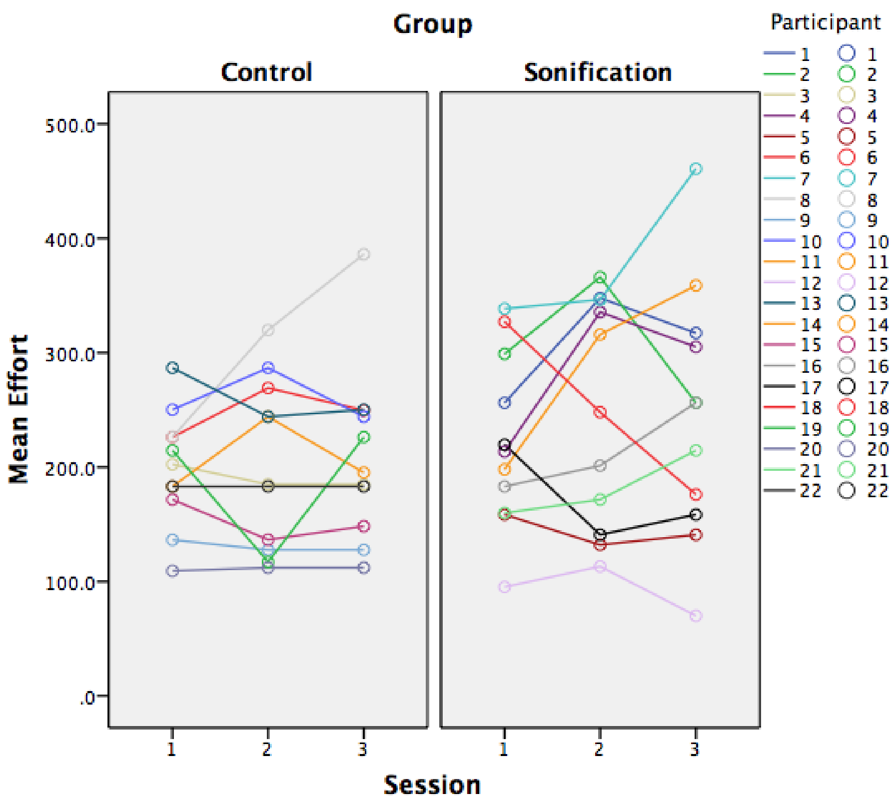


Figure 8.4: Progress of the effort variable for each participant

Figure 8.4 presents the performance of this variable for all participants. In the Control group, only one participant (No. 8) showed a distinct improvement throughout the sessions. Interestingly, Nos. 6, 10 and 11 (all from the Control group) performed better in the second session but then dropped down in the final session to a similar level to their first session performance. Also, No. 19 is an extreme case where the participant did much fewer repetitions in the second session than the other two. Other participants tended to perform more consistently without much variation in this metric. Because there is no strict restriction on how many repetitions the participants should do, and they were not given their previous effort results as a reference, we might expect to have this low variation in performance.

More improved cases can be seen in the Sonification group. 6 participants in this group show encouraging improvement throughout sessions. Strangely, there are four participants whose performance worsened. Especially No. 18, whose effort results dropped greatly as the sessions progressed from 327.1 to 176 (53%). The variation between individual progress results signals a possibility that sonification might work both ways based on the user's own preference. Referring to the analysis of Linear mode comments in the Pilot Study (Section 7.3.2), two participants showed completely different preferences based on the same reason - the sound is close to an electronic music effect. Similarly, this kind of personal difference could lead to very different motivational outcomes when using the sonification system.

In general, the Control group participants performed more steadily without much improvement. By contrast, the Sonification seems to affect this variable more noticeably.

In terms of the average group results, Figure 8.5 presents the boxplot comparison between two groups over the three sessions. An increase in the medians is observed in the Sonification group, as well as the upper 50% (quartile group 3 & 4). However the lower quartile's performance dropped in the final session. Both groups have similar lower quartiles, but the upper quartiles are higher in the Sonification group in all sessions. It is also worth noticing that the boxplots in the Sonification group (especially in session 3) are taller than the Control group, which suggests that the participants' effort varied greatly with the use of sonification.

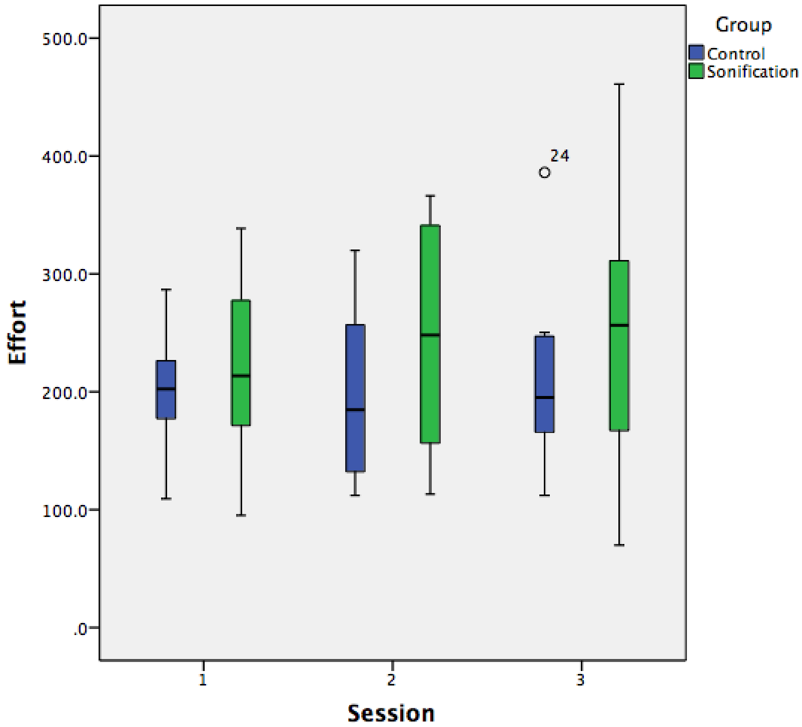


Figure 8.5: Boxplots of the group effort over the 3 sessions

According to Table 8.3, the mean values in the Sonification group are higher in all three sessions. However, the group also has higher standard deviations, pointing to a wider spread group performance on this variable. Even though the mean values of both groups improved throughout the sessions, the sonification group improved more with 10.8% improvement between the final session and the first session, whereas the control group only improved 5.4%.

Session	**Group**	**Mean**	**SD**
1	Sonification	222.6	76
	Control	199	50.3
2	Sonification	247.1	98.5
	Control	202.2	74.1
3	Sonification	246.7	111
	Control	209.7	75.8

Table 8.3: Mean effort

An independent t-test (equal variance assumed) was conducted to compare the final results (session 3) between two groups. Despite the higher mean value with Sonification ($M = 246.7$) compared to 209.7 in the Control, the significance level is not enough ($p > 0.05$) to suggest that there is clear difference between two groups for the effort variable.

8.3.4 MANOVA

A one-way multivariate analysis of variance (MANOVA) was conducted to investigate the overall effect of the sonification on these three variables to discover which variable(s) has a stronger effect. The only categorical, independent variable is the participant Group. The null hypothesis is that the population means of repetition time, movement range and effort do not vary across different groups. Preliminary assumption testing shows no serious violations (of normality, linearity, univariate and multivariate outliers, homogeneity of variance-covariance matrices).

The multivariate tests measure the significance of the differences among effect and control groups on a linear combination of the three dependent variables. The results are displayed in Table 8.4. Wilk's Lambda shows that there is no statistically significant difference between two groups on the combined variables, $F(3, 18) = 2.373$, $p = 0.104$, partial eta squared (effect size) = 0.283.

Effect	**Value**	***F***	**Hypothesis df**	**Error df**	***p***	**Partial Eta Squared**
Group Pillai's Trace	0.283	2.373	3.000	18.000	0.104	0.283
Wilk's Lambda	0.717	2.373	3.000	18.000	0.104	0.283
Hotelling's Trace	0.395	2.373	3.000	18.000	0.104	0.283
Roy's Largest Root	0.395	2.373	3.000	18.000	0.104	0.283

Table 8.4: Tests of between-subjects effects

To consider the dependent variables separately, the results of repetitions time has shown a strong effect, $F(1, 20) = 6.577$, $p = 0.018$ and partial et squared = 0.247. The variable has a large effect of 24.7%. The MANOVA results indicate that among all three quantifiable attributes, the sonification system worked best at reminding participants about the speed of repetitions, helping them to achieve a slow and steady exercise pace.

To sum up, the test shows no significant combined effect for the three variables. Yet a strong effect is found with repetition time compared to movement range and effort.

8.3.5 Post Session Survey Results and Analysis

Participants in the sonification group were asked to comment on their experience of using the sonification system. Overall, positive responses were gathered as shown in Table 8.5[1]. 8 out of 11 gave favourable comments on the sound.

Among the positive comments, 4 participants commented differently on how they used the auditory feedback as a reference cue to regulate their exercise movements. Other comments are more to do with the general enjoyment of the sound during the exercise. A negative comment was made by No. 2, criticising the other modes except the Linear mode for their lack of functionality. However, the comment was based on the trial session. During the action sessions, this participant used only the Linear mode, which was described as being able to create the 'most accurate representation' of the exercise movement. Also, participants 4 & 18 commented that the sound worked well as a distraction from fatigue. This distraction effect was also studied in (Szabo et al., 1999), which found that the use of music during sports activity could distract subjects temporally from feeling fatigue.

[1]The +/- column is the assessment of the comments, where '+' means positive comment and '-' means negative comment.

Type	Comment	No.	+/-
Sound related	Enjoyed the sound.	1, 2, 7	+
	Used the pitch as a reference for movement.	1, 18	+
	Aimed at a clearer sound that feels stronger.	12	+
	Tried to move slower based on the sound.	1, 12, 14	+
	Sync the motion with sound.	18	+
	At first the sound was annoying, then it kept me going.	16	+
	The sound was distracting in a good way, which made me more aware of the muscle activity.	4, 18	+
	I tried and didn't like the other sounds except the linear mode. They are not useful.	2	-
General	Not feeling any difference.	5	-
	I worked harder this time.	4, 7	+
	Feeling stronger.	17, 18, 21	+
	Not in the mood for exercise.	2	-

Table 8.5: Comments collected from the sonification group participants

In terms of the general exercise result, one participant did not feel the sonification had contributed to any difference in the exercise result. Five participants expressed that they worked harder and felt stronger after the session. One participant mentioned that he was not in the mood for the session. It is concerned that if a participant was emotionally in a bad mood, the sonification could cause adverse effect and potentially lead to annoyance.

8.4 Experimental Findings

In this experiment, the following findings have been drawn:

1. Among all three dependent variables, the repetition time is most influenced by the presence of sonification. Without the sonic cue, the control group participants did the repetitions quicker in general and did not seem to slow down over the sessions.

2. The sonification did not improve the movement range, even though

the linear pitch (9 out of 11 participants chose the linear frequency mapping) provided reference to the vertical hand position.

3. On average, participants managed more repetitions *with* the sound in all three sessions than the Control group. However, the statistical analysis shows that the difference is not significant. Based on the survey collected from the Sonification group participants, they general found the sonification had a positive effect on their exercise.

4. Mostly positive comments were collected from the survey. Participants found the sonification useful as a reference for the pacing and movement range. A participant even expressed that she could feel the sound was getting 'stronger' as her muscle was getting stronger. In other words, the participant used the sound as an analytic tool to make a judgement of the exercise quality.

5. Participants were free to choose any of the four sonification modes. 82% chose the Linear mode, and the rest chose the music player. This result shows that the Linear mode is still the most popular option for participants, as it creates a more comprehensive representation of the exercise movement than the others.

8.5 Summary

The experiment compared the exercise quality between subjects who did biceps curl exercises using the sonification system and others who did the same exercise yet *without* real-time feedback. All participants completed the three-session experiment. The experimental results show that sonification is able to make users aware of the pace of their movements. No difference was found between groups in terms of movement range. The sonification conveyed a raw representation of the vertical position of the active hand. However, the mapping did not seem to encourage users to aim for a larger range. Overall, although the effort variable is greater *with* the sonification, the difference is not significant.

The results have shown some clear strengths of the sonification system, as in the monitoring and control of repetition time. The results also point out the possibility that the use of sonification could lead to a positive motivation as the participants enjoyed the exercise experience using the sonification system. Increased motivation could, over time, result in a much better exercise progress than without the audio feedback.

Chapter 9

Experiment 3 - Crossover Trial

9.1 Introduction

The comparative experiment presented in the previous chapter compared the difference in biceps curl quality with and without real-time sonification. However, the number of sessions in that experiment was limited in its ability to show the development of a pattern of exercise results and quality measures over time. In addition, the individual differences of participants' physical condition may also affect the outcomes. Subsequently, this third experiment investigated the same comparison but over a longer time-scale. In this experimental set-up, every participant experienced both with and without sonification. Analysis of the same attributes as described in Chapter 8 is presented.

In this experiment, a crossover trial was conducted to measure the effect of the sonification over time in more depth. The 8-session biceps curl routine allowed subjects to act as both the effect and control group. Half of the participants completed the exercise with sonification for the first four sessions, then without it for the remaining four sessions. The opposite arrangement was applied to the other half of the participants.

9.2 Implementation

The experiment was carried out in two locations: Audio Lab teaching room and Electronic Department media suite, both are at the University of York. The reason for having two different locations for experiments is to let the participants choose the nearest one for them, in order to maximise participation. The rooms are functionally identical in that the same equipment is used in both, and there are no other factors that could potentially alter the experiment results.

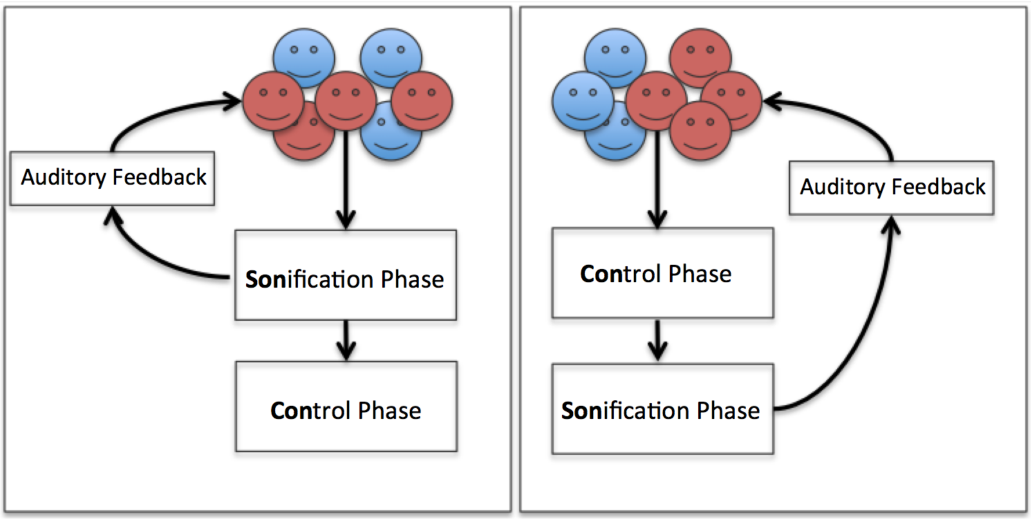


Figure 9.1: Diagrammatical portrayal of the crossover trial

14 University students participated in the experiment: 8 females and 6 males, aged 24 ± 3. All subjects were healthy with no current physiological conditions or injuries of the upper limbs. Participants were assigned to two equally numbered groups named *Con-son* (first four sessions **Con**ventionally without sound then the remaining four sessions with **Son**ification) and *Son-con* (sonification first four sessions then the remainder without). This experimental configuration is shown in Figure 9.1.

Between each session, participants took a 1-3 day's gap for necessary rest. Then between the crossover point, a one-week break was given, and participants were advised not to undertake any substantial biceps-related training during that time. All participants signed a consent form (Appendix F) prior to the experiment explaining the procedures. Participants were also advised to choose a dumbbell weight that was relatively challenging, but light enough to be able to complete at least three sets of five repetitions in each session. The weight of the dumbbell could be increased or decreased based on their motivation throughout the sessions.

Prior to the session, details of the experiment were explained to the participants. This involved:

- A demonstration of the biceps curl exercise
- Safety issues
- Data privacy
- The crossover setup
- Usage of the sonification device.

At the beginning of the first sonification session (the first session of the Son-con group and the fifth session of the Con-son group), the auditory feedback was explained in detail, which mainly concerned how the movements were mapped into the variations of sound. Participants were given a short trial to explore the sonic interaction freely without holding a dumbbell. The entire experiment used the Linear Frequency Synthesis mode only. In comparison with the other three types of sound, this mode had been shown to provide the most comprehensive sonic portrayal of the biceps curl movement in terms of both physiological locomotion and muscular activity (findings are presented in Section 7.4). It was the most used option in the previous experiment. In addition, using only one sound mode ensures the consistency of the auditory feedback across all subjects, which is beneficial for the purpose of data analysis.

Similar to the comparative experiment, three main quality criteria were defined and explained to the participants:

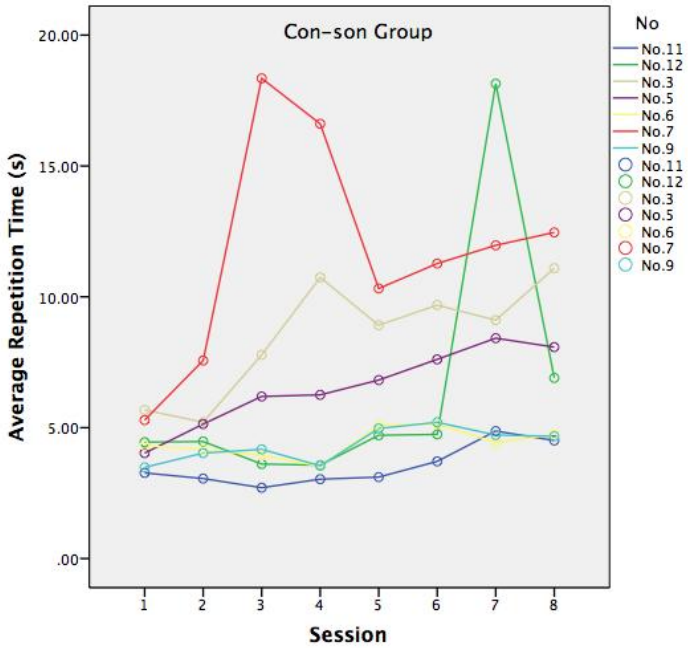
1. Subjects were advised to aim for a slow and steady pace, with each repetition completed in a minimum of 4 seconds.
2. Subjects should aim for a large movement range of the forearm, with the upper arm remaining stationary.
3. Subjects should complete at least 3 sets of a minimum of 5 repetitions in each session. However, the participants were told that this was for the purpose of getting sufficient data for analysis. Subjects were not encouraged to do as many repetitions as possible, even though this was desired.

Since this experiment required a much longer period (8 sessions) than the previous two experiments (2 and 3 sessions respectively), exercising on only one arm could have caused unbalanced muscle strength development. In order to let participants receive a balanced training, they were asked to exercise both arms (one at a time). However, for analysis purposes, we excluded the data from the subjects' dominant arm. It is because the predominant arm usually receives more daily exercise from activity such as playing ball games, using tools, writing, etc. All participants reported that their dominant arm was the right arm, and so data was gathered exclusively from the left arm.

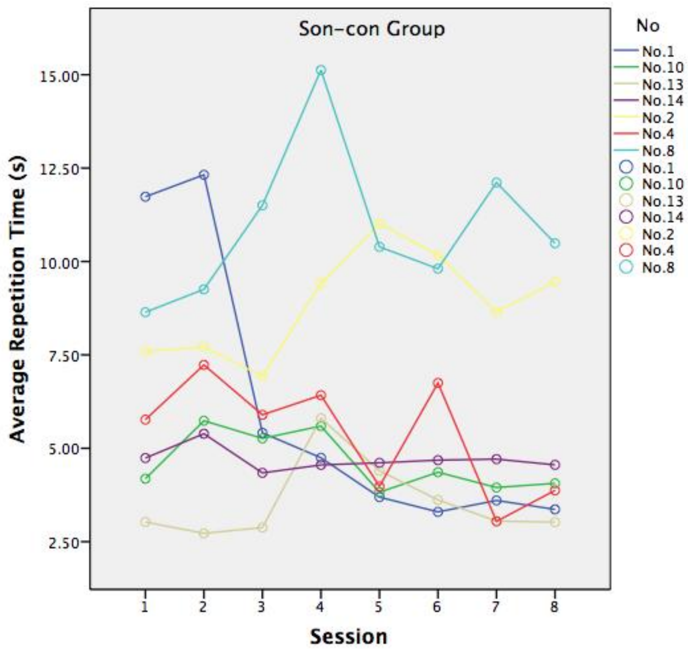
9.3 Quantitative Results and Analysis

The analysed data includes - repetition time, movement range and the total effort, which is the product of dumbbell weight and the number of repetitions.

9.3.1 Average Repetition Time



(a) Con-son group's progress.



(b) Son-con group's progress.

Figure 9.2: Progress of the average repetition time of each participant

Firstly, the average repetition time of each session and how this changed over time was investigated. Figure 9.2 presents the progress of this variable for all participants, which is split according to the group. Subfigure (a), Con-son, shows that most participants improved gradually throughout the sessions. Subject Nos. 3, 5, 7 and 12 improved more dramatically than others. For example, for subject No. 12 the repetition time remained similar in the first 4 sessions then improved dramatically (with the introduction of sonification) in the remaining sessions. Nos.6, 9 and 11 did not see much improvement in the control sessions, yet moderate improvements are shown in the sonification sessions.

In the Son-con group (Fig. 9.2b), 5 participants gradually improved their repetition time in the first four sessions. 6 participants experienced different levels of decrease in quality in sessions 5-8, except No.14 who performed steadily in all eight sessions. Participants Nos. 2 (yellow) and 8 (light blue) are good examples to see the possible effect of the sonification. Gradual improvement can be seen at the beginning of the 4 sessions (sonification). Then the overall trend dropped in the later sessions even though the average time at the last session is still higher than the beginning session.

Figure 9.3 presents the mean progress of the two different groups. Holistically, an overall increasing trend can be observed in the Con-son group. In the Son-con group, an overall improvement can be seen in the Sonification phase but then a decrease in quality is shown in the remaining sessions without the sound.

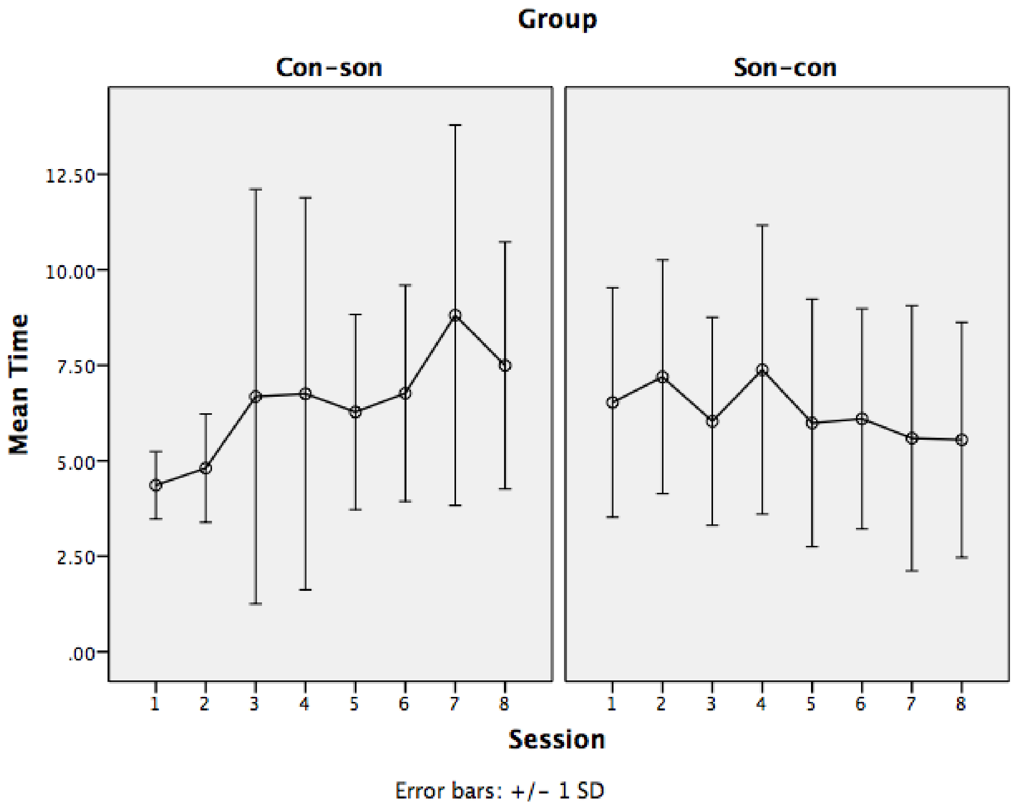


Figure 9.3: The average repetition time progress throughout sessions by group

The next part of the analysis investigates the difference of this variable in each treatment (4 sessions), and the results are shown in Figure 9.4 and Table 9.1. In Figure 9.4, each data point represents the average repetition time of the 4 sessions with the same treatment; the blue triangle represents the Sonification phase and red circle the Control phase. A greater repetition time implies better exercise quality (slower movement velocity). Then the difference percentage column in Table 9.1 is calculated as follows:

$$d_t = \frac{t_{son} - t_{con}}{t_{con}} \times 100\%$$

which means that the result represents the difference between the Sonification phase and Control phase. If the difference percentage is positive the Sonification phase result is larger than the Control phase result, and vice versa.

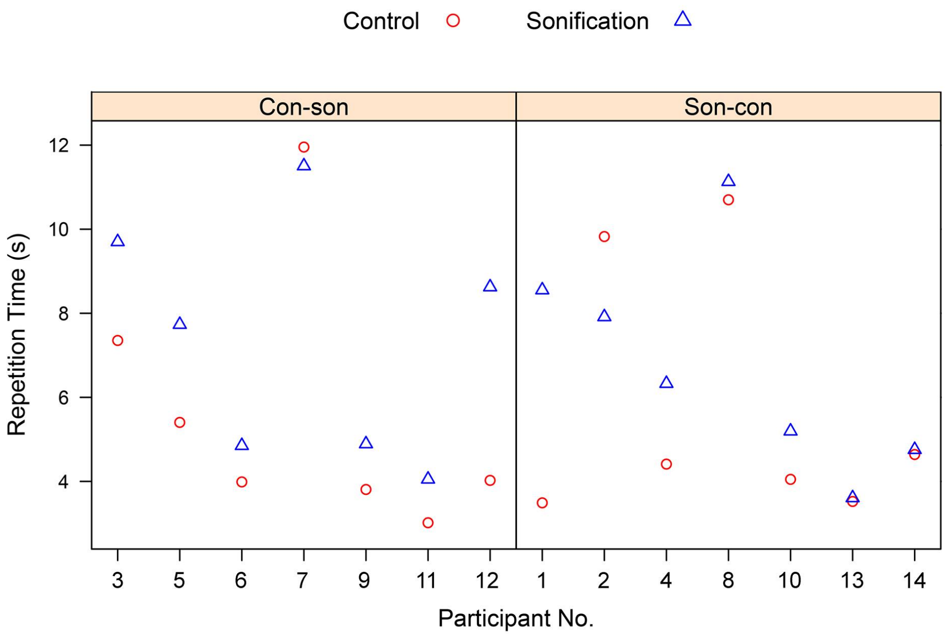


Figure 9.4: Average repetition time

Son-con					Con-son				
No.	Sonification	Control	Difference	Difference (%)	No.	Control	Sonification	Difference	Difference (%)
1	8.55	3.49	5.06	145%	3	7.35	9.7	2.35	32%
2	7.91	9.83	-1.91	-19%	5	5.4	7.73	2.33	43%
4	6.33	4.41	1.92	43%	6	3.99	4.85	0.86	22%
8	11.13	10.7	0.43	4%	7	11.95	11.5	-0.45	-4%
10	5.2	4.05	1.15	28%	9	3.81	4.89	1.08	28%
13	3.61	3.52	0.09	2%	11	3.02	4.05	1.04	34%
14	4.76	4.64	0.12	3%	12	4.02	8.62	4.6	114%

Table 9.1: Average repetition time of the two groups

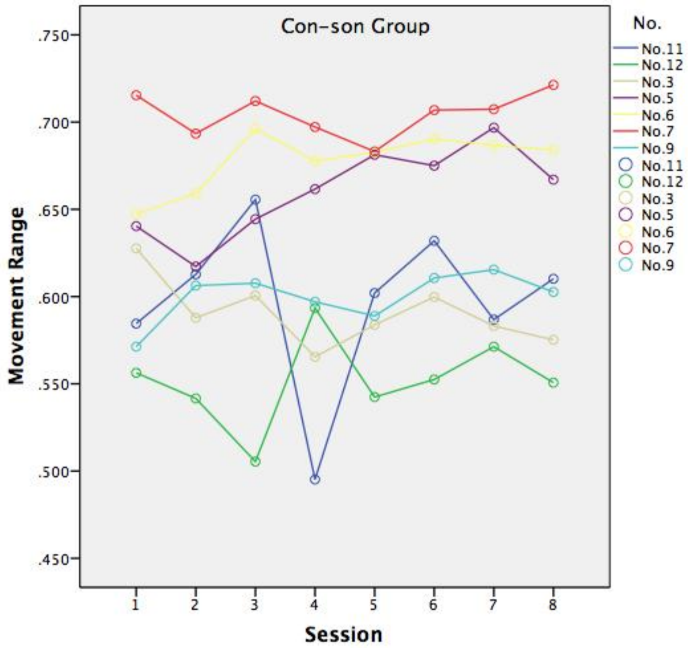
As shown in Figure 9.4, only two participants performed worse in the Sonification phase with the differences of 19% (No.2) and 4% (No.7). All the other participants performed better in the Sonification phase to different extents than the Control phase. Three people performed marginally better (within 5% slower speed in the Sonification phase). Half of the participants performed significantly better with the sonification (between 20% and 50%). Lastly there are two extreme cases where the performance in the Sonification phase is more than 100% better than the Control phase. A paired t-test was conducted to confirm this difference. The result showed that the average repetition time in the Sonification phase ($M = 7.06$, $SD = 2.62$) was significantly greater than in the Control phase ($M = 5.73$, $SD = 2.98$); $t(13) = 2.68$, $p = 0.02$. The t-test result suggests that sonification could provide cues to help users exercise at a slower speed as listed in Criterion 1 in the Implementation section (9.2).

Finally, it is worth singling out the results of participant No. 7 (Con-son group) who performed better in the control exercises, at odds with the majority of participants. The subject started the exercise without the sonification and had a mean repetition time of 11.95s in the first four sessions, which then fell to 10.5s in the Sonification phase, reporting a 4% increase in speed. First of all, these two results are the highest of all participants thus both data points are considered to fall in the zone of good quality. Secondly, having such a slow speed left little room for improvement with the Sonification phase.

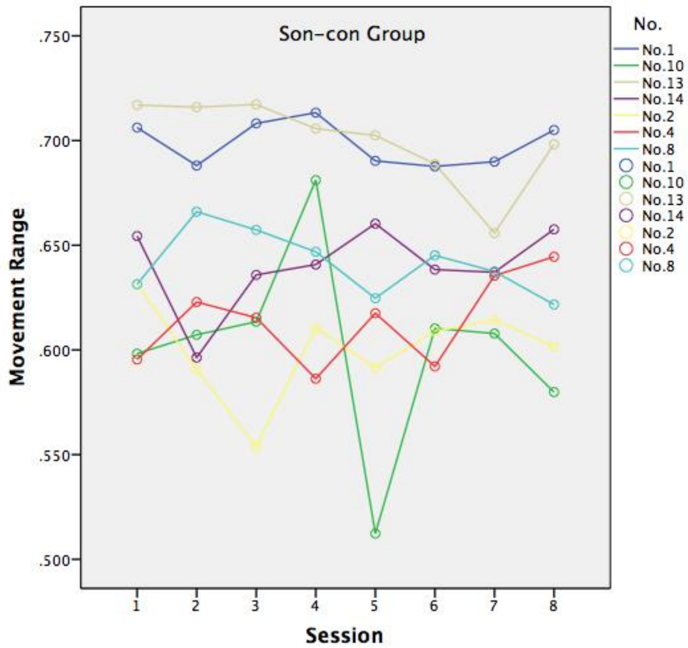
9.3.2 Movement Range

The movement range is the relative distance travelled by the hand per repetition. Firstly, the progress of each participant is examined in Figure 9.5.

From the figures, it can be seen that the progress of this attribute is harder to observe than the repetition time as the results fluctuate more. In Figure 9.5a, only three participants (5, 6 and 9) showed a clear ascending trend. Then in Figure 9.5b, little clear difference can be observed comparing progress in sessions 1-4 and 5-8. Throughout the whole process, the performances between sessions fluctuated greatly. It is suspected that there is a certain unpredictability involved in participants' movement range. However, the sonification did not seem to work to improve it, which could indicate a weak point in the sonification design. It is interesting to point out participant No.10, whose movement range improved and peaked at session 4, then decreased severely when the sound was removed. Although, in the later session, the performance increased again, a descending pattern is still observed.



(a) Con-son group's movement range progress.



(b) Son-con group's movement range progress

Figure 9.5: Progress of the average movement range of each participant

When the average results for the groups are presented, irregular fluctuations can still be observed in both groups (Fig. 9.6). Interestingly however, when the overall levels are considered, the performance in the Con-son group is generally lower than Son-con group. This result leads to the assumption that if the sonification (effect treatment) was given at the beginning, the performance is generally better than starting the sessions without the sonification.

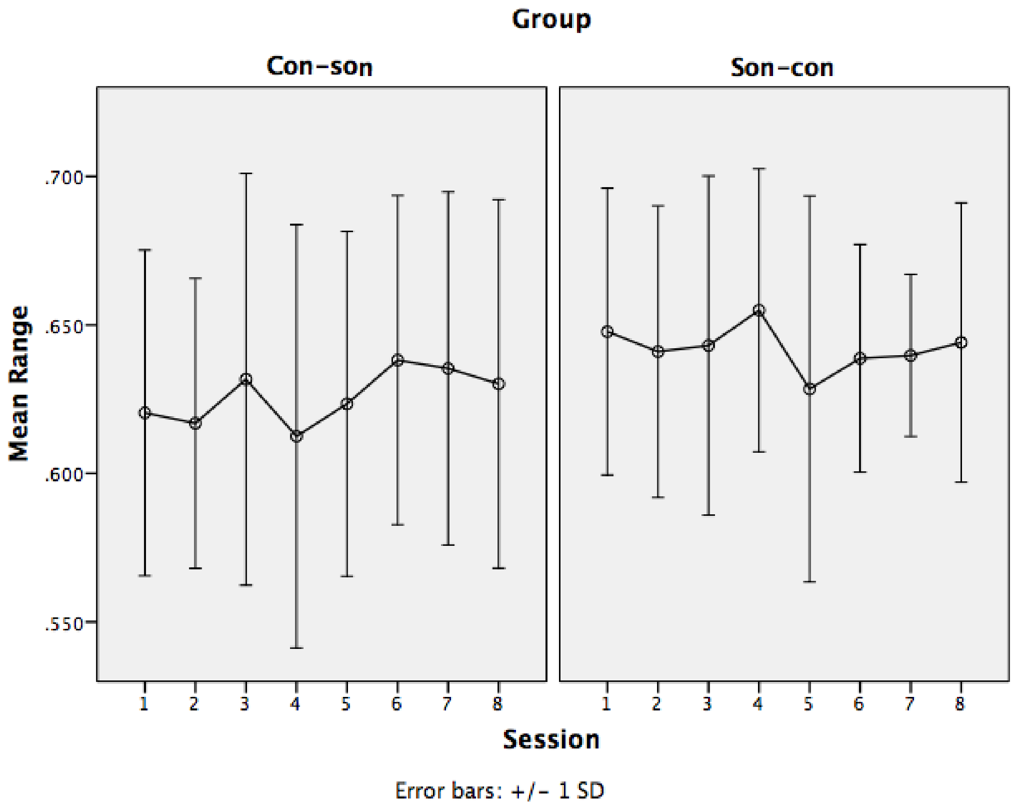


Figure 9.6: The average movement range progress throughout sessions

The next part of the analysis compares the average movement range in the two different phases. The comparative results are shown in Figure 9.7 and figures are presented in Table 9.2. In the Son-con group, 4 participants (57%) performed better in the Sonification phase. However, in the Con-son group, 5 participants (71%) performed better in the Sonification phase and 1 did not show any difference in performance between two phases. Overall, 9 out of 14 participants (64%) showed better results in the Sonification phase. This result (for movement range) is not as statistically significant as the repetition time: a paired t-test was conducted and showed no significant difference between the movement range between the Sonification phase ($M = 0.639$, $SD = 0.051$) and Control phase ($M = 0.629$, $SD = 0.047$), $t(13) = 1.93$ and $p = 0.076$.

Son-con				**Con-son**			
No.	Sonification	Control	Difference	No.	Control	Sonification	Difference
1	0.704	0.693	0.011	3	0.595	0.585	-0.010
2	0.597	0.604	-0.007	5	0.641	0.680	0.039
4	0.605	0.622	-0.017	6	0.670	0.686	0.016
8	0.650	0.632	0.018	7	0.705	0.705	0
10	0.625	0.578	0.047	9	0.596	0.604	0.009
13	0.714	0.686	0.028	11	0.587	0.608	0.021
14	0.632	0.648	-0.017	12	0.549	0.554	0.005

Table 9.2: Average movement range of the two groups

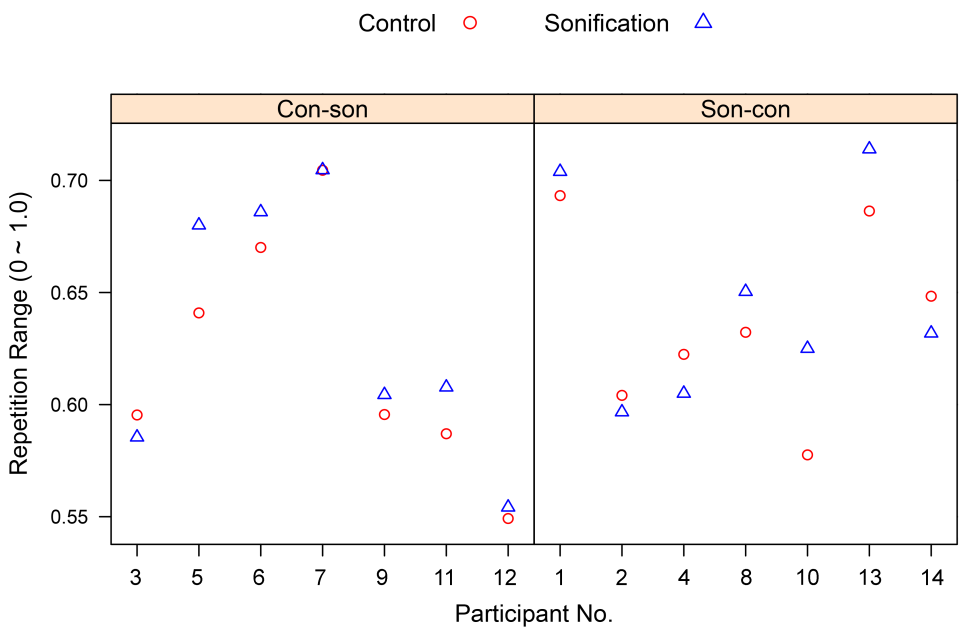
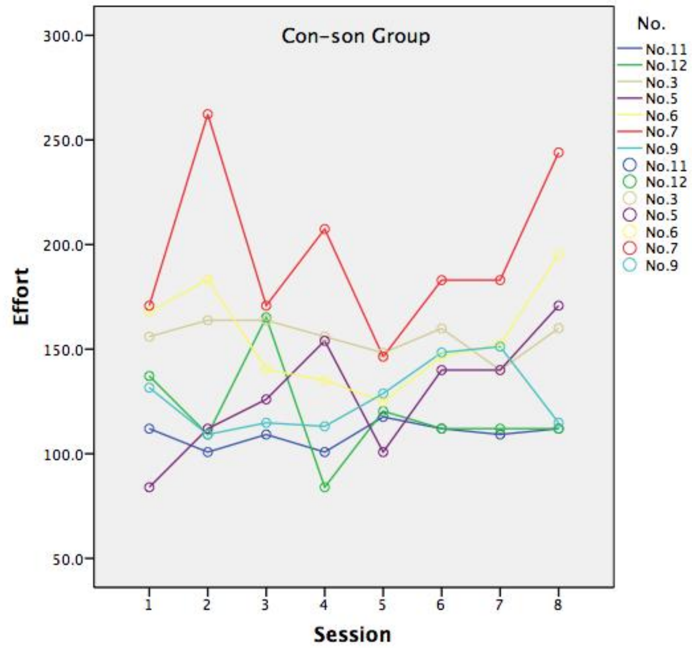


Figure 9.7: Average repetition range

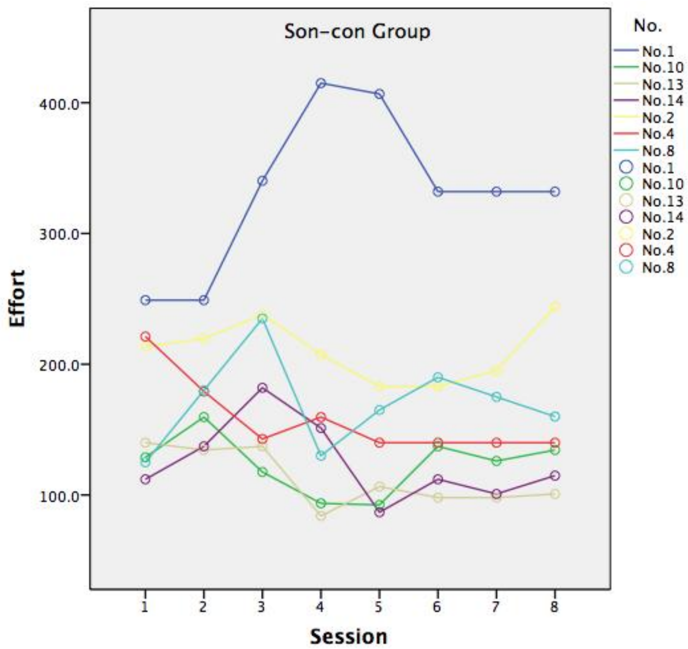
9.3.3 Effort

Effort is defined as the product of dumbbell weight and the total number of repetitions. There was no instruction asking participants to aim for more repetitions/sets or a heavier dumbbell. Hence, this attribute serves as a hidden quality factor aiming to quantify the participants' motivation. Thus, the effort results could imply whether the sonification can make the exercise more interesting in the Con-son by seeing whether there was an increase of total effort from session 5 onwards, and similarly whether removing the sound made the exercise less engaging for participants in the Son-con group, which could cause a decrease in this variable.

The first part of the analysis of this attribute examined the progress across all sessions, which is shown in Figure 9.8. In the Con-son group (Fig. 9.8a), the progress varied a lot across sessions and there are no clear patterns holistically. The progress in the Son-con group (Fig. 9.8b) is generally more stable than the other group. It can be seen that three participants showed clear signs of improvement in the first four sessions. The performance in the remaining sessions (Control phase) tended to be relatively stable.



(a) Con-son group's effort progress.



(b) Son-con group's effort progress

Figure 9.8: Progress of the average effort of each participant

When the progress of the average effort in the two groups was explored (Fig. 9.9), more obvious improvement can be seen in the Sonification phase (Session 5-8 in Con-son and 1-4 in Son-con). Similar to the movement range results presented in Section 9.3.2, it seems that starting the sessions with sonification leads to a greater overall performance.

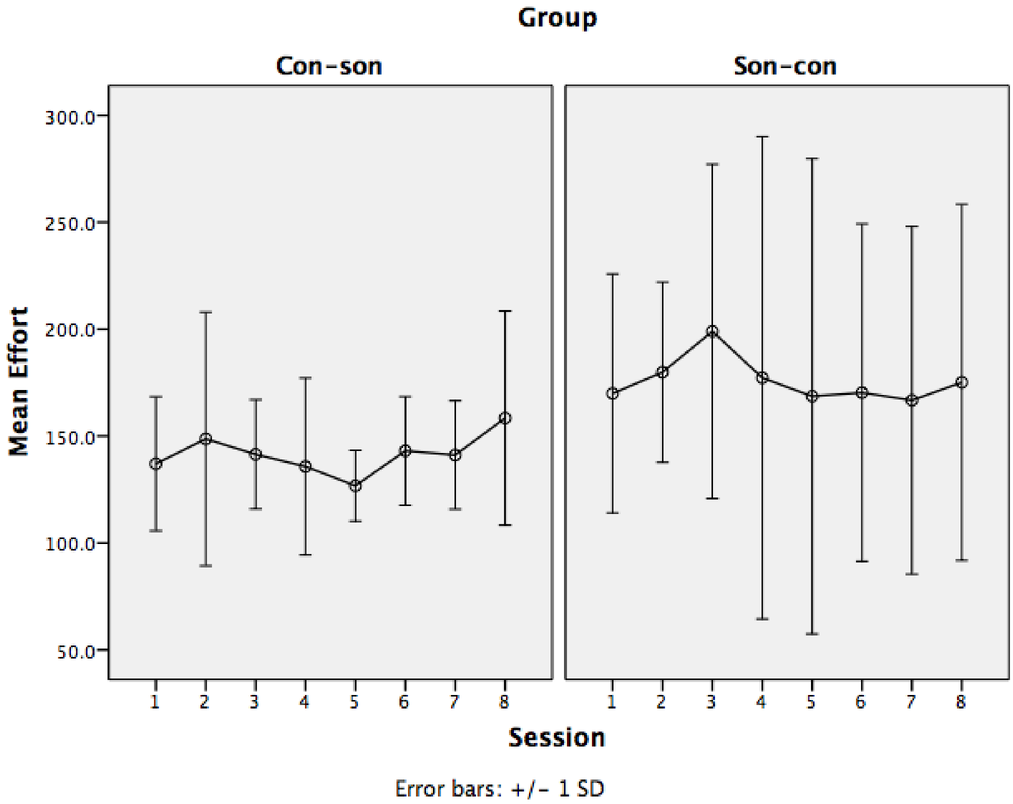


Figure 9.9: The average effort throughout sessions

The next part of the analysis looks at the average efforts across sessions. The comparative result is shown in Table 9.3 and Figure 9.10. In Table 9.3, the difference in percentage columns is calculated as follow:

$$d_e = \frac{e_{son} - e_{con}}{e_{con}} \times 100\%$$

Son-con					Con-son				
No.	Sonification	Control	Difference	Difference (%)	No.	Control	Sonification	Difference	Difference (%)
1	313.3	350.7	-37.4	-11%	3	159.9	152.0	-7.9	-5%
2	219.6	201.3	18.3	9%	5	119.0	137.9	18.9	16%
4	175.7	140.0	35.7	26%	6	156.6	154.8	-1.8	-1%
8	167.5	172.5	-5.0	-3%	7	202.8	189.1	-13.7	-7%
10	124.9	122.5	2.4	2%	9	117.2	135.8	18.6	16%
13	123.9	100.8	23.1	23%	11	105.7	112.7	7.0	7%
14	145.6	103.6	42.0	41%	12	123.9	114.1	-9.8	114%

Table 9.3: Average effort of the two groups

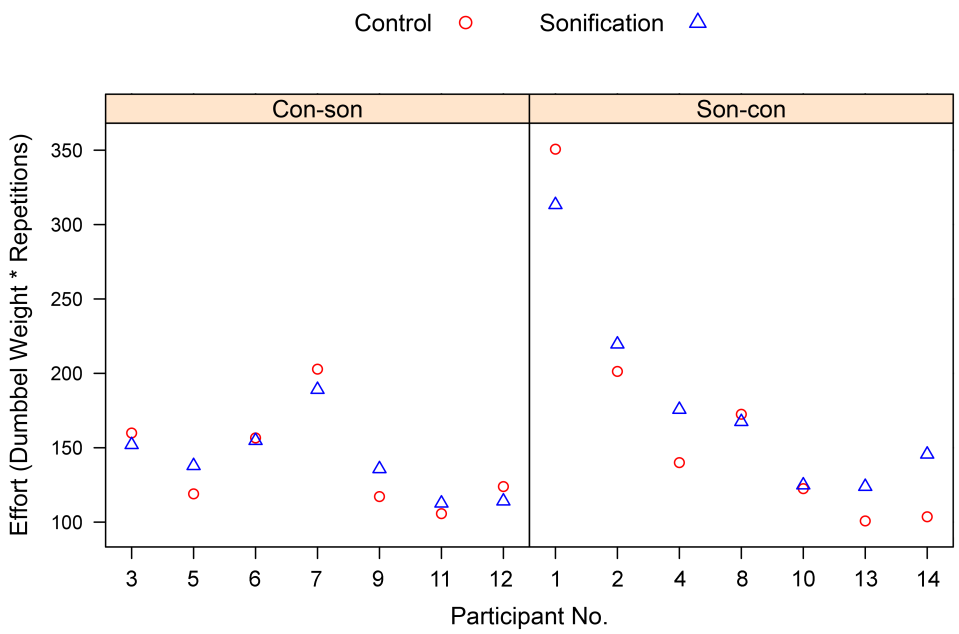


Figure 9.10: Average repetition effort

8 positive results (57%) and 6 negative results (43%). A paired t-test showed no significant difference ($p > 0.05$) in this attribute between the Sonification phase ($M = 162$, $SD = 53$) and Control phase ($M = 155$, $SD = 66$).

It is not surprising that no significant result is shown because the participants were not aware that they should aim for a greater amount of repetitions or increase the dumbbell weight. In the Son-con group, Nos. 1, 4, 13 and 14 expressed that the exercise became more tedious after the removal of the sonic feedback. No. 2 expended 26% more effort in the Sonification phase, 23% for No. 13 and 41% (the largest increase) for No. 14. It was possible that boredom resulted in a decrease in repetitions as the participants became less motivated. No. 1 shared the same opinion but still exhibited higher effort in the Control phase than the Sonification phase. This participant commented that although the Control phase was less interesting, his muscles were getting stronger and hence he could still manage to finish more repetitions than in the initial phase.

In the Con-son group, 3 participants showed improvement in effort in the Sonification phase; 3 showed a decrease, and 1 remained unchanged. Although the mean value is still higher in the Sonification phase (2.6%), it is much less than the 12.4% observed in the Son-con group. It seems that the order of the treatments also affected the outcome.

9.4 Survey Results

At the end of each session, the participants completed a questionnaire (Appendix F). They answered on a scale between 1 to 10 on:

1. How much do you enjoy the session? (Not at all → Very enjoyable)
2. How tired do you feel? (Not tired → Exhausted)

There were also questions exclusive to the sonification treatment:

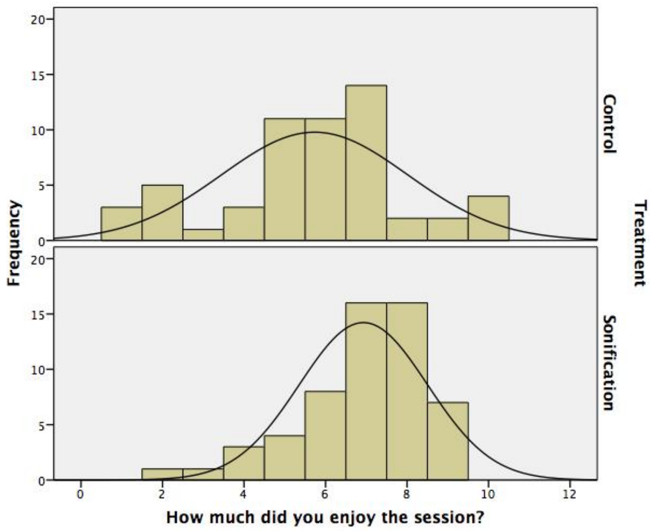
1. How would you rate the sound? (Highly disliked → Highly liked)
2. Did the sound provide sufficient feedback? (Very confusing → Very informative)

In addition, optional comments were offered by some participants about their experience of the sessions. The following provides an analysis of this qualitative data, which starts with the descriptive analysis of the survey results. Hypothesis tests were conducted to see whether there were significant differences between the same questions in the two different treatments. Lastly, the comments are presented.

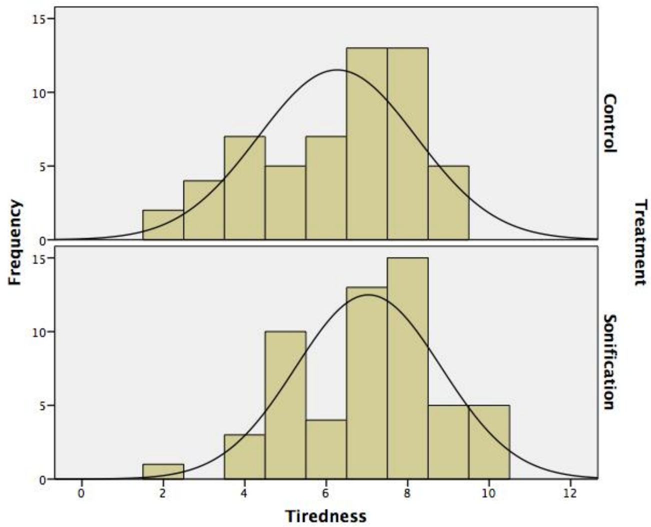
9.4.1 Descriptive Analysis of the Questionnaire Results

Firstly, the histograms in Figure 9.11a & b present the frequency distributions of the two questions from the two treatments. The use of histograms in section to show the distribution of the participants' answers. The histogram of Question 1 (How much did you enjoy the session?) displays a difference in the centre tendency and spread as the Sonification phase has a narrower distribution and a higher centre. In the Control phase, we can see a fair amount of votes located towards the lower end of the scale (< 5). This shows that the Sonification phase received more high-value results than the other phase.

Secondly, the histogram of Question 2 (Tiredness) displays the peak of the scores falls between 7 and 8 (most people are reasonably tired for all sessions, possibly indicating that they exercised well). Yet more scores are shown below 4 in the Control phase, and reversely we can see more top scores (very tired) in the Sonification phase.



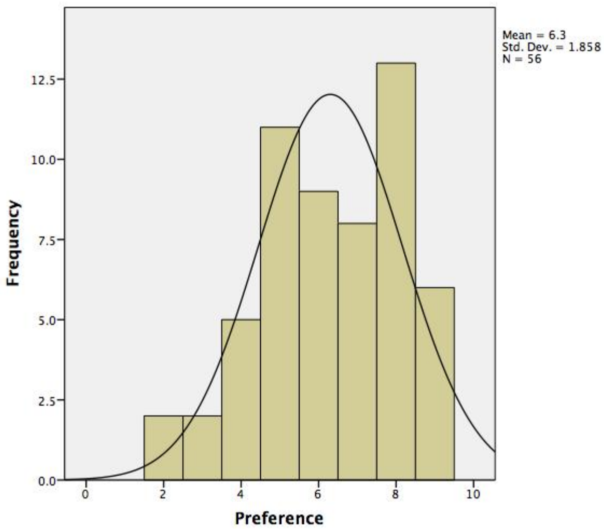
(a) Question 1: How much do you enjoy the session?



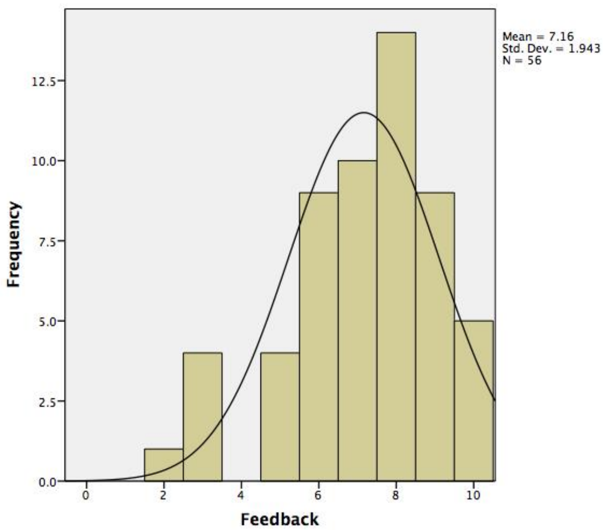
(b) Question 2: Rate your tiredness.

Figure 9.11: Histograms of the survey questions

The next part looks at the questions about whether the sound is interesting or informative. The mean preference rating is 6.3 ($SD = 1.858$), and the mean feedback rating is 7.16 ($SD = 1.943$). These results are relatively satisfactory. In Figure 9.12a & b, we can see most scores fall in the higher spectrum (> 5). The results show that most participants enjoyed the sound and found it capable of delivering useful information of the exercise.



(a) Preference rating.



(b) Feedback rating.

Figure 9.12: Histograms of the two sound-related questions

9.4.2 T-Test of the Questionnaire Results

Paired t-tests were conducted to compare the differences between the two treatments in the enjoyment rating and tiredness. As shown in Table 9.4, both tests show significant results. The mean enjoyment rating in sonification is 6.93 ($SD = 1.57$) and 5.73 ($SD = 2.28$) in control; $t(55) = 3.87$, $p < 0.001$. The mean tiredness in sonification is 7.04 ($SD = 1.79$) and 6.27 ($SD = 1.94$); $t(55) = 3.37$, $p = 0.001$.

Question	Control		Sonification		95% CI for Mean Difference	t	df	p
	M	SD	M	SD				
Enjoyment	5.73	2.28	6.93	1.57	.576, 1.816	3.867	55	.000
Tiredness	6.27	1.94	7.04	1.79	.311, 1.225	3.369	55	.001

Table 9.4: Paired sample t-tests of the enjoyment and tiredness rating

The t-test results indicate that participants enjoyed the training more with the sonification than without. This provides statistical support to claim that the sonification provides a positive effect on the subjects' experience of the exercise. The tiredness level was also higher with sonification, which points to the possibility that participants were willing to work harder with the sound.

9.4.3 Open Comments

This part presents the collated results of some participants open comments, which was shown in Table 9.5. Selected results are presented, which exclude comments which were mainly based on participants physical condition such as "feeling tired".

Type	Comment
Sound feedback	Paid attention to the sound.
	Aimed for a slower pace based on the sound.
	Became more interesting (than without sound).
	Aimed at a steady sound.
	Exercise frequency affected by the sound.
Without feedback	Boring.
	Not as much fun.
	Exercise felt more difficult than with the sound.
End of sessions	Feeling stronger.
	Exercise became easier.

Table 9.5: Crossover trial participants' comments

In general, positive comments were collected on the auditory feedback generated from the biceps curl. The comments mainly focus on the sound being to able to help the participants aim for a slower pace of movement and improve the steadiness. The sound also made the sessions more interesting. Equivalently, three Son-con group participants expressed that the Control phase felt less interesting because of the lack of auditory feedback.

9.5 Experimental Findings

This data analysis draws the following findings:

1. In terms of exercise quality, the sonification has a strong impact on maintaining a good pace of the repetitions. T-test recorded a significant difference of 0.55s more repetition time (95% CI: 0.10s to 0.96s).
2. There is not enough statistical evidence to show that the auditory feedback could lead to a large biceps curl movement range.
3. Although no obvious improvement is shown in the total effort, the

post-session survey indicates that participants felt more motivated with the auditory feedback. In addition, participants generally felt more tired with the auditory feedback ($p = 0.001$), indicating that the participants worked harder with the auditory feedback.

4. An interesting conclusion can be drawn from the average progress graphs of the three variables between two groups (Fig. 9.3 in Section 9.3.1; Fig. 9.6 in Section 9.3.2 and Fig. 9.9 in Section 9.3.3). It seems that starting the exercise with the effect treatment (sonification) led to better overall performance than starting with the control treatment (no sound).

5. A significant result is shown that the participants enjoyed the exercise more with the feedback than without.

6. The survey shows that the sonification could provide sufficient feedback for the exercise.

7. Moderate preference rating indicates the sound aesthetics still has room for improvement.

9.6 Summary

This experiment investigated the difference between doing biceps curl with and without sonification. 14 participants took part in the 8-session crossover trial (AB-BA method). The population was split into Son-con (sonification then control) and Con-son (control then sonification).

The quantitative results show that the sonification effectively reminded the users to slow the pacing of the movement. The movement range was again higher with the sonification, but this result was not found to be statistically significant. Although the average effort (product of dumbbell weight and number of repetitions) is greater with sonification, the difference was not significant. However, the survey showed a higher tiredness level when participants exercised with sonification, implying that participants worked harder *with* the sound. Last but not least, both the open comments and the enjoyment rating confirmed that participants felt significantly more motivated during the Sonification phase than in the Control phase.

The crossover trial shows similar results to the between-subjects test presented in Chapter 8 (better paced exercise with sonification; obvious difference in movement range; better motivation with sonification). This shows the consistency of the sonification system and strengthens the validation of the findings to support the hypothesis.

Chapter 10

Conclusions and Further Work

10.1 Introduction

The chapter restates and explains the hypothesis. Major findings are presented to support the hypothesis in Section 10.3. The implication of the results and the scope of the findings are discussed. Section 10.5 considers various limitations of the research. Section 10.6 presents further work based on a short-term and long-term perspective.

10.2 Review of Hypothesis

To restate the research hypothesis:

> By listening to real-time sonification of healthy adults' muscle activity along with kinesiological data in biceps curl exercises, subjects are able to improve performance and make better progress, whilst at the same time experiencing improved motivation than subjects who do the same exercises but without any real-time

audio feedback.

This research proposes a novel way to create real-time auditory feedback using a person's muscular activity and kinesiological information during biceps curls. This feedback provides useful cues for the user to improve their exercise quality and performance results, and at the same time experiencing better motivation. To achieve the above objectives, the following actions have been taken:

(1) Sonification System Development

A sonification system was developed with two sensory devices and a program created using Max. Regarding the hardware, the EMG belt extracts muscular activity from the biceps. The Kinect camera outputs the hand's positional coordinates during the repetitions. Then the software maps these two information streams into sound engine parameters to generate the auditory feedback. The software provides multiple sound options for users to choose from. These include:

1. linear frequency synthesis to provide a raw representation of the biceps curls;
2. MIDI note synthesis that uses probability matrices to generate variable melodies from the movement;
3. a music player that allows users to play back their own music files. The muscular activity controls the cut-off frequency of the low-pass filter to shape the brightness of the sound, and a pitch-shifter is used to alter the pitch of the music if the movement is too fast;
4. an ambient sample (sea wave sound) to create a sense of environmental immersion. This is focused more on helping participants to relax.

(2) Experiments to Examine the Effect of the Sonification

Three experiments were carried out. The first experiment was the 2-session pilot study to examine the system and evaluate user experience. The second experiment was a 3-session between-subjects comparative test to compare the quality of exercise between two groups. Participants were randomly assigned to the sonification group and control group (no feedback given). The repetition time, movement range and effort (product of dumbbell weight and repetitions) were analysed and compared. Comments on the experience of sonification were collected. In the final experiment, a within-subjects crossover trial was conducted to investigate the differences in the same quantitative variables over different exercising conditions (with and without the feedback). The experiment lasted eight sessions where two groups of participants did the exercise in two sequences of treatments, sonification-control and control-sonification. Participants also filled in a post-session survey with rating questions and open comments.

10.3 Summary of Findings

The experiments have yielded the following findings based on the quantitative results and the user comments:

1. The sonification, especially the linear frequency synthesis mapping, *can* provide useful information about the exercise movement.
2. Providing multiple sound options *can* accommodate different people's personal preferences.
3. The sonification has a *strong influence* on encouraging the user to exercise at a slower pace.
4. The sonification did *not* contribute to the improvement of the movement range.

5. Participants generally found the sonification *enjoyable* to exercise with and consequently tended to expend *more effort* on the exercise.

6. The overall quality standard is higher *with* the sonification than without.

The following sections present feedback from the experiments to support these findings.

10.3.1 The sonification, especially the linear frequency synthesis mapping, *can* provide useful information about the exercise movement

This is the fundamental criterion for the application of sonification to exercise. The mapping design in this system carefully considered the hand movement and the biceps activity as the two key aspects of the exercise to be monitored.

Comments from the three experiments (Sections 7.3.2, 8.3 and 9.4) all show evidence to support this finding. The pilot study recorded a mean comprehensibility rating of 3.71 out of 5 ($SD = 0.4$). In the same test, the linear frequency mode was considered the most informative representation among all four modes. Then in the survey of the crossover trial, the result shows that participants found the sonification (linear frequency mode) informative, with a mean value of 7.16 out of 10 ($SD = 1.943$).

10.3.2 Providing multiple sound options *can* accommodate different people's personal preferences

The system offers four different sound modes in order to provide a choice of listening options to the user. This decision was supported in the pilot study survey. From the preference rating, each participant has at least one favourite mode with a full score of 5. Also, there is no 'perfect' mode meaning that each mode received at least one ‘dislike’ (below 3) in terms of comprehensibility and preference. Participants’ comments also show a mixture of positive and negative responses for each mode, indicating that all modes have strengths and weaknesses which suit different people’s preferences.

Providing multiple output options may appear contradictory to some other sonification research which used singular mapping method for a more consistent and reproducible feedback. Also the MIDI note mode uses probability matrices to generate different melodies from the hand movement meaning that it is impossible to be reproduced in an exact same way under this mode.

As quoted from Hermann’s definition of sonification in Taxonomy and Definitions for Sonification and Auditory Display:

> “The sonification is reproducible: given the same data and identical interactions (or triggers) the resulting sound has to be structurally identical.”
>
> (Hermann, 2008)

The use of ‘structurally’ is to exclude the inevitable changes due to certain conditions such as different speaker volume.

However, this research focused more on providing users with good experience and more variation. Also, we have taken the fact that an individual’s personal preference (or often referred as ‘taste’) can be very different from others. For example, in the pilot study, an interesting point was found that two participants liked and disliked the linear frequency sound for an apparently the similar reason, which was that the sound was comparable to electronic music and not traditionally musical. Therefore, this decision may have challenged Hermann’s argument, yet it was based on the consideration for a general user’s point of view rather than an analyst’s. For that matter, we feel that providing multiple options can work better than a singular mapping scheme.

In the same paper, Hermann further describe the concept of *reproducibility* as

> "Sample-based identity is not necessary, yet all possible psychophysical tests should come to identical conclusions." (ibid)

From his perspective, to be able to exactly recreate the same sonic output might not necessary. What is more important is that the effect of the output should lead to an identical *result*. In this research, the purpose of designing multiple sonic options is not to create contradictory mappings but simply to provide a richer user experience.

10.3.3 The sonification has a *strong influence* on encouraging the user to exercise at a slower pace

The between-subjects comparative test analysis shows a significant difference ($MD = 3.98s$, 95%CI: 0.74s to 7.22s) for the repetition time through an independent t-test, which indicates that the sonification group generally exercises at a slower pace than subjects who exercised without the feedback.

The crossover experiment also shows a significant difference ($MD = 0.53s$, 95%CI: 0.1s to 0.96s). First of all, the application of sonification again most strongly influences the maintenance of a good movement pace. The paired t-test shows that the repetition time in the sonification phase is significantly higher than the control phase.

To conclude, from the experiments we know that the sonification of biceps curls is highly effective at influencing the speed of the movement. From a perceptual perspective, the sonification helped users to recognise the speed of movement based on sonic patterns. The sonic patterns' temporal characteristic worked as a constant reminder.

10.3.4 The sonification did *not* contribute to the improvement of the movement range

Neither comparative tests shows a significantly better result for the movement range among subjects who used the sonification. However, although the first finding shows that the sonification is rather informative, this hints that despite sonification being capable of presenting the movement *position*, it did not remind users to aim for a large movement *range*.

This finding teaches an important lesson about designing an appropriate mapping scheme. The original design resulted in a continuous mapping (such as the pitch mapping in the linear frequency mode), which could provide a raw portrayal of the hand's vertical position. However, this auditory information merely *reflects* the data rather than *interpreting*. Therefore, this feedback was not suggestive enough to let the user realise whether the current pitch pattern was good enough or not. As a result, the feedback could not contribute to the improvement of this variable. This leads to a conclusion that an effective real-time sonification system should deliver information that is originally difficult to perceive.

10.3.5 Participants generally found the sonification *enjoyable* to exercise with and consequently tended to expend *more effort* on the exercise

From the second experiment, although the total effort was consistently higher for the sonification group, the t-test showed that the difference was not significant enough. When combining the effort results and participants' comments, we found that participants mostly found the sonification useful and interesting to use. This implies that the motivation is higher when the users exercise with the sonification.

From the crossover trial, the comment analysis showed that participants found exercising with sonification more motivating and helpful than no feedback. A significant result is found for the enjoyment rating questions that participants enjoyed more using the sonification in the training. A significantly higher tiredness rating suggests that participants generally worked harder with sonification, also indicating better motivation.

The total effort results and the qualitative data both provide supportive evidence to show that participants achieved better motivation exercising with the sonification. The sonification made the exercise more informative and interesting, which could make users want to spend more time in the exercise.

10.3.6 The overall quality standard is higher *with* the sonification than without

From the group progress comparison (Fig. 9.3 in Section 9.3.1; Fig. 9.6 in Section 9.3.2 and Fig. 9.9 in Section 9.3.3), it seems that the Son-con group performed better for all three attributes from the beginning. From the Con-son group progress, the values of the attributes gradually improved to the similar level of the Son-con group's first session. This has the very important implication that if the sonification was given from the beginning, the performance would be consistently higher throughout the sessions.

10.4 Result Implications

10.4.1 Sonification Produces an Overall Benefit to Exercise

From this research, we see that the exercise information such as muscular activity and kinematic data can be portrayed sonically in real-time. By listening to the sonic feedback, the exerciser receives a comprehensive representation of the monitored body states. This information can help the exerciser to decide whether an adjustment is required as a way to improve exercise quality. The experiments have shown that sonification has a strong effect on improving the pacing of the biceps curl exercise. It can make physical exercise more enjoyable as the feedback transforms the conventional exercise into an interactive process. This interaction can distract the user from feeling fatigue, and also the users participate in the generation of sound and melody through exercising, which makes it more fun. This project has shown its potential of improving the quality of physical activity and the willingness to exercise.

10.4.2 Sonification Produces a Motivational Element to Exercise

To some extent, the interactive sonification system can be regarded as a gaming platform, a concept which is currently becoming increasingly popular in many physical exercise programmes. (Robinson et al., 2011) found that the acceptance level and user experience improved significantly in using gaming platforms for healthy adult subjects who do not regularly exercise. A similar effect was discovered during the experiments described in this thesis, as participants found that using the feedback was more enjoyable and they subsequently expended more effort on the exercise.

It is interesting to consider whether exercise itself could inherit some qualities of entertainment. If the rewards of exercising could be greatly improved, this could have significant impact on those who predominantly live a sedentary lifestyle and currently lack the motivation to do physical exercise.

10.4.3 The Results of Biceps Curls are More Widely Applicable

Although the research used biceps curl as an example to show the effect of sonification, this could be extended to a wide range of other physical movement-related programmes. This thesis is being written at a time when many new products are coming into the market to assist in the tracking of physical exercise. Mobile technology is maximising the possibility of using sensor technology portably where exercise is taking place. Sonification can contribute to aid accessibility whilst exercising due to its screen-free characteristic.

10.4.4 Early Training with Sound Improves Long-Term Results

In the final experiment, even though both groups exercised with the two different treatments (in different orders), the group which *started* with sonification had a higher performance than the group which started with no feedback throughout the sessions. On average, the Son-con group performance did not drop much in the later control phase. By contrast the Con-son group showed more defined improvement in the later sonification phase.

10.4.5 Sonification Can be Used Alongside Music

The use of music has been widely applied in both recreational and professional physical training. It has many psychological benefits, including the ability to distract from fatigue, to improve or maintain motivation level and to create an effective mind-set (Mohammadzadeh et al., 2008). Ideally, if the sonification can inherit these advantages *and* also deliver useful information, the result will be a highly effective eyes-free feedback system.

10.4.6 Mappings Should be Designed According to User Type

When designing a real-time sonification system for monitoring human body movement, there are a few important considerations to make, which could affect the mapping decision. The first is to identify the target population. In this research, we targeted healthy adults who are neither professional athletes nor therapeutic patients, which distinguished this research from previous work. The key difference between these three groups is that the motivation in healthy subjects is usually lower as they do not feel the urgency to improve the quality of physical exercise. Hence, in the sonification design, we need to pay more attention to the user's experience, enjoyment, and sound aesthetics. In the experiments, the movement range did not improve significantly from the use of sonification. However, the participants who experienced the sonification thought that the sound did in fact represent the movement change directly. These results teach us that presenting the raw representation of the input data is not always the best way of conveying information. Non-specialist users might not have the expertise to understand the feedback. It will be easier and more straightforward for the user to receive processed (analysed) data instead. For example, instead of giving the direct pitch mapping to the position of the hand, we could calculate the movement range and only send out an alarm signal if the range is not large enough. Therefore, the original raw information will be turned into a more concise message that is more easily understood by the user.

10.5 Limitations

This research does have some limitations. This section discusses the limitations in terms of the system design and the experiments.

10.5.1 System Limitations

The Kinect device is capable of sending out coordinates of multiple body joints in real time. It is very accurate and the open-source tracking programme Synapse can output the coordinate in open sound control (OSC) format, which makes the system development much easier. At the time of development, we considered sonifying various body parts for different types of training.

Therefore, the Kinect was an appropriate option for the sake of this research approach. However, the use of Kinect limits the portability, in that the user needs to face towards the camera in a room with a suitable size to ensure tracking quality. Kinect also requires a computer to function, which also limits the portability. For system improvement, accelerometers can replace the Kinect in the future. The use of EMG with a small accelerometer could greatly improve the portability of the device. This could also be used to track the velocity of movement in order to help the user to exercise at a defined speed.

From the sound preference rating and comments from the experiments, we conclude that the aesthetics of the sound are still not good enough. Providing multiple sound modes can partially improve this issue. Even so, we still note that the current sound designs have some weak points. Improvement should be made for the MIDI note mode to make it generate more melodic patterns. Currently, the probability matrices do not generate particularly pleasing melodies. A possible way of improving this would be to analyse the note progress probability from some famous songs and use this to feed the probability table. This approach used generative music design. Another improvement required is in the ambient sound, which had the lowest preference in the pilot study, and nobody used it in the second experiment. The mapping of this sound needs to be enhanced to include more sonic variation.

10.5.2 Experiment Limitations

In the second experiment, there was no baseline session (session 0) for all participants to compare the initial differences between two groups without using any auditory feedback. Without that, it is hard to justify whether the sonification group had a better performance from the beginning, or it was due to participants' physical differences. With a session 0 (baseline session), the participants could be evenly assigned to two treatment groups to achieve a more balanced initial performance. In such a case, we could argue more effectively that any difference between the two groups' performances was due to the use of sonification. The final experiment (crossover trial) eliminated the individual physical differences, and the findings from that experiment are similar to the second experiment. Therefore, we can still rely on the results from the second experiment.

There is an inconsistency in the survey question design. In the pilot study, the survey questions scaled between 1 and 5. However, this was considered to be too general. Therefore, the survey questions in the final experiment were adjusted to a scale between 1 and 10.

In the survey of the final experiment, there are some questions which turned out to be redundant, and which were not very useful for testing the hypothesis. Also, some of the questions could be considered as too subjective.

Perhaps the way of asking the participants to choose the weight of the dumbbell was too subjective. The original idea was that the dumbbell weight needed to be relatively challenging. Yet because the participants had full control of the decision, it was possible that some participants decided to make the sessions a little easier by choosing a lighter weight compared to their ability.

Another limitation is that the EMG data was only used for mapping (data to sound) but not for the analysis. This was due to two factors. Firstly, the EMG sensor available at the time and within budget was not designed for medical use, and therefore the precision was not up to analytical standard. Secondly, at the testing stage we realised the some people generated a very small range of EMG signal level even though they were relatively strong. This was perhaps mostly due to the body fat that affected the reading of the signal, and which caused the problem that some people could achieve a full mapping range from the EMG whereas others could only achieve a very small range.

Yet the design idea was to let the user hear the variation in muscular activity during contractions rather than know exactly the value of the EMG signal. Therefore, the EMG signal was normalised to a fixed range based on a particular user's own maximal voluntary contraction. By doing so, we could ensure that every user could achieve a full range of sound parameter mapping between muscle resting stage and full power contraction. As a result, the normalised EMG could not be used for analysis.

10.6 Further Work

This section discusses potential further work from short-term and long-term perspectives. The short-term work considers actions that can be taken subsequently after this doctoral period, whereas the long-term work more concerns the researcher's vision and the potential of real-time sonification.

10.6.1 Short-term Continuation

Firstly, as discussed in the previous section, the sonification system could be further improved by replacing the Kinect camera with an accelerometer sensor to deduce movement velocity. In combination with the EMG sensor, these two small size portable sensors would form a wearable device, such as a sonification arm-band. Data transmission could still be achieved wirelessly. Another possibility is to use a new muscle activity measurement kit called

MYO by Thalmic Labs[1]. At the time of writing this thesis, the MYO armband (Fig 10.1) was newly released. It facilitates an array of EMG sensors to recognise gestures (arm, hand, etc.) with high precision. This product, along with its development kit, could be used to improve both the quality and usability of our current EMG sensor set-up.

Figure 10.1: MYO armband, a gesture control device developed by Thalmic Labs.

The next step to further develop the system is to introduce the concept of gamification in order to improve user experience. Gamification is the introduction of video game elements to non-gaming contexts (Deterding et al., 2011). The sonification described in this thesis has turned the exercise into a type of human-computer interaction, where the user does biceps curl to generate different patterns of sound. It would become even more interesting and rewarding to introduce a scoring system, such as that which commonly exists in video games. The scoring system could record the exercise results and output a dedicated score of the exercise session. This could encourage the user to aim for a higher score than the previous exercise.

The current experimental set-up compared the quality of biceps curl

[1]https://www.thalmic.com/en/myo/

with and without sonification feedback. Yet visualisation is a very common approach for displaying information. Hence, a continuation of the research could investigate the difference in exercise quality between sonification and visualisation. Instead of trying to understand the difference in movement precision, such as (Matsubara et al., 2013), this new experiment would focus on studying the variance of user experience. This is an important research goal because for a general user, it is perhaps more useful and practical for a sonification system to be interesting and engaging rather than being able to convey precise information. This differentiates it from applications for professional athletes and therapeutic patients where accurate information can sometimes be more desirable than the listening experience.

10.6.2 Long-term Implications

Sonification Framework

In long-term, we hope to contribute to a sonification framework for movement-based information portrayal. Such a framework could benefit developers who are interested in this field. The framework should provide predefined mapping schemes that can be quickly used to link the movement information and sonic parameters together. To be able to do this, we would need to study comprehensively what movement information is essential for exercise quality enhancement. At the same time, we also need to investigate what is the optimal sonic feedback.

Smartphone Application

One of the key advantages of an auditory display is that it does not require a screen, thus freeing up a user's visual attention. This is hugely beneficial in physical exercises where the user's attention is focused elsewhere, such as outdoor sports activity) where the eyes are fully engaged on the motor tasks being carried out). There is also a key requirement for portability in such situations. Smartphones are excellent platforms for developing movement-based sonification. A smartphone is usually equipped with certain sensors, such as accelerometer, and it works with many external sensory devices. In the not-too-distant future, this sonification system has the potential to be migrated to a smartphone platform as an application, using the phone's internal sensors or an external sensor device (such as MYO) to extract movement information. The application will contain a synthesis engine to generate real-time sonic output. Moreover, because smartphones are ubiquitous devices nowadays, and almost a necessity for most people, such a sonification mobile phone application could reach many potential users to help them exercise at a high-quality standard.

Smart Tool Development - Sonic Dumbbell

Nowadays, sensor technology is integrating into every corner of daily life. There are more and more popular new words with the prefix 'smart-', such as smartphone, smart watch, smart car, smart lamp and so on. For a device to become smart, it usually contains an important characteristic: it is *interactive*. For closed-loop interaction to occur, a device needs to be able to measure input data, then output the processed data in one or many forms: sound, visual display, haptic and so on.

An example to extend the work in this project is the *Sonic Dumbbell*. This would investigate the integration of the sonification system into the apparatus itself, in this case the dumbbell. The sonic dumbbell could incorporate the use of one or several accelerometers to detect the acceleration and velocity of the exercise movement. The user could then select to a particular type of training (e.g., explosive, slow, ultra slow), and the device provides sonic guidance appropriate to the pacing of the movement. In terms of the sound feedback, a simple approach can be applied considering the hardware limitation (needs to be small enough to be installed on the dumbbell). The sound can be a beeping metronome or a periodic pitch pattern. The real-time feedback is then mapped by the pacing of the repetition movement, then if the pacing matches the predefined speed a notification sound will be given (or inversely a warning is given if the pacing is far off).

The sonic dumbbell is merely one of several potential opportunities for smart tool developments, which incorporates the use of real-time auditory feedback. The use of sonic feedback can be applied to many other aspects not just for physical exercise.

Interdisciplinary Collaboration

This sonification project itself involves many disciplines, such as electronic engineering, auditory display, human-computer interaction (HCI) and sports science. We hope to see collaborations from a range of experts get involved in this field and take human body movement sonification to the next level. This could involve people such as artists, sports scientists, computer programmers and engineers.

10.7 Thesis Summary

In the research, the effect of real-time sonification of subject's physical exercise was examined. A novel approach was proposed of using a combination of muscular activity and kinematics as inputs to generate four different types of sonic output for the subject to listen to while doing biceps curls. Software and hardware developments have both been accomplished in order to create the sonic feedback (Chapter 6).

The use of sound to portray exercise information is a relative new field. In order to examine the effect, three experiments were conducted, including a user experience test, between-subjects and within-subjects comparative experiments. Details of the experiments and their results are presented in Chapters 7 to 9. Overall, we found that sonification can effectively portray a subject's physical movement and muscular activity during the exercise. Each sound mode has its own strengths and weaknesses, partially dependent on each user's preference. The main comparative experiments show that sonification has a statistically significant effect on reminding the participants to exercise at a slower pace. However, there was no significant result to show that the sonification improved the movement range. Participants found using the sonification more interesting, which led to a higher total effort expended, indicating by more repetitions or an increase in dumbbell weight. In summary, most of the results support the research hypothesis. The limitations are presented in Section 10.5.

Interactive sonification not only provides information about the input sources, but also creates a new and interesting way of interacting with the data from the user experience point of view. With the dawning new age of wearable devices and the current technological focus on fitness and health, an exciting period is just ahead. This project has the potential to contribute to the field of fitness assistive devices and thus to encourage more people to do regular physical exercise to a relatively good standard.

Appendices

Appendix A - Publication of Pilot Study Results

SONIC TRAINER: REAL-TIME SONIFICATION OF MUSCULAR ACTIVITY AND LIMB POSITIONS IN GENERAL PHYSICAL EXERCISE

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ABSTRACT

The research outlined in this paper uses real-time sonic feedback to help improve the effectiveness of a user's general physical training. It involves the development of a device to provide sonified feedback of a user's kinesiological and muscular state while undertaking a series of exercises. Customised sonification software is written in Max/MSP to deal with data management and the sonification process with four types of sound feedback available for the participants.

In the pilot study, 9 people used the sonification device in a 'biceps curl' exercise routine. Four different sonification methods were tested on the participants over two sessions. Clear improvement of the movement quality was observed in the second session as participants tended to slow down their movements in order to avoid a noise alert. No obvious improvement in the physical range of movement was found between these two sessions. The participants were interviewed about their experience. The results show that most participants found the produced sounds to be informative and interesting. Yet there is room for improvement mainly regarding the sound aesthetic.

This study shows the potential of using real-time interactive sonification to improve the quality of resistance training by providing useful cues about movement dynamic and velocity. Suitable sonification algorithms could help to improve training motivation and ease the sensation of fatigue.

1. INTRODUCTION

The movement of the human body often produces acoustic energy. We can gain information about that movement by perceiving motion-related sounds. For instance, the loudness of a badminton racket swing can reflect the strength and speed of the swing.

Effenberg describes the relationships between music and sport as 'interwoven' [1]. Music is an essential part of many rhythm-driven sports, such as figure skating and synchronized swimming, both for aesthetic and informative reasons. Also, many people like to listen to music while doing physical exercise. Apart from simply enjoying some favourite music the sound itself provides useful cues for maintaining good rhythmic motor coordination and relaxation, and it can also lead to a positive mood and a raising of confidence and motivation [2, 3, 4].

Computer technologies have traditionally used visual displays, and so data analysis has been carried out with graphical techniques. The relatively recent development and study of auditory display techniques, conveying information through the use of sound objectively [5], provides us with new opportunities for analysing data and feeding back information to human users.

There are many advantages to using sound to study and interact with data. Firstly, sound allows a screen-free scenario which enables users to focus more on their main physical task. For instance, an auditory monitoring system can help anaesthetists to improve their working efficiency during an operation, as it reduces the mental workload of having to focus on visual monitors while carrying out many other responsibilities [6].

Secondly, sound shows its superiority in attracting people's attention. A visual alert may be easily neglected if a person's visual attention is focused elsewhere. However, sound is highly suitable for alarm systems because not only can it attract people's attention while they are looking elsewhere, but the sound itself can carry extra implicit information, e.g., "this is a fire alarm; leave now" [7].

In the domain of general physical exercise, such as free weight training, there is a common problem that many people tend to focus more on quantity rather than quality. People in a gym are likely to carry out a certain number of repetitions without as much regard for the smoothness of the movement or the way that sets of muscles are activated. This problem is compounded when exercising at home, because of the absence of professional trainers. Although this may not seem much of a problem to general public, it becomes immensely important for patients who require physiotherapy treatment following an accident or operation.

This paper considers how we can help people to improve the quality of their physical exercise by introducing auditory feedback to their exercise routines. The research has potential applications in daily physical exercise, elite sport or physical rehabilitation. Artificial auditory signals can be generated based on the user's real-time movement, using computer technology to play the role of a virtual trainer, by guiding the movement and potentially leading to an improvement of the exercise. Hence, we present a sonification system that provides real-time auditory feedback of a user's exercising movement as a tool aiming to help improve the quality of the training.

In this pilot study, the main aim was to investigate subjects' experiences in four different sonification modes, and test how these four modes of sonification influence the exercise quality across two identical sessions. As such it did not include a control group, but a control-based comparison experiment will be conducted in the future research as explained later in this paper.

The structure of this paper is as follows: Section 2 demonstrates the concept of interactive sonification referring to literature about sonifying human body movement. Sections 3 and 4 present an overview of the sonification system we have developed, with the usage demonstrated in Section 5. Section 6 contains the procedure, results and implications of a pilot study. Finally Section 7 discusses further work and potential extension of the work done so far.

2. SONIFICATION OF HUMAN BODY MOVEMENT

Sonification is a subset of the area of auditory display. It is defined as the interpretation and transformation of data into perceivable non-speech acoustic signals for the use of conveying information [8]. Interactive sonification serves an additional purpose which allows the manipulation of data based on the sonified feedback. In this research, we hypothesise that sonic feedback can serve as a real-time training quality monitor and motivator to help maintain a good quality of exercise.

The research concept is concerned with whether we can expand the richness of naturally occurring acoustic cues by producing artificial sonic feedback to give extra information about the quality of the exercise to the user, in order that they can make appropriate adjustment in response.

Vogt et al. [9] developed PhysioSonic in 2009, using a camera tracking system with markers placed on a user to study shoulder movement and provide both metaphorical and musical audio feedback. The system motivated patients with arm abduction and adduction problems via the synthesised or sampled feedback. Kleiman-Weiner and Berger [10] developed an approach to sonify the motion of the arm to improve the action of a golfer's swing. Barrass et. al. [11] studied how different sonification methods performed in outdoor jogging. Other researches on the sonification of human body movement can be found in [1, 14, 15, 12].

Two types of bio-information were sonified in this study. Firstly, the visible kinetic aspects of the movement were captured using a Microsoft Kinect system. Such visible motion reflects the most straightforward impression of movement quality, such as displacement, dynamics and speed. There are also hidden attributes such as strength, which is harder to observe visually. Strength, effort and tension are generated from within the muscles and therefore this requires a more direct and dedicated muscle measurement system, for which we use an electromyography (EMG) sensor.

When a muscle is activated, muscle cells produce electrical potential. The resultant electrical signal can be detected by EMG sensors. EMG is widely used in the study of postural tasks, functional movements and training regimes [13]. Pauletto and Hunt sonified EMG data from leg muscles in 2006 [14]. They developed an alternative way of portraying the data from EMG sensors using sonification instead of a visual display. EMG sonification can also be seen in [15], where muscular activity of a timpani player's performance was sonified.

The following section explains the construction of the sonification device, which is capable of extracting both kinetic and muscular data in real time. A diagrammatic overview of the system is shown in figure 1.

3. SONIFICATION SYSTEM - HARDWARE

Two types of sensory devices are used to capture arm movement and muscular activity separately. The first is a Microsoft Kinect sensor (fig. 2) to capture real-time limb movement in a format of 2D coordinates (left-right, up-down) related to the centre of mass. The frame rate is 30fps. Extrapolated from the basic coordinates, we also calculate the vertical component of the velocity, which is a key indicator for the biceps curl exercise quality.

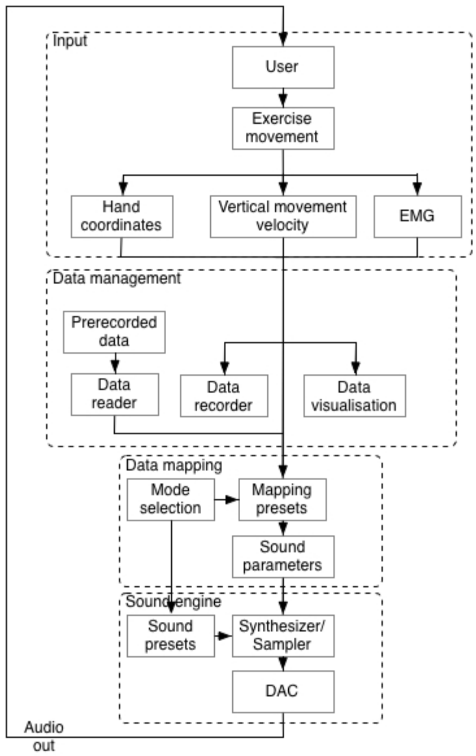

Figure 1: *Physical exercise sonification system*

To measure the muscular activity, a wearable EMG belt shown in fig. 3 was designed to manage the myoelectric signal acquisition and wireless transmission to the computer. This belt comprises an EMG sensor unit[1] powered by two 9v batteries, an Arduino Duemilanove microprocessor (9600 baud) and a Bluetooth modem.

4. SONIFICATION SYSTEM - SOFTWARE

The sonification software (fig.4) was developed using Max/MSP[2]. It consists of three main functions, described in the following paragraphs.

4.1. Data management

The data management section handles EMG data and Kinect data acquisition through serial communication (sampling rate 500Hz) and the Open Sound Control (OSC)[3] protocol. The EMG device introduces a baseline offset of approximately 0.170.03v (signal ranges between 0 to 5v). Hence, baseline adjustment was used to remove the offset. In order to give participants a more obvious alteration in sound between muscle rest state and contraction state, EMG normalisation was also used to ensure all users benefitted from the full range of data mapping. A data recorder was

[1] http://www.advancertechnologies.com/
[2] http://cycling74.com/
[3] http://opensoundcontrol.org/

Figure 2: Kinect motion capture camera

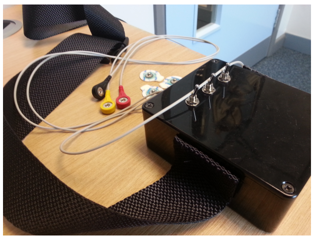

Figure 3: EMG sensory belt

used to store all the bio-information into a text file. Hence, bio-information can be sonified or studied either in real time or offline. In addition, plots of the Kinect and EMG data are shown graphically. Kinect data - in the form of the positions of body joints - is presented through several knobs (for display only) shown on the right side of fig.4. The Kinect data acquisition allows a total display of up to 15 body joints, however only a few were numerically displayed in real time to make the display more compact. The EMG data can be monitored through the oscilloscope on the left side

4.2. Sound engine

The sound engine is designed separately and is linked with the main interface through the data mapping patch, (explained in 4.3). Hence, it is not graphically displayed on the main interface while the system is in use. The sound engine consists of a subtractive synthesizer and an audio sampler. Theoretically, every parameter in the sound engine can be controlled by the movement data. However, in practice, only a few parameters have been chosen for the control (based on some initial tests) in order to produce the most distinguishable acoustic results. These parameters are: loudness, pitch, filter cut-off frequency (brightness), sample playback speed and noise level.

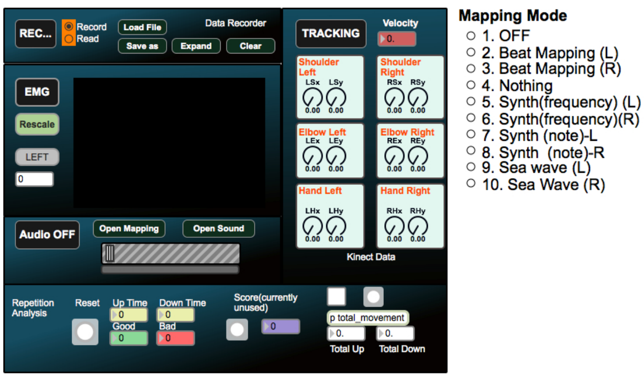

Figure 4: *Main interface of the sonification software*

For the sound design, we customised four sonification mapping schemes for the pilot test with different acoustic textures and responses. These four schemes are selectable by the user. The assumption was that the majority of intended users would not have a background in audio synthesis or programming, so a selection from pre-sets was the best way of presenting a choice.

- Linear Frequency Synthesis Sound Mode
  In this mode, the synthesiser is set to produce a sound with rich spectral content. It consists of a combination of triangular and square waves. In terms of the mapping, the current vertical position (low to high) of the hand is mapped to a linear scale of frequency (valid frequency: 20 to 570Hz). The velocity of movement is set to trigger a white noise sound when it exceeds a threshold value, which notifies the user of movement that is too fast. The use of noise for this notification helps to distinguish the 'speeding' indication sound from the main sonic feedback. To avoid annoyance, if the noise sound occurs too frequently due to bad quality of movement, the white noise is softened by using a band-pass filter and an amplitude envelope with a slow attack time.
  The EMG signal is mapped to the cut-off frequency of a band-pass filter. This mapping allows the EMG data to affect the brightness of the sound. Larger EMG values (indicating more muscle power) lead to a brighter and clearer tonal quality.
- 'MIDI Note' Synthesis Sound Mode
  The same timbre and mapping scheme are used as the previous mode. Yet instead of playing the sound with a linear pitch change, the full vertical range of arm movement is divided into 10 sections. Each section plays a note on the synthesiser which is quantised in pitch to an equal temperament scale in the range of C4 to E5 with fixed velocity and length. To avoid boredom for the listener, the note selection is not fixed, but based on two customised first order Markov chain probability tables. This means that the current note is selected based on the previous note. Considering each note as a state, each state will generate one of only a few other states. For example, when the current state is C4, the next state has a 45% chance to be D4, 25% chance to be E4, 10% to remain the same note and 20% chance to be E4. Therefore, tonally, this will result in a similar (but different) progression of notes in each set of movement. Different melodic patterns are played according to the direction of the arm movement. Contraction of the biceps results in an ascending melody while extension produces a descending pattern. The melody is different each time because of the probability tables.
- Rhythmic Sound Mode
  This mode emits a rhythmic arpeggiator loop when the user starts moving the forearm to a certain height. Then the loop will keep playing along with the movement until the user's forearm is back at the original height level again, indicating the completion of a repetition. The purpose is to help the user scale the timing of a full repetition to match the full length of the musical loop. The white noise sound is again used as an indication of moving too fast.
- Ambient Sound Mode
  Similar to the rhythmic mode, this triggers a sample of sea waves instead. It aims to create a relaxing sensation for the user rather than giving precise information on the movement. Because of the richness in the spectrum of the sound, playing a noise as a warning for moving too fast becomes hardly audible as it is masked by the ambient sound. Therefore, the noise was replaced by a sine wave beep.

Audio examples can be downloaded, see section 8.

There are two main reasons for providing multiple types of sound for the same movement set. 1) People have different personal preference for sounds. Therefore, consideration needs to be given about how to provide sonic options for each user. 2) Each mode type has its own emphasis in terms of providing sonic feedback. The linear frequency can represent the most straightforward vertical displacement of the hand. The MIDI mode focuses more on reminding users to slow down their movements, in order to generate a measured progression of a melodic pattern. The rhythmic mode aims to improve the steadiness of the movement, whilst the ambient mode aims to help users to relax.

Audio examples can be downloaded in the footnote below [4].

4.3. Data mapping

The final major functionality is the mapping patch, which links the bio-information from the data management section with various sound parameters from the sound engine such as pitch, filter cut-off frequency, volume, etc. Parameter mapping [5, 8] is used as the main mapping method. The EMG data and Kinect data are scaled appropriately in the patch in order to result in the correct range of values to control the sound parameters.

5. HOW TO USE THE SYSTEM

The user wears the EMG belt and has electrodes placed on the skin surface directly over the dedicated muscle, in this case the biceps. Technical details of the electrode placement are not included in this paper; for more information, please refer to [13]. The user also stands in front of the Kinect sensor, facing towards it. When the device is activated the user can hear sounds being generated according to their arm movement.

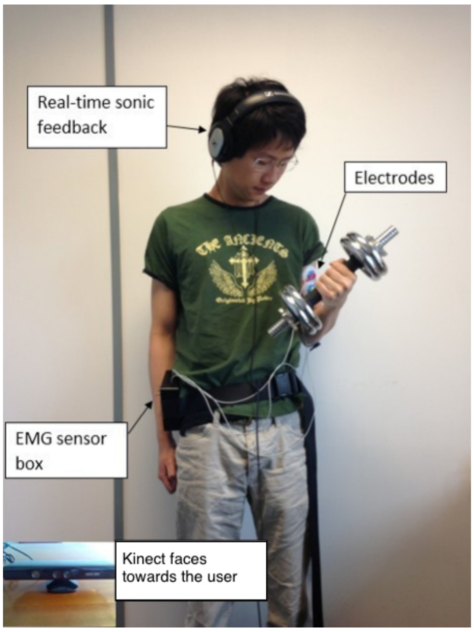

Figure 5: *Demonstration of using the device*

[4]https://sites.google.com/a/york.ac.uk/jiajun/shared-files

This paragraph describes a set of benchmark data recorded from a regular gym trainer. As shown on fig.6, the position changed smoothly and slowly (approximately 8 seconds per repetition). Within each repetition, in muscle contraction, the EMG signal rose slowly and peaked at roughly the highest vertical position. Then in muscle extension, there is another small EMG peak indicating the subject tried to prevent the dumbbell from lowering too fast.

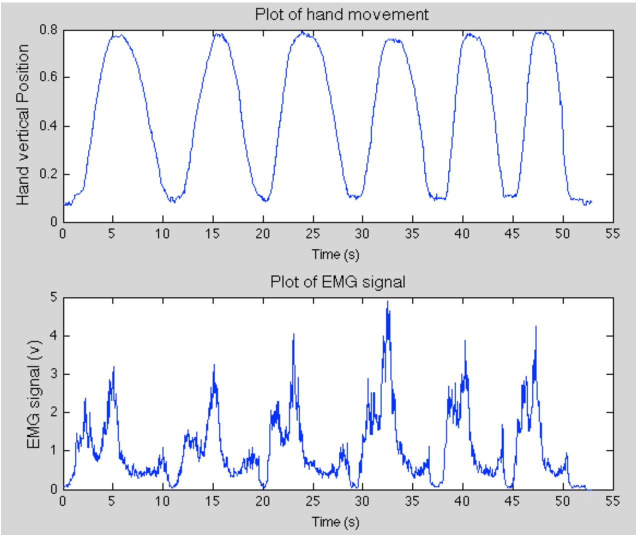

Figure 6: *Hand vertical position and EMG signal of a set of good quality movement (benchmark)*

6. PILOT STUDY AND DISCUSSION

6.1. Overview

The purpose of the pilot study was to examine the use of the device and to gather user experience and suggestions. We also gained an initial impression on how this sonification system can influence the user's body movement during biceps curls by interviewing participants after their exercise sessions.

Nine participants (all male, mean age 25.8 ± 3.0)were recruited to participate in a test made up of two sessions. In each session, participants were asked to do four sets of dumbbell curls with one of the four sonification modes played in each set. Participants were told to listen to the sonic feedback and try to respond to the sound while exercising. Each participant experienced all four sonification modes and therefore we could study their relative experience of each via a post-session interview. Their Kinect and EMG data were both recorded for offline sonification study and analysis purposes.

We defined a good quality of exercise as consisting of the following two criteria: 1. The maximum dynamic range of movement possible, which means that the forearm should aim to reach the lowest and highest positions while the upper part of the arm remains still. 2. The concentric and eccentric contractions should be executed at a steady and relatively slow speed, with a total of 4 to 8 seconds per repetition. This has been shown to help improve blood flow which can lead to a better training results [16].

6.2. First Session

At the beginning of the session, a copy of the consent form was given to the participant to sign and the purpose and procedures of the test were clearly explained. An adjustable dumbbell was prepared and the participant could adjust the weight by adding or removing plates to the two sides of the dumbbell.

The participant was then fitted with the EMG device and positioned to stand in front of the Kinect sensor. A set of Sennheiser HD 201 headphones was provided for the participant to listen to the sonification. Prior to the session, a trial was conducted to give the participant some familiarity with the exercise and the resultant sound.

During the test, participants did several sets of exercises, each with a different sound mapping. The repetition quantity in each set was entirely up to the participant to decide upon, based on their own motivation and physical condition. 1-2 minutes rest was given between each set. After the session, a copy of the questionnaire was given to the participant and they were asked to rate each sonification mode in terms of its comprehensibility and preference from an integral scale between 1 to 5 (very poor, poor, moderate, good, excellent). Each participant was also asked to comment on the experience of using the device with each mode. Comments were recorded either orally at the session or in written form.

6.3. Second Session

In the second session, participants were asked to complete the same four sets of biceps curls with the same sonification modes. After the session, participants again rated the four sonification modes. The reason for conducting an identical second session is because, at the first session, a participant may have been unfamiliar with the whole process and found the sounds strange to listen to. Therefore, we looked for any difference in both the exercising quality and subjective opinions of the sonification, after they became more familiar with the sound and system.

6.4. Quantitative Results

Figure 7 shows the plots of both EMG signal strength and the hand's y coordinate (dumbbell height) during a set of repetitions using the linear frequency mode. The EMG data was normalised (0 to 1.0) so that it could be viewed more easily together with the y coordinate. Peaks in the EMG signal can be seen to be occurring during vertical lifting, which is what would be expected, but also in the lowest part of the movement, where the dumbbell is being decelerated.

Figure 8 represents the velocity progression of the same set of repetitions as the previous graph. We defined a velocity threshold of $v_t = \pm 0.78$ whereby the white noise would be sounded if the absolute velocity $|v|$ was greater than v_t.

The mean movement dynamic range and mean repetition time gathered from the participants' two-sessions of exercise were analysed. We had hypothesised that an improvement of mean dynamic range and repetition time would be found in the second session as participants gained familiarity with the system.

In terms of the mean dynamic range, such improvement could not be statistically supported (table 1). A paired-samples T test shows a significance level with $p = 0.191$ and a low correlation of 0.138. However the table demonstrates that for several participants there was indeed an improvement from the first session to the second.

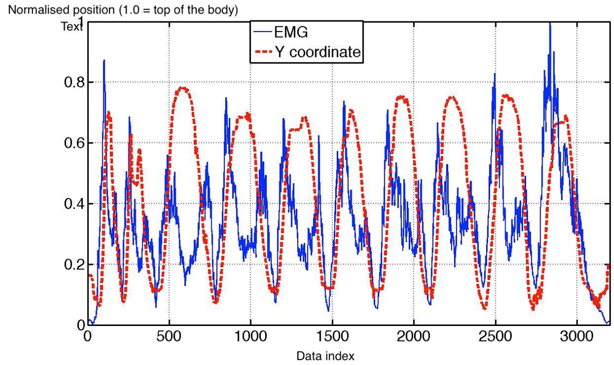

Figure 7: *EMG and dumbbell height plotted together*

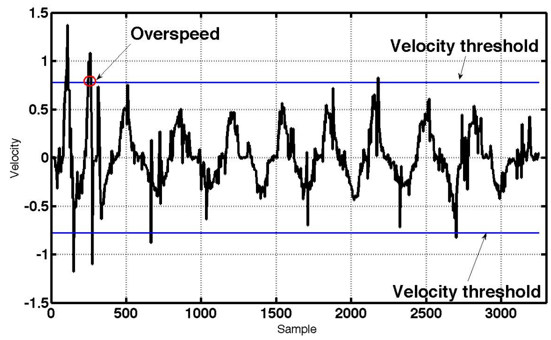

Figure 8: *Changes of hand velocity throughout a whole set of movements using the linear frequency mode.*

The same test was conducted to study for the mean repetition time. The result shows a significance level with $p = 0.003$, and an average increase in the repetition time of 1.58 second.

The different extents of improvement can be seen from table 2. Slower movements were executed in the second sessions for all participants, (remembering that in curls, a slow and steady movement is desired as opposed to a fast and spiky movement). During the second session, no extra instructions were given to the participants. Therefore we did not purposely introduce factors that may have led to a change of curl velocity. Two participants (No.2 and No.5) made the least improvement on average time per repetition with only 3% and 5% increment respectively. Yet the mean repetition time of participant 5 already lies in the high standard range. A greater amount of improvement was achieved by the other participants.

6.5. Qualitative Results

The questionnaire collected subjective opinions of participants' experience. Participants rated each mode in terms of the comprehensibility and preference from a scale of 1 to 5, where 1 means 'highly disliked' and 5 means 'highly favoured'. The results show a moderate overall rating (across all four modes) in comprehensibility and preference with 3.71 and 3.41 out 5 respectively. As shown in table 3, on average, participants found that the linear frequency mode delivered a better sonic representation of the curl

Table 1: Mean Dynamic per Repetition

Participant	1st Session	2nd Session	Differences
1	1.247	1.653	+33%
2	1.569	1.450	-8%
3	1.235	1.693	+37%
4	1.586	1.531	-3%
5	1.558	1.480	-5%
6	1.512	1.524	+1%
7	1.399	1.539	+10%
8	1.650	1.791	+9%
9	1.265	1.255	-1%

Table 2: Average Time per Repetition (unit: second)

Participant	1st Session	2nd Session	Differences
1	3.23	6.85	+121%
2	3.58	3.75	+5%
3	4.26	6.73	+58%
4	5.50	6.99	+27%
5	7.45	7.66	+3%
6	3.11	4.01	+29%
7	4.66	6.24	+34%
8	7.37	9.48	+29%
9	3.78	5.42	+43%

compared to the others. It scored 4.22 on mean comprehensibility with a standard deviation of 1.31. The majority of participants found this mode sufficiently informative and only one participant thought it was confusing. The rhythmic mode seems to be the least informative among all four. This may be caused by the specifics of this mode's mapping; the vertical movement only control the initial activation of the sound – once activated the sound plays independently until the position is back to the initial level (where the arm is in a natural straighten position). The movement does not alter the sound greatly apart from the brightness changes due the change of the EMG data. Therefore, participants generally felt less in control over the sound.

Table 3: Mean rating and standard deviation of four sonifications

	Comprehensibility		Preference	
Mode	Mean	Std	Mean	Std
Linear frequency	4.22	1.31	3.56	1.54
MIDI note	3.56	1.15	3.33	1.24
Rhythmic loop	3.29	1.18	3.67	1.28
Ambient sound	3.78	1.11	3.06	1.43

As shown in figure 9, apart from the rhythmic mode, the upper quartile of each of the other modes is equal to the maximum rating of 5. This is also an indication that using sound to provide movement feedback is effective. Ratings for all four modes range from 'moderate' to 'excellent' and users are able to understand the sonic feedback easily.

The users' preference in sound aesthetic varies more significantly as shown in figure 10. This is also apparent in the subjects' comments. These pinpoint the fact that there is still room for improvement in terms of sound aesthetics.

Based on the interviews, not all participants responded positively to all four modes of the sonification, yet at least one mode is favoured by each participant either from a comprehensibility point of view or by preference. Listed below are summarised comments abstracted from the interviews about participants' experience of each mode. These comments have been re-worded into categories based on their meaning.

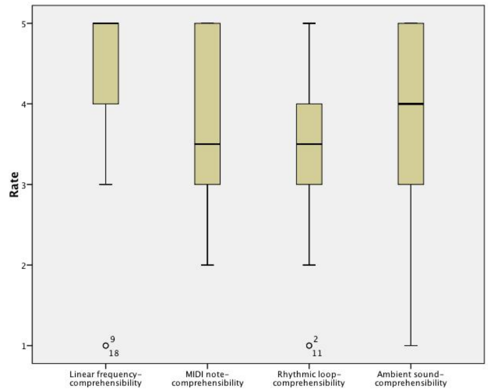

Figure 9: *Comprehensibility rating*

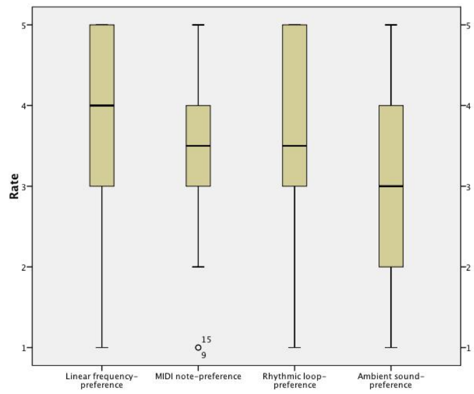

Figure 10: *Preference rating*

1. Linear Frequency Synthesis Sound Mode

> *"It is easy to understand and it functioned clearly; the dynamic representation is very clear."*
>
> *"You can listen to the change of the muscle and it is the most raw presentation."*
>
> *"The noise indication is really useful. In terms of the movement, specific motions are easy to repeat."*
>
> *"Aesthetically not good enough. The sound is noisy."*
>
> *"I like the sound because it is new to me. I slowed down more than I would usually do to prevent hearing the noise."*

Most participants (89%) agreed that this mode gave sufficient information reflecting their exercise. Yet their major concern is the unfamiliarity with the linear synthesis sound and aesthetic preference. 33% report that they did not enjoy listening to this type of sound because they do not regard it as a musical tone.

2. MIDI Note Synthesis Sound Mode

   > *"I don't think it provides as good feedback as the frequency mode."*
   >
   > *"Faster notes seem to indicate worse exercise. But it also creates a big leap if I moved too fast. So I didn't enjoy it that much."*
   >
   > *"The sound was unrepeatable, so the feedback felt a little random."*
   >
   > *"This mode is the most interactive one. I needed to slow down my pace a lot to generate a clear melodic pattern. And the melody is different each time. But it didn't seem to inform me much about the dynamics of my movement."*
   >
   > *"It was difficult to understand."*

   This mode was designed to split the movement range into 10 steps. However, generally, people without much training experience tend to do curls much faster than desired (less than 4 seconds per repetition). This results in a quicker MIDI note change, which leads to less clear melodic progression. One of the participants called it a 'big leap'. Hence, the preference for this mode is inversely related to the movement speed; people who moved slower enjoyed the sound more than people who moved quickly.

3. Rhythmic Sound Mode

   > *"There is a progression I enjoyed listening to. But the loop starts again every time I finished one repetition. I would rather be able to hear the whole melody."*
   >
   > *"I didn't like it because I kept getting the wrong sound. It was distracting. It motivated me though to try to do it right because I hated the wrong sound though."*
   >
   > *"It is a good idea. But at the moment it doesn't help me too much. It would be better if the sound could be changed to my own mp3 files."*
   >
   > *"This one is very interesting. The exercise is periodic, just like most music. So I adjusted my pace to try and fit with the rhythm of the sound."*
   >
   > *"The sound was pleasant to listen to."*

   This mode provides the most musical content compared to the other three. It is interesting that it became the most popular mode in the second session with an average preference rating of 4.0 and a standard deviation of 1.0. It transferred periodic movement into periodic music. Yet it has the problem of being too repetitive, and because of this a few participants suggested making the music selectable from their own music playlist.

4. Ambient Sound Mode

   > *"It has the right balance between information and aesthetic. It was pleasant and natural."*
   >
   > *"Generally it is good but it is too relaxing and makes it harder for me to concentrate."*
   >
   > *"Comprehensible; the louder and more intense the sound means more muscle strength."*
   >
   > *"It is quite random." "I felt less control over the sound." "Not enough feedback."*
   >
   > *"It is special and immersive." "It is relatively easy to recognise."*

   Currently this mode has the lowest ratings in preference from both sessions, and received the most negative comments (56% of negative opinions). Despite ranking second in mean comprehensibility for both test sessions, interviews still showed that people thought they had less control over the sound. Only one participant showed support for this mode. The positive response reflects the purpose of this mode for creating a relaxing sonic atmosphere. Yet having such a low popularity clearly indicates that this mode either requires a major improvement or faces removal in the planed future tests.

6.6. Discussion

The results from the pilot study indicate that a novel approach of providing real-time sonic feedback of biceps curl exercises can produce useful cues to the user and can influence the quality of the exercise. Comparing the results in dynamic range and repetition time between two sessions, we did not observe a significant result in the change of movement dynamic range. However, a significant increase in repetition time was achieved. Overall, subjectively, most participants found the device useful for maintaining a good pace of movement, and good for reducing the sensation of fatigue. Yet there are concerns over the listening experience, which is mainly due to personal preference of the sounds.

Our initial plan was to provide four types of sonification so that there were several choices to accommodate the issue of personal music preference. The rating of the questionnaire supports this concept as all participants have at least one preferred sound that they found both informative and enjoyable. However, further development of the sound design is essential to provide a better listening experience. It is also suggested that improvement is required of the sonification mapping for a clearer indication of the dynamics of the arm movement.

We believe that the sonification device has great potential to improve the quality of general exercise. However, due to the design of the pilot study, we focused more on the user experience in order to help us improve the system for a future test. This study did not include a control group to provide comparative statistical evidence to support the hypothesis. Therefore, a thorough hypothesis test will be conducted in the near future including both latitudinal and longitudinal experiments to compare the exercise results between a group of participants with the sonification feedback and a group without. In addition, the subsequent experiment will also study on the influence of fatigue and whether the sonification feedback has a positive or negative effect when user is feeling tired.

7. FURTHER WORK AND CONCLUSION

We are developing a game-based difficulty system that introduces a "hi-score" concept to motivate the user do to better each time they use the device. We aim to provide more tasks to further professionalise the user's movement through sonic feedback, and to further optimise the sound design.

In the subsequent hypothesis test, a latitudinal experiment and longitudinal experiment will be conducted. These two tests aim to discover and track the differences in exercising quality between participants who use the real-time sonification feedback and a control group who do the same exercise but without audio feedback. We will be looking into factors such as movement dynamic and velocity, repetition, EMG patterns, and subjective comments. Appropriate statistical methods such as student's T test and Pearson's chi-squared test will be used for comparative analytical purposes.

One of the possible extensions of the project to the area of **physiotherapy** is to use the sonification device in rehabilitation training. In this context sonified bio-feedback could be used to correct the patient's prescribed exercise. This has the potential of accelerating the recovery process from conditions such as strokes, which often requires a sustained level of rehabilitation exercises. Such a device could be used at home so that patients can receive feedback without the constant presence of a physiotherapist.

Another prospect is to migrate the sonification device to a **smartphone external device** or watch-based wearable computer with a suitable software application. This would offer better accessibility to users and allow more possibilities of getting feedback for outdoor exercise.

8. RESOURCES

The software and audio examples can be downloaded from the following link:

https://sites.google.com/a/york.ac.uk/jiajun/shared-files

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Appendix B - Publication of Between-Subject Comparative Test Results

REAL-TIME AUDITORY FEEDBACK OF ARM MOVEMENT AND EMG IN BICEPS CURL TRAINING TO ENHANCE THE QUALITY

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ABSTRACT

In this paper, we describe the design of a sonification device using an electromyography (EMG) sensor and Mircosoft Kinect motion tracking camera to extract muscular and kinematic data while undertaking biceps curl exercise. A software platform has been developed using Max/MSP to convert acquired data into sonic feedback.

The system has been tested in a comparative user trial, with 22 participants being split into two groups. One group had the auditory feedback and the other did not. All participants completed a 3-session experiment on different days. We investigated whether the extra sonic feedback provides positive influence on both the exercise quality and training outcome.

Three parameters were analysed: movement speed, range of movement and total repetition effort. The results indicate that the sonification group performed consistently better than the other group except the movement range, which shows no improvement in both groups. They also indicate that sonification contributed the most to keeping a good steady pace of movement. Subjects in the sonification group also gave positive comments on the presence of sound, especially about distracting them from feeling fatigue.

This study underlines the potential of developing sonic interaction programmes for both general exercise and physiotherapy.

1. INTRODUCTION

In recent years, we have been seeing an increase in the variety of ways for presenting and interacting with computer data. This trend is seen in the increasing popularity of mobile computing devices and the newly introduced wearable devices. Companies such as Apple, Samsung, Nike, Microsoft have released fitness products incorporating body sensory devices. Still more products are under development and we assume that a new age of wearable devices is imminent.

Researchers have noticed a strong connection between the use of sound and the quality and extent of human body movement [1]. The most commonly used example is the use of music to assist rhythmically critical actions such as figure skating, dancing, etc. Sonification, serving as a method to objectively convey and interact with data through the use of sound [2, 3], has some advantages when used in assisting sport activities. Firstly, sound allows a screen-free situation, which enables users to focus more on their intended physical task, such as rowing [4] and jogging [5].

Secondly, music or sound can provide useful information for maintaining good rhythmic motor coordination and relaxation, and can lead to a positive mood and a raising of confidence and motivation [6]. In [7], researchers found the volume and tempo of music had effects on running speed, heart rate, and exercising arousal levels under a treadmill running condition.

Thirdly, sound is more attention grabbing than visual alerts when it comes to notification. This makes it superior in alarm situations [8]. In the same way, sound can be useful in improving sports movement that by notifying users if any changes needed to be made.

The structure of this paper is as follows: Section 2 gives an overview of the research hypothesis. Section 3 provides a description of the sonification system we developed. In Section 4, full details of the experiment are presented with the results and analysis. Section 5 covers the analysis of subjects' comments. Sections 6 & 7 draw conclusions and discuss the next stage of the research and its prospective as a commercial product in the future.

2. RESEARCH OVERVIEW

In this study, we hypothesized that by listening to real-time auditory feedback of healthy adult's muscle activity (during biceps curls) along with kinesiological data, subjects will have better exercise performance and progress than those who do the same exercise without real-time audio feedback.

We envisaged that sonification could serve as a virtual training supervisor that provides instant feedback on the movement itself as well as notification sounds to correct any movement deficiencies.

The criteria of the sonification are:

- Reflective: The sonification should directly reflect the movement being performed.
- Suggestive: The sound should be capable of reminding the user about the quality of the exercise. It should also suggest where the user could make changes if necessary.
- Listening experience: the sound also should be interesting to listen to or at least have sufficient variation to prevent boredom.

3. SYSTEM DESCRIPTION

Based on the research hypothesis, a sonification system has been developed featuring both sensory devices (hardware) and a software platform. This section presents the design of the sonification system.

3.1. Hardware

The muscle's activity and the kinematic data of hand movements are chosen as inputs to the sonification mapping. Two types sensors are used accordingly.

For muscular activity, a surface EMG (electromyogram) sensor is used to extract myoelectric signals directly from the active muscle. The EMG signal is a direct reflection of the muscle current level of activation. EMG is widely used in the study of postural tasks, functional movements and training regimes [9].

A wearable EMG belt was designed (see Figure.1a), consisting of an EMG sensor[1], an Arduino Duemilanove microprocessor and a Bluetooth modem. The EMG signal is sent to computer via the Arduino at 9600 baud.

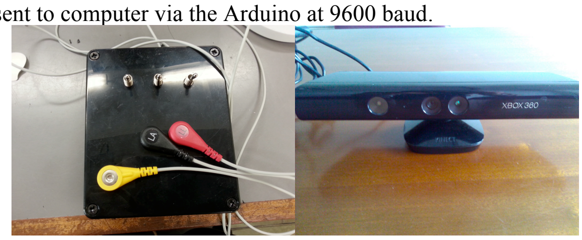


Figure 1 a) EMG Belt (Left), b) Kinect Camera (Right)

For limb position extraction, a Microsoft Kinect (Figure.1b) camera was placed in front of user. A tracking program named Synapse[2] was used to acquire 2D coordinates relative to the center of the subject's torso and to transmit the coordinates via Open Sound Control (OSC). The reason for using relative coordinates is to provide consistency regardless of the position that the user stands within the visual frame.

3.2. Software

The software platform (see Figure 2) was developed using Max/Msp, and has 3 main functionalities.

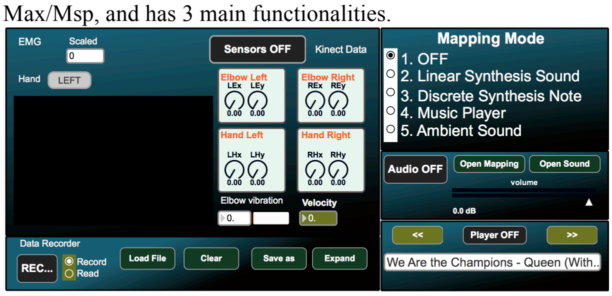


Figure 2: Main interface of the sonification software

(1) **Data management**: This section handles bio-signal acquisition. The sampling rate for the data recorder is set at 50Hz, because biceps curls are relatively slow action exercises (typically less than 1Hz). Therefore, being able to output 50 sets of data (coordinates, EMG, speed, etc.) per second is more than enough for both sonification and analysis purposes. This part of the program also handles basic analysis of the data, such as finding the rate of change (v) of the y-coordinate and the dynamic range of the movement (difference between the lowest and highest y-coordinates of the hand).

(2) **Sound engine** featuring a subtractive/FM synthesizer and an audio sampler. In order for the sound to distinctively represent the movement and muscular activities, the following 5 parameters are controlled by the bio-signal in different combinations. They are: loudness, pitch, filter cut-off frequency (brightness), noise level and sample playback speed.

To avoid boredom in long-term use, four types of sounds are available to choose from:

- **Linear frequency synthesis**

This preset produces a synthesised sound with a linear pitch variation during the biceps curl. The sound itself comprises a sawtooth waveform and a triangular waveform, resulting in a rich spectral content. The pitch is linearly controlled by the current vertical position of the hand with a valid frequency range from 0Hz (lowest hand position) to 620Hz (highest position). The amplitude of the EMG signal shapes the brightness of the sound through a linear mapping to the cut-off frequency of a band-pass filter. The overall sound characteristic was described as 'sci-fi' by some of the users. In additions, a white noise will be triggered if the movement velocity is over a threshold value, thus encouraging the exercise to be taken at a slower pace.

- **Discrete bell-like sound**

In terms of the timbre, this preset is spectrally simple. The vertical hand position triggers a range of notes between C4 and E5. The vertical range is divided into 10 equidistant sections. When the y coordinates moves from one section to another a new note will be triggered. To avoid boredom, the note selection varies each time based on two Markov chain probability matrices. One is used in biceps contraction (moving up) with an ascending note progression and the other is used in biceps extension (moving down) with a descending note progression. The same white noise as above is used as a warning to slow down.

- **Music player**

This mode allows users to upload their *own* music files and have them played back during exercise. The EMG signal is used to control the brightness of the sound via a low-pass filter. Thus the more activity generated from the muscle the greater the clarity in the music. This is to encourage users to work hard to hear good quality music. If the user moves his/her arm too quickly, the pitch of the right channel is altered so that the music does not sound 'correct'. This is used as a warning or a penalty if the user is moving too quickly. The incorrect effect only lasts for one repetition and will then be reset to normal pitch.

- **Ambient sound**

This also uses the sampler as above, but triggers the sound of a soft breeze blowing during the exercise. It aims to create a relaxing sensation for the user rather than giving precise feedback on the movement. The EMG signal is mapped to control the cut-off frequency of a low-pass filter so that wind sounds 'harsher' when more effort is put in. The speed warning

[1] Purchased from http://www.advancertechnologies.com/
[2] http://synapsekinect.tumblr.com/

is replaced by a sine wave beep instead of white noise, which would be hard to hear in the noise-based soundscape.

(3) **Mapping engine**: manages the data connection between the bio-signal and the sonic parameters. The sound presets are stored and changed in this patch. Parameter mapping [2, 3] is used as the main mapping method.

If more hardware details are required, please refer to the previous paper of this research, which focused on the user experience of different types of auditory feedback [10].

4. EXPERIMENTATION & DATA ANALYSIS

The sonification system was applied in the comparative trial. Full details are described in the following sections.

4.1. Experimental Setup

The experiment was carried out in the Audio Lab, University of York, U.K. 22 people participated: 19 males, 3 females. A laptop was used with the sonification software installed. Auditory display is via a pair of speakers.

Subjects were randomly assigned to one for the two groups: *sonification group* and *control group*. Auditory feedback during the exercise was given only to the sonification group.

The experiment involved three sessions on different dates. In each session, participants were asked to select a dumbbell, whose weight was challenging for the subject's own standard. All three sessions involved the same type of exercise. Yet participants had control of the quantity of repetitions and sets as a factor of studying progression and participants' motivation of exercise.

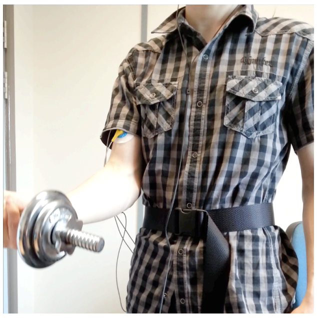


Figure 3. Demonstration of the exercise

Prior to the exercise, subjects were briefed (and shown a demonstration) that there are *three quality criteria*:

(1) Aiming for a large movement range, which means trying to lift the dumbbell as high as possible and when lowering the dumbbell trying to return to the natural straight-arm position.
(2) Aiming for a slower pace. The ideal speed for each direction (up or down) of movement is at least 2 second.
(3) Subjects are free to do whatever amount of exercise they feel comfortable with but the more the better.

Participants in the sonification groups were also demonstrated the four different sound presets and they are allowed to choose any of the presets based on their own preferences. After each session, all subjects were asked to fill in a survey to express their tiredness and comment on their experience.

The following data were recorded

(1) **Normalised EMG**: Due to differences between different subjects' biceps, some might have a larger range while others might have smaller. Therefore, in order for all users to be able to achieve a full control range, calibration is required based on subject's rest-stage EMG and the maximum contraction EMG then scale this range to a control range of 0 to 1023.

(2) **Active hand y coordinate**: This parameter reflects the vertical movement (relative height) of the active hand.

(3) **Velocity of y coordinate**: The rate of change of the y-axis coordinate. Positive velocity indicates biceps contraction whilst negative velocity indicates biceps extension.

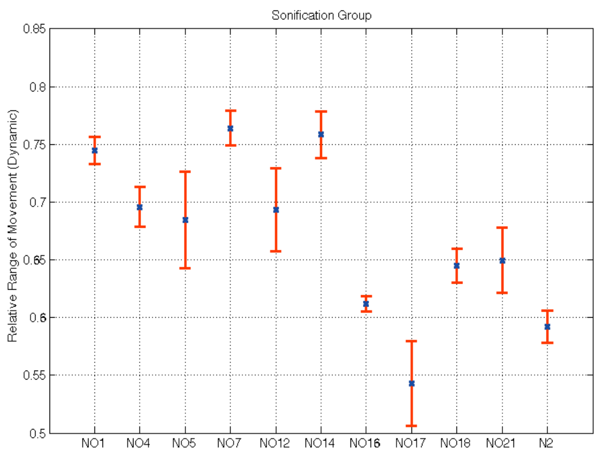
(4) **Dynamic of y coordinate**: The difference between the highest y coordinate and lowest y coordinate in each repetition.

4.2. Experimental Results and Analysis

Three dependent variables were collected in the experiment. They are movement range, movement velocity and effort. This section presents discussion on each variable then follows with an influential statistics section.

4.2.1. Movement Range

The *movement range* is the distance completed in a repetition. The distance is the vertical coordinate difference between straight-arm hand position and peak-hand position when lifting the dumbbell. The coordinate is ranged from 0 (straight-arm position) and 0.8 (shoulder position) and 1.0 (top of the head). Referring to the quality criteria in 4.1, subjects should aim for a large movement range. Figure 4 demonstrates the average dynamic per repetition of each participant from all three sessions (the sonification group being shown at the top and below that the control group).



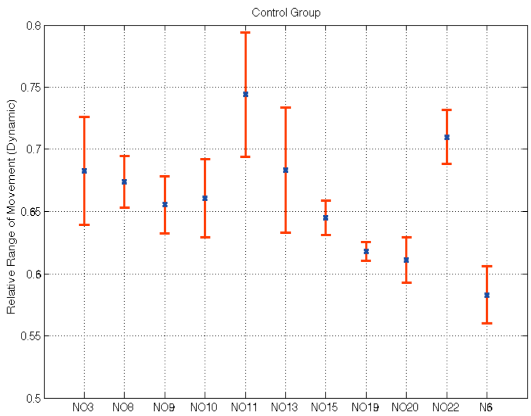


Figure 4. Movement range comparison (blue crosses are the mean movement ranges, error bars are the standard deviations)

For the group performance, the mean movement range for the sonification group and control group are 0.67 and 0.66 respectively. According to the graph, surprisingly, the control group performed more stably than the sonification group. The standard deviations of the mean movement range between groups are 0.07 (sonification) and 0.04 (control).

Although the sonification provided reference to the vertical position of the subject's hand, it did not contribute to any variation in exercise quality. During the experiment, the researcher observed that 3 participants in the sonification group did not achieve a good movement range. They either started another repetition without completely lowering the forearm or did not reach the top possible position. It appears that tired subjects do not use the sound to maximize their movement range. This may be because they are not explicitly warned that their movement is falling short of the maximum.

4.2.2. Movement Velocity

This data represents the average velocity (vertical coordinate change per second) per repetition in a session. Based on the quality criteria in 4.1, a lower velocity value is considered to be better quality.

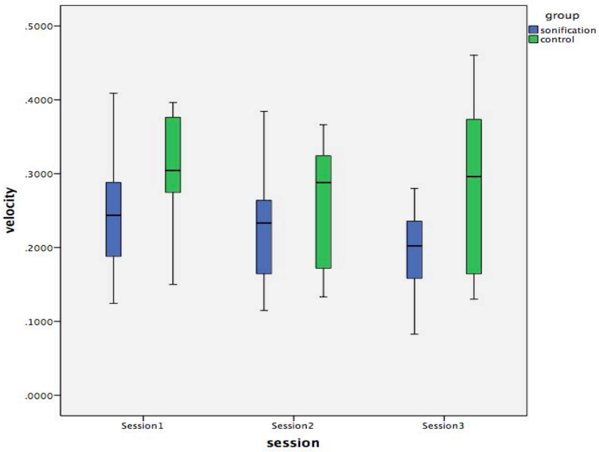


Figure 5. Average velocity comparison

This is the most influential attribute out of the three dependent variables as sonification showed its superiority in maintaining a slow pace of the exercise (see Figure 5). The boxplot suggests that, overall the sonification group had a lower velocity value. The sonification group also improved consistently throughout the three sessions. Yet without audio feedback, subjects in the control group tended to exercise much quicker even though a demonstration was shown at the beginning of the first session about the criteria of exercise. The extra sonic cue seems to have served as an active *reminder* of the speed of movement.

4.2.3. Total effort

Prior to the experiment, we compared the mean weights of the dumbbell selection. They are 5.0kg (sonification group) and 4.7kg (control group). Therefore, we treated the initial mean dumbbell weights as approximately equal (6% in difference). The total effort is a combination of the weight of dumbbell and the amount of repetitions. It is calculated as the equation below,

$$effort = w \cdot r$$

where w is the weight, r is the repetitions. The results in three sessions are shown in Figure 6. There is an increase in the medians of the sonification group. In all sessions, the sonification group is noted with both higher upper quartiles and median values although the lower quartiles are very similar.

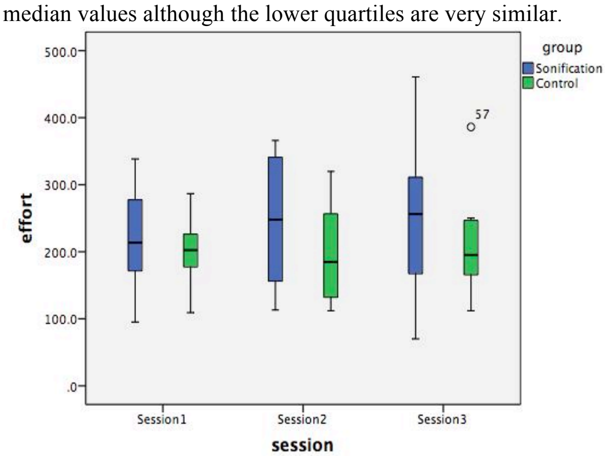


Figure 6. Total effort comparison

However, it should be noted that the experiment only lasted for 3 sessions whereas generally weight training requires a longer time to show clear improvement in muscle strength. The difference between two groups is not significant enough to make a judgment that sonification can definitely lead to a quicker improvement in exercise quality than the control group. Yet, the results underline a possibility that if subjects enjoyed listening to the sonic feedback the motivation improved, which caused a better improvement in the amount of repetitions completed.

4.2.4. Influential Statistics

A one-way multivariate analysis of variance (MANOVA) was conducted using the abovementioned three dependent variables for the final session between two groups. It aims to investigate the difference in the overall exercise quality between two groups. No serious violations were found in the preliminary assumption testings, including normality, linearity, univariate and multivariate outliers, homogencity of variance-covariance matric es. There is no statistically significant difference between sonification group and control group on the combined dependent variables, $F(3, 18)$, $p = .161$ (Wilk's Lambda), partial eta squared = .244.

When the dependent variables results were considered seprately, we found a significant difference of the velocity, $F(1, 20) = 4.934$, $p = .038$ and partial eta squared = .198. This dependent variable has a large effect size (19.8%) . The results show that sonification group has a slower movement velocity ($M = .191$) than control group ($M = .279$). The results indicate the sonic feedback serves best at reminding the speed of movement in order to achieve slow and steady exercise movements.

5. QUALITATIVE RESULTS

Comments have been gathered from the sonification group about the use of sonification. 8 out of the 11 subjects expressed that the sounds they received had a positive effect on their exercise. 2 participants in the same group did not make any comments of the sonic feedback and one expressed that he did not enjoy it.

The following is some of the comments made by the participants:

"I enjoyed the sound"

"I tried to avoid the over-speeding sound"

"The sound distracted me from feeling tired" – Three participants expressed that the sound served as a distraction from fatigue. This is also supported by [11].

"It felt annoying at first but later it kept me going."

"I think the sound is getting clearer comparing to the last session."

"Personally I wouldn't listen to this while I was exercising." – Two participants mentioned that they did not enjoy the sound at all and felt it sound very noisy to them (both used the linear synthesis sound preset).

"I just felt very tired"

These comments indicate that the sonification feedback provided a mostly positive effect on both providing training guidance and general experience. It is reasonable that some people may find the sound uncomfortable to listen to. It pinpoints a fact that the current sound design consideration is still biased to being informative and not enough effort was put into accommodating different aesthetic preference. We believe with careful fine-tuning the sound aesthetic can be improved in order to provide a better experience.

6. CONCLUSION

In this research, a sonification system was designed for providing real-time feedback of subject's physical exercise. A latitudinal experiment was conducted to compare the exercising quality between a sonification group and a control group (no sound feedback) over a three-sessions period. The exercise quality was monitored regarding participants' movement speed, range and the total effort.

The study shows that sonification group performed consistently better in terms of movement velocity and effort, but there is no difference in the movement range. Although MANOVA analysis shows there is no significant difference between two groups in session 3 considering the combined dependent variables, significant result was found in movement velocity with a large effect size, indicating that the sonification a strong influence on maintaining a slow biceps curl speed. Although there is no significant result in the total effort, the post-session survey concluded that most participants in the sonification group found the auditory feedback to have positive effect on their actions.

We believe that the sonification device has the potential to be further improved and eventually developed into a sophisticated product to improve the general quality of physical exercise.

7. FUTURE WORK

At the time of submitting this paper, a crossover experiment has been carried out to study the difference between doing biceps curl with and without sonification feedback in different phases.

With the new age of wearable device and the technology focus on fitness and health, an exciting period is waiting ahead. This project has the potential to contribute to the field of fitness assistive devices and thus to encourage more people to do regular physical exercise to a relatively good standard. As for the system, although it is still in its prototype stage, it can be developed into a smartphone add-on, offering convenient accessibility to users.

Another possible extension of the project is to facilitate the sonification system in rehabilitation training. In this context sonified bio-feedback could be used to monitor and correct the patient's prescribed exercise.

8. ACKNOWLEDGEMENT

We would like to express our sincere gratitude to all the participants who took part in the experiment.

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Appendix C - Publication of Crossover Experiment Results

Real-time Sonification of Biceps Curl Exercise Using Muscular Activity and Kinematics

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ABSTRACT

In this research, we developed a real-time sonification system to be used in biceps curl. The sonification is generated using a parameter mapping method based on exercise information collected from a muscle sensor and Kinect camera. A cross-over trial (AB-BA method) using biceps curl exercises was conducted, which included 14 healthy subjects equally assigned to two different groups. The first group started their sessions without any feedback then received sonification in the last sessions. The other group completed the sessions with the sonic feedback in the early stages.

The experimental results show that the sonification worked well at portraying temporal information to help subjects improve the pacing of their movement. Results also show greater improvement in exercise metrics (greater average repetition range and total effort) when participants exercised with sonification, but not statistically significant. However, a significant result is that participants enjoyed the training more with the sonification than without. Positive comments were made on the sound feedback. The study demonstrates the potential for a real-time auditory feedback oriented training device to be used in fitness training or physical rehabilitation.

1. INTRODUCTION

1.1. Background

Sonification, as a means of portraying data using non-speech acoustic signals [1], has been applied in areas such as sport training and physical rehabilitation for many years. Typically, the output sounds are created based on a subject's body movement and bio-information. Biofeedback is used to provide an indication of the state of a bodily process using external sensors [2]. The purpose is to increase the awareness of a physiological response. In physical exercise, the use of biofeedback has the potential to improve the quality of exercise in many aspects, such as movement precision, temporal accuracy and muscular activity patterns [2].

Sound is a suitable candidate for portraying biofeedback due to several advantages [3]:

- The biofeedback is not restricted by a screen monitor, thus allowing visual attention to focus on the action or surroundings.
- Acoustic energy is very alerting and can be detected rapidly.
- Auditory information is superior to visual information in portraying time-sequenced (rhythmic) data.

For example, [4] developed auditory feedback of an ankle exercise, based on leg/foot ankle angle, which aimed to help visually impaired or bedridden patients improve the quality of physical rehabilitation. [5] is another example where the user's body movement was completely guided by sonification in sporting activity. Auditory biofeedback has also been applied to patients who lack proprioception as a means of improving the limb movement accuracy [6]. The use of biofeedback was also used in physical therapy related projects, such as the use of electromyography (EMG, a measurement of muscular activity) sonification in [7, 8].

The biceps curl is a highly popular training method, which involves both concentric contraction (lifting the dumbbell) and eccentric contraction (the lowering phase) of the key muscle. Yet many people do not pay enough attention to the *quality* of the exercise, for example lowering the dumbbell too quickly and skipping the effort of eccentric contraction. Therefore, this exercise is a good option with which to test the sonification device. This could also lead to applications in a wider range of physical exercise from fitness training to physical rehabilitation. Motor control can be improved through practice regardless of the complexity of the movement [9]. This assertion is highly important in physical exercise as better quality can contribute to quicker and greater improvement in body condition.

1.2. Research Overview

This study investigated whether the quality of physical exercise can be improved using real-time auditory feedback of users' exercise routines. In particular, we developed a sonification system facilitating sensory devices to measure a user's muscular activity and arm kinematics and mapped them into synthesis parameters for generating real-time auditory feedback. By listening to the feedback, we hypothesized that the users would be able to gain better awareness of their exercising states, which could potentially lead to a better exercise performance and progress. Another aspect we looked into was the general experience of using the sonification.

A cross-over trial was conducted to measure the effect of the sonification. In this method, equivalent groups of subjects receive counterbalanced sequences of each treatment, which cancels ordering effects and allows each subject to participate in all of the experimental manipulations [10, 11]. Specially, this experiment studied the effects of real-time auditory biofeedback in biceps curl exercise over an 8-session trial. Among the sessions, half of subjects were asked to do the exercise *without* the sonification for the first 4 sessions, then with the sonification for the other 4 sessions. The other half of the participants completed the same experiment but in the opposite fashion.

The experiment documented in this paper is a continuation of the previous between-subjects experiment

[12], which studied the effect of the sonification of biceps curls between two groups of participants in a 3-session setup. The between-subjects design could not avoid the individual differences of a participant's physical condition, which could influence the outcomes. The crossover experiment (within-subjects) eliminates the factor of individual differences. It was also performed over a longer scale than the previous experiment.

1.3. Paper Structure

Section 2 presents an overview of system design including descriptions of the sensory devices and the software platform. Section 3 provides details of the experiment, which consists of the experimental setup and procedures, and the quantitative/qualitative results. The summary section concludes the study and discusses the implications of the results.

2. SONIFICATION SYSTEM DESCRIPTION

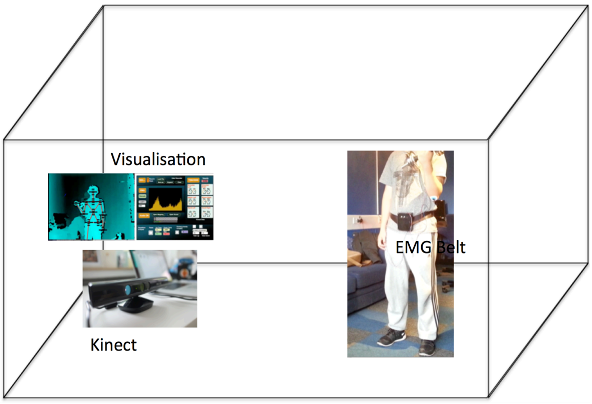

Figure 1: Setup example

A real-time sonification system was developed featuring an EMG (electromyogram) belt for muscular activity measurement and a Microsoft Kinect camera for limb position tracking. A software program was developed on Max/Msp to work with the sensory devices for generating the sonic feedback and data storage. A pictorial demonstration of the setup is shown in Figure 1.

The EMG belt consists of a surface EMG sensor for measuring myoelectric signals from the active muscle. The EMG signal is then transmitted to the computer (9600 baud) using an Arduino Duemilanove microprocessor with a Bluetooth modem.

The other sensory device, the Microsoft Kinect, is used to track the coordinates of a subject's arm relative to the centre of the torso. A program named *Synapse* [13] was used for tracking the movement, and coordinates of different body joints are then transmitted via Open Sound Control (OSC), which can be acquired directly in the sonification program.

The software environment is shown in Figure 2, which has three main functionalities:

(1) The *data management* section, also the main interface, consists of data visualization, data recorder, system setup and sound selection. The sampling rate for the data recorder is set at 50Hz, which is sufficient for recording the relatively slow biceps curl. Information being stored includes the EMG signal, hand coordinates, speed, repetition range. This section contains the basic analysis of the data, including calculating the rate of change of the y-coordinate of the hand (indicating the speed of biceps curl) and the range of repetition (difference between the lowest and highest y-coordinate of the hand).

(2) The *sound engine* used in this experiment is designed using frequency modulation and subtractive synthesis methods. As shown on the top right side of Figure 1, there are four different sound outputs for selection. However, this particular experiment only used the *Linear Synthesis Sound* option, which is different to our previously published experiment where participants were free to choose one of the four sounds according to their own preferences.

The linear synthesis sound produces a spectrally rich sound using two triangular oscillators. The pitch of the synthesizer varies continuously rather than using discrete MIDI signals. A band-pass filter is used to shape the brightness of the tone. Some users describe the overall tonal characteristic of this sound as "sci-fi". A white noise unit is used separately to function as a warning. This sound is triggered if the speed of movement is over a threshold value to encourage the user to exercise at a slower speed.

(3) The *data mapping* section links the bio-information to selected sound parameters, which were used to generate audio output. Parameter mapping [14] is used. We have chosen the EMG signal, y-coordinate of the active hand, movement velocity and repetition count as the input parameters. This data is scaled accordingly in order to create the correct range of values to control the sound parameters. Specifically, the pitch of the synthesizer is controlled by the active hand's y-coordinates and has a valid frequency range between 0 to 620Hz (from the lowest hand position to the highest). The EMG signal is mapped to control the cut-off frequency of the band-pass filter. As a result, the brightness of the sound is directly controlled by the biceps contractions (both concentric and eccentric). As more effort is exerted, the brighter the tone becomes. A white noise unit is also in use, which is controlled by the movement velocity. When the movement velocity is over a threshold value, the noise is triggered and heard by the user indicating that the user needs to slow down the pace of their exercise movement.

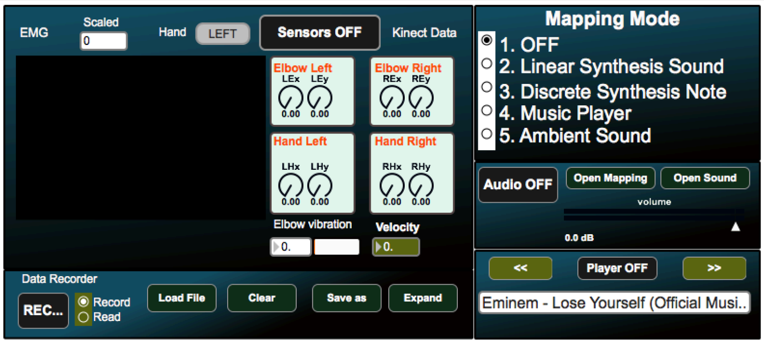

Figure 2: Main interface of the sonification software

3. EXPERIMENTS & ANALYSIS

3.1. Experimental Setup

This study was conducted to find out the difference in exercise quality between two phases for the same participant: effect phase and control phase. This means that all participants experienced doing biceps curl exercises both with and without the sonification feedback. The experiment was carried out at the Audio Lab in the Electronics Department, University of York, UK. 14 healthy university students participated in the experiment (8 females, 6 males, aged 24 ± 3). All participants were reported to be healthy with no conditions or injuries which could affect the exercise.

Participants were randomly assigned to two groups, referred to as *Con-son* (first four sessions **Con**ventionally without sound then the remaining four sessions with the **Son**ifcation) and *Son-con* (sonification first four sessions, then the remainder without). All participants signed a consent form prior to the first session, which explained the procedures and safety advice of the experiment. All participants completed the full 8-sessions of the experiment. There was 1-3 day's gap between each session to allow for the necessary muscle rest. Between the cross-over (before the fifth session), participants received a one week break with no heavy biceps-related training during this time.

Participants were advised that there were *three main criteria* in terms of the quality. Criterion 1 is to aim for a slow and steady pace, with each repetition to be completed in at least 4 seconds. Criterion 2 is to aim for a large range of motion of the lower arm, with the upper arm remaining static. Criterion 3 is to complete at least 2 sets of a minimum of 5 repetitions in one session. Participants were not encouraged to do as many repetitions as possible even though it was desired. This was to allow the participants to manage the quantity of exercise at their own motivation. However, being able to perform more repetitions is also an indication of good performance. The exercise and any safety issues were demonstrated to all participants prior to them commencing.

3.2. Quantitative Results

3.2.1. Repetition Time

The repetition time is the average time in seconds to complete one repetition of the biceps curl. Figure 3 presents the average repetition time in the two different treatments. Each data point is the overall average repetition time of that participant in the 4 sessions with the same treatment. The data is arranged according to participant's group.

Greater repetition time indicates slower movement velocity, which also indicates better exercise quality. Apart from participants 2 and 7, there were better results in the sonification phase (triangle) than the control phase (circle). Also, notice that the repetition times for participant 2 and 7 are very large already (No. 2: 7.9s in Sonification and 9.8s in Control; No7: 11.5s in Sonification and 11.95s in Control), which means that there was very little room for improvement.

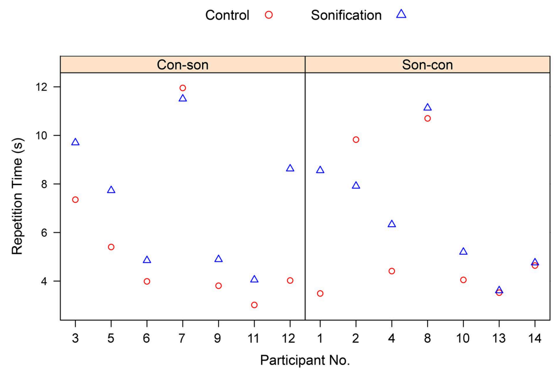

Figure 3: Average repetition time

A paired T-test was conducted, which indicated a significant difference between the mean value in the sonification phase (M = 7.06s, SD = 2.62) and the control phase (M = 5.73, SD = 2.98); $t(13) = 2.68$, $p < 0.05$. This indicates that the sonification worked very well at providing extra awareness to help participants to exercise at a slower pace (Criterion 1).

3.2.2. Repetition Range

The repetition range is the relative distance completed per repetition. The vertical hand coordinate (modified from the Kinect sensor) ranges between 0 (straight-arm position) and 0.8 (shoulder position) and 1 (top of the head). Figure 4 shows the comparison of the average repetition range of the participants based on the two different treatments. 9 out of 14 participants showed better results in the sonification phase.

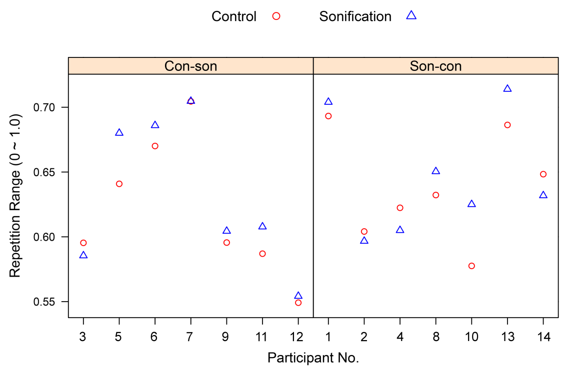

Figure 4: Average repetition range

No significant improvement was found in this variable between Sonification phase (M = 0.639, SD = 0.051) and Control phase (M = 0.629, SD = 0.047). However the significance level (p = 0.076) indicates the result is not far from being significant (0.05). This could be due to the relatively low difficulty of the exercise; most participants were already capable of achieving a good range of movement. Also, the relatively small sample size could affect the significance level.

3.2.3. Total effort

Total effort is defined as the product of dumbbell weight and the total repetition amount. This is because subjects were allowed to increase or decrease the selected dumbbell weight between sessions. If the weight is increased, achieving the same repetitions becomes more difficult.

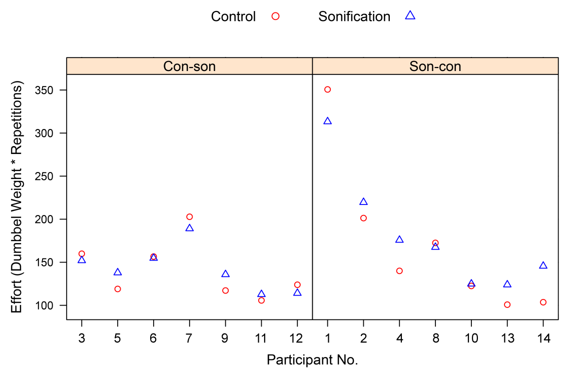

Figure 5: Effort comparison

The comparative result is shown in Figure 5. Paired T-test showed no significant difference ($p > 0.5$) in the effort results between the Sonification phase (M = 162, SD = 53) and Control phase (M = 155, SD = 66) even though the sonification phase has a higher recorded mean effort. However, some participants in the Son-con group expressed that after the sound was taken out, the exercise became more tedious to complete (No. 1, 4, 13, 14). Also, participant 1 said that while it had become less interesting without the sound, his muscle was already feeling stronger and hence he could still manage to finish more repetitions than in the initial sessions. In the Con-son group (adding the sound feedback from the fifth session), 3 participants showed improvement in the sonification phase; 3 have shown a decrease in effort and, 1 remained unchanged.

3.3. Survey Results

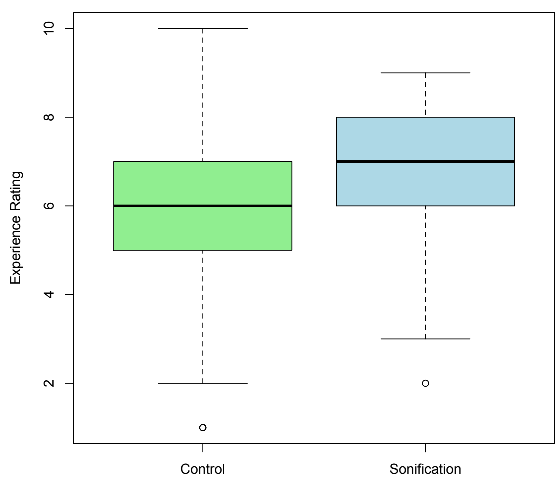

Figure 6: Boxplot of the user rating comparison

Participants were asked after each session to rate how much they enjoyed the workout after the exercise on a scale from 0 (not at all) to 10 (very enjoyable). Figure 6 shows that subjects in general had a more enjoyable experience when exercising with the sound feedback than without. A paired t-test was conducted to compare the mean rating for the two treatments. There is a significant difference in the rating for sonification (M = 6.93, SD = 1.57) and control (M = 5.73, SD = 2.28); $t(55) = 3.89$, $p < 0.001$.

Subjects were also asked to rate, on a scale of 0 (confusing) to 10 (informative), whether the sound gave sufficient feedback to the exercise movement. The mean value for this variable is M = 7.16, SD = 1.94, which indicates that the feedback was relatively informative to the majority of subjects. Regarding the sound aesthetic rating (0 being disliked to 10 highly enjoyable), the result is M = 6.30, SD = 1.86. The paired t-test shows a significant result of $t(55) = 3.87$, $p < 0.001$. A strong p value suggests that participants enjoyed the exercised more with the sonic feedback presented.

In addition, there was an optional question in the survey to let participants make open comments on the sessions. Selected results are shown in Table 1. Other results, which were mainly based on participant's physical condition after the session such as "feeling tired", have been excluded.

Type	Comment
Sound feedback	Paid attention to the sound. Aimed for a slower pace based on the sound. Able to get a smoother sound. Became more interesting (than without sound). Getting a steady sound. Exercise frequency affected by the sound.
Without feedback	Boring. Not as fun. Exercise felt more difficult than with the sound
By the end of the sessions	Feeling stronger Exercise became easier

Table 1: Subjects' open comments

Overall, participants made positive comments on the sound feedback, which mainly focused on how the sound feedback can affect the pacing of movement and make exercise more interesting. Similarly, three participants in the Son-con group felt the sessions had become less interesting after the sound feedback had been removed.

4. ANALYSIS

The three main conclusions that can be drawn from these experiments are as follows:

1. The sonic feedback has a strong impact on the pacing of the movement. There is not enough support to indicate the auditory feedback could lead to a larger repetition range. Although no obvious improvement is shown in the total effort, the post-session survey indicated that participants felt more motivated with the auditory feedback.

2. A significant result is shown that the participants enjoyed the exercise more with the feedback than without.

3. Participants generally found the auditory feedback informative. However, the sound aesthetic still has room for improvement. While this particular experiment used only one type of sound for the sonification, the system provides other options such as probability-based melodic mode, sea wave sounds, and a music player allowing users to upload their own music files. Hence, there are more options to accommodate a user's personal preference.

5. SUMMARY

This paper presented a study of the effect of real-time sonification on a subject's biceps curl exercise based on muscular activity and movement information. A sonification system was developed, which consisted of an EMG sensor belt and a Microsoft Kinect camera as hardware, and custom sonification software using Max/Msp. A cross-over trial was conducted to study the difference in exercise quality between 2 phases (exercise with auditory biofeedback and without auditory biofeedback) in 2 different sequences.

The experimental results resonate with the previous experiment we conducted based on fixed treatment group comparisons. This latest study shows that participants performed better with sonification in terms of pacing, but no significant difference was seen in movement range. This result indicates that the auditory feedback is more effective at portraying the temporal characteristic of the movement. Also, participants found exercising with the sound more motivating and interesting. This is an important finding, especially as a repetitive exercise over a longer time scale is often considered to be tedious. According to participant feedback, the sound was considered to be informative.

A conclusion is drawn concerning the movement range mapping. The movement range was portrayed with a linear mapping of the pitch of the synthesis. The continuous mapping could provide a raw portrayal of the hand's position yet is not suggestive enough for the listener to realise the quality of that variable. Further adjustment is required to make this mapping more intuitive. A possible approach is to use notification to sonically present whether the movement range is considered as 'good' or 'bad' quality rather than the current raw representation.

In summary, the sonification used in this research does not only relate to the biceps curl itself, but also shows that the auditory cue could help the users to regulate their action in order to satisfy certain exercise criteria. The sonification has the potential to improve the quality of physical exercise and the current system can be developed further to suit more exercise types. This has applications both in fitness training and physical rehabilitation. In comparison to some of the commercial products such as Wii Sports and Xbox games, this system places more attention on portraying the user's muscular activity, which is an essential attribute in weight training. In addition, the exclusive use of sonic display has possibilities for multitasking and portability.

One of the possible further developments of this system involvement is to replace the Kinect camera with an accelerometer to detect movement velocity. By doing so, the system can be developed as a wearable device, which has greater accessibility for situations such as outdoor physical activity. In recent years, we have experienced a revolution of portable computing device and wearable technology. Products such as smartphones, smartwatches and fitness tracking gadgets provide sonification designers with a huge worldwide platform for developing auditory assistive tools and devices to help to improve our general health. As more situations are made possible to extract biodata, auditory biofeedback has the advantage of being screen-free and interesting to use, while delivering sufficient bio-information to increase the awareness of the exercise. With more advanced sensory devices becoming available to the public and the advantage of the mobile application market, the next stage for the research is to implement the sonification into mobile platforms, which could hence improve the portability and accessibility.

6. ACKNOWLEDGMENT

We would like to express our sincere gratitude to all the people who took part in the experiment.

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Appendix D - Pilot Study Forms

THE UNIVERSITY *of York*

Department of Electronics, Audio Lab

Participant consent

Purpose:

The purpose of this pilot study is gather user experience on the sonification of real-time physical exercise. The purpose is to improve the software design and the experimental design for future experiments. This study is part of Jiajun Yang's doctoral research in music technology to facilitate auditory feedback for improving physical exercise quality, under the supervision of Dr. Andy Hunt.

The participants will put on an EMG sensor, and stand in front of a Microsoft Kinect sensor. The participants will then do a few sets of general physical exercise (e.g. dumbbell lifting). The exercising length and intensity is up to the participants to decide depending on their interest. During the session, different types of real-time sonic feedbacks will be played back to the user.

The participants will fill up a questionnaire at the end, which gathers information on the user experience of the system and opinions toward the sonic feedback.

Because this study is mainly to find out user's opinion of the real-time auditory feedback, additional verbal comments may be recorded.

Procedure:

If you agree to participate this study, you will be asked to do the following:

1. Attach the EMG sensor on dedicated training muscle. Face toward the kinect sensor while exercising. Because the study requires **attaching electrodes on subject's arm muscle**. <u>We suggest you to wear a T-shirt for the ease of electrode attachment</u>;
2. Perform several common physical exercise (such as free weight lifting.
3. The amount of repetitions for each exercising set is entirely up to you.
4. Complete a questionnaire at the end of the session.

Your participation in this study is entirely voluntary and you may refuse to complete the study at any point during the experiment, or refuse to answer any questions with which you are uncomfortable. You may also stop at any time and ask the research any questions you may have. Your name will never be connected to your results or to your response on the questionnaires. Instead, a number (such as Participant 1) will be used for identification purposes. The researcher will guarantee that none of the personal information will be released to the public. Information that would make it possible to identify you or any other participant will never be included in any sort of report. The data will be accessible only to those working on the doctoral research.

Contact Detail:

If you have any questions regarding this study you may contact Jiajun Yang at jy682@york.ac.uk.

Statement of Consent:

I have read the above information. I have asked any questions I had regarding the experimental procedure and they have been answered to my satisfaction. I consent to participate in this study.

Name of Participant (please print): ____________________ Date:________________

Signature of Participant:____________________________

Thank you for your participation!

THE UNIVERSITY of York

Department of Electronics, Audio Lab

Questionnaire

1. Do you do regular physical exercise?

2. If so how often?

3. Do you use computer technologies (such as app, gadget, etc.) to assist physical exercise?

4. What do you think of the sounds used in the session? In terms of information, interaction, and general preference? (Leave blank if the sound is unused)

- Synthesis sound (linear frequency):
  Comprehensibility:
  0 (Low) 1 2 3 4 5(High)

  Preference:
  0 (Dislike) 1 2 3 4 5(Like)

  Comment:

- Synthesis sound (MIDI note):
  Comprehensibility:
  0 (Low) 1 2 3 4 5(High)

  Preference:
  0 (Dislike) 1 2 3 4 5(Like)

  Comment:

- Drum beat:
  Comprehensibility:
  0 (Low) 1 2 3 4 5(High)

  Preference:
  0 (Dislike) 1 2 3 4 5(Like)

  Comment

- Sea wave sample:
  Comprehensibility:
  0 (Low) 1 2 3 4 5(High)

  Preference:
  0 (Dislike) 1 2 3 4 5(Like)

  Comment:

7. Please leave any additional comments and suggestions that you have.

Contact Detail:

If you have any questions regarding this study you may contact Jiajun Yang at jy682@york.ac.uk.

Again, thank you for your participation!

Appendix E - Between-Subjects Comparative Experiment Forms

No.

THE UNIVERSITY of York

Department of Electronics, Audio Lab

Comparative Test Participant Consent

Purpose:

The purpose of this study is to compare the difference in doing biceps curl exercises (with a dumbbell) with and without real-time auditory feedback. The experiment involves three sessions. Participants will be asked to perform the same exercise in each session.

This study is part of Jiajun Yang's doctoral research of facilitating auditory feedback for improving the quality of general physical exercise.

Procedure:

If you agree to take part in this study, you will be asked to do the following:

1. Fill in a pre-participation form;
2. In the test, you will be asked to stick an EMG sensor on your skin above the biceps. Because of this we suggest that you wear a T-shirt for the ease of attaching the electrode. You will be asked to face towards the Kinect camera for movement tracking.
3. Choose a suitable dumbbell weight, which will be maintained through out the three sessions;
4. Perform biceps curl exercises. Even though the quantity is entirely up to you, it is suggested that you do approximately 10 – 12 repetitions in each set.
5. If you are assigned to the sonification group, you will also be hearing auditory feedback through speakers or headphones while exercising.
6. On the other hand, if you are assigned to the control group, the same training sets are still required but no auditory feedback will be given.
7. Complete a questionnaire about how you feel about the training result and (if you are in the sonification group) the auditory.

You will be asked to complete all three sessions of the study. The first session will last approximately 20 - 30 minutes, then the following sessions will be shorter. A small selection of edible treats is provided after each session.

Disclaimer

Your participation in this study is entirely voluntary and you may refuse to complete the study at any point during the experiment, or refuse to answer any questions with which you are uncomfortable. You may also stop at any time and ask the researcher any questions you may have. Your name will never be connected to your results or to your response on the questionnaires. Instead, a number (such as subject 1) will be used for identification purposes. The researcher will guarantee that none of the personal information will be released to the public. The Kinect camera does not store your image, but instead is used to track the positions of your arms and legs. Information that would make it possible to identify you or any other participant will never be included in any sort of report. The data will be accessible only to those working on the doctoral research.

Contact Detail:

If you have any questions regarding this study you may contact Jiajun Yang at jy682@york.ac.uk.

Statement of Consent:

I have read the above information. I have asked any questions I had regarding the experimental procedure and they have been answered to my satisfaction. I consent to participate in this study.

Name of Participant (please print): ____________________ Date:________________

Signature of Participant:____________________________

Contact Email: ____________________________

Age Group:

Below 15 15--- 20 21 --- 25 26 --- 30 31 --- 40 Above 40

Thank you for your participation!

Participant Record

Participant No.:

Which arm: L R

Group: Sonification Group Control Group

Session 1:

Recent biceps workout:

Quantity:

Time:

Modes used:

Tiredness after the session:

1 2 3 4 5 6 7 8 9 10

(Not tired) (Very Tired)

How do you feel?

Note:

Session 2:

Recent biceps workout:

Quantity:

Time:

Modes used:

Tiredness after the session:

1 2 3 4 5 6 7 8 9 10

(Not tired) (Very Tired)

How do you feel comparing to the last session?

Note:

Session 3:

Recent biceps workout:

Quantity:

Time:

Modes used:

Tiredness after the session:

1 2 3 4 5 6 7 8 9 10

(Not tired) (Very Tired)

How do you feel comparing to the last session?

Note:

Appendix F - Crossover Experiment Forms

Participant No.

THE UNIVERSITY of York

Participant consent --- Group A (Con-son)

Purpose:

The study is a crossover trial to measure the difference in biceps curl exercise quality with and without real-time auditory feedback. The experiment involves eight sessions. Participants will be asked to perform the same exercise in each session. You are assigned to Group A, which means the auditory feedback will be provided in the last 4 sessions instead of the beginning 4 sessions.

This study is part of Jiajun Yang's doctoral research of facilitating auditory feedback for improving the quality of general physical exercise.

Procedure:

If you agree to take part in this study, you will be asked to do the following:

1. Fill in a pre-participation form;
2. In the test, you will be asked to stick an EMG sensor on your skin above the biceps. <u>Because of this we suggest that you wear a short sleeve cloth for the ease of attaching the electrode.</u> You will be asked to face towards the Kinect camera for movement tracking.
3. Choose a suitable dumbbell weight. The weight of the dumbbell cannot be changed within the session but it may vary in the future sessions.
4. Perform biceps curl exercises. Even though the quantity is entirely up to you, it is suggested that you do approximately 10 – 12 repetitions in each set.
5. Complete a short survey after each session.
6. In the feedback trial, the facilitator will explain to you the use of the auditory feedback. You will need to listen to the feedback while doing the same exercise.

You will be asked to complete all eight sessions of the study. Each session will take approximately 20 minutes. A small selection of edible treats is provided after each session.

Disclaimer

Your participation in this study is entirely voluntary and you may refuse to complete the study at any point during the experiment, or refuse to answer any questions with which you are uncomfortable. You may also stop at any time and ask the researcher any questions you may have. Your name will never be connected to your results or to your response on the questionnaires. Instead, a number (such as subject 1) will be used for identification purposes. The researcher will guarantee that none of the personal information will be released to the public. Information that would make it possible to identify you or any other participant will never be included in any sort of report. The data will be accessible only to those working on the doctoral research.

Contact Detail:

If you have any questions regarding this study you may contact Jiajun Yang at jy682@york.ac.uk.

Statement of Consent:

I have read the above information. I have asked any questions I had regarding the experimental procedure and they have been answered to my satisfaction. I consent to participate in this study.

Name of Participant (please print): ____________________ Date:________________

Signature of Participant: ____________________________

Age:

Gender:

Thank you for your participation!

Department of Electronics, Audio Lab

Session record:

1.

Date:

Weight

Repetitions:

Mode use:

2.

Date:

Weight

Repetitions:

Mode use:

3.

Date:

Weight

Repetitions:

Mode use:

4.

Date:

Weight

Repetitions:

Mode use:

5.

Date:

Weight

Repetitions:

Mode use:

6.

Date:

Weight

Repetitions:

Mode use:

7.

Date:

Weight

Repetitions:

Mode use:

8.

Date:

Weight

Repetitions:

Mode use:

Participant No.

THE UNIVERSITY of York

Participant consent --- Group B (Son-con)

Purpose:

The study is a crossover trial to measure the difference in biceps curl exercise quality with and without real-time auditory feedback. The experiment involves eight sessions. Participants will be asked to perform the same exercise in each session. You are assigned to Group B, which means the auditory feedback will be provided in the first 4 sessions instead of the final 4 sessions.

This study is part of Jiajun Yang's doctoral research of facilitating auditory feedback for improving the quality of general physical exercise.

Procedure:

If you agree to take part in this study, you will be asked to do the following:

1. Fill in a pre-participation form;
2. In the test, you will be asked to stick an EMG sensor on your skin above the biceps. <u>Because of this we suggest that you wear a short sleeve cloth for the ease of attaching the electrode.</u> You will be asked to face towards the Kinect camera for movement tracking.
3. Choose a suitable dumbbell weight. The weight of the dumbbell cannot be changed within the session but it may vary in the future sessions.
4. Perform biceps curl exercises. Even though the quantity is entirely up to you, it is suggested that you do approximately 10 – 12 repetitions in each set.
5. Complete a short survey after each session.
6. In the feedback trial, the facilitator will explain to you the use of the auditory feedback. You will need to listen to the feedback while doing the same exercise.

You will be asked to complete all eight sessions of the study. Each session will take approximately 20 minutes. A small selection of edible treats is provided after each session.

Disclaimer

Your participation in this study is entirely voluntary and you may refuse to complete the study at any point during the experiment, or refuse to answer any questions with which you are uncomfortable. You may also stop at any time and ask the researcher any questions you may have. Your name will never be connected to your results or to your response on the questionnaires. Instead, a number (such as subject 1) will be used for identification purposes. The researcher will guarantee that none of the personal information will be released to the public. Information that would make it possible to identify you or any other participant will never be included in any sort of report. The data will be accessible only to those working on the doctoral research.

Contact Detail:

If you have any questions regarding this study you may contact Jiajun Yang at jy682@york.ac.uk.

Statement of Consent:

I have read the above information. I have asked any questions I had regarding the experimental procedure and they have been answered to my satisfaction. I consent to participate in this study.

Name of Participant (please print): ____________________ Date:________________

Signature of Participant: ____________________________

Age:

Gender:

Thank you for your participation!

Department of Electronics, Audio Lab

Session record:

1.

Date:

Weight

Repetitions:

Mode use:

2.

Date:

Weight

Repetitions:

Mode use:

3.

Date:

Weight

Repetitions:

Mode use:

4.

Date:

Weight

Repetitions:

Mode use:

5.

Date:

Weight

Repetitions:

Mode use:

6.

Date:

Weight

Repetitions:

Mode use:

7.

Date:

Weight

Repetitions:

Mode use:

8.

Date:

Weight

Repetitions:

Mode use:

Control Trial

Survey

1. Please rate your tiredness:

1 2 3 4 5 6 7 8 9 10
(Not tired) (Exhausted)

2. When you were lifting the dumbbell, how often did you use other parts of your body to help out (such as bending your waist)?

(1) Never
(2) Only when I am very tired
(3) Around half of the time
(4) Mostly

Please skip question 3 & 4 if this is your first session.

3. Did you feel easier compare to the last session?

1 2 3 4 5 6 7 8 9 10
(Lot harder) (No difference) (Lot easier)

4. How would rate the overall exercise quality compare to the last session?

1 2 3 4 5 6 7 8 9 10
(Lot worse) (No difference) (Much better)

5. Do you feel any improvement in terms of the muscle strength?

1 2 3 4 5 6 7 8 9 10
(Lot worse) (No difference) (Much better)

6. How much did you enjoy the work out?

1 2 3 4 5 6 7 8 9 10
(Not at all) (Very enjoyable)

7. Please describe the difference you notice?

8. Have you done any biceps relative exercise since the last session?

Thank you!

Sonification Trial

Survey

1. Please rate your tiredness:

1 2 3 4 5 6 7 8 9 10
(Not tired) (Exhausted)

2. How would you rate the sound?
1 2 3 4 5 6 7 8 9 10
(Dislike) (Like)

3. Do you think the sound gave you sufficient feedback?
1 2 3 4 5 6 7 8 9 10
(Confusing) (Informative)

4. How much attention did you pay to the sound during the exercise?
1 2 3 4 5 6 7 8 9 10
(Little) (Lot)

5. When you were lifting the dumbbell, how often did you use other parts of your body to help out (such as bending your waist)?
(1) Never
(2) Only when I was very tired
(3) Around half of the time
(4) Mostly

Please jump to question 10 if this is your first session

6. Did you feel easier compare to the last session?
1 2 3 4 5 6 7 8 9 10
(Lot harder) (No difference) (Lot easier)

7. How would rate the overall exercise quality compare to the last session?
1 2 3 4 5 6 7 8 9 10
(Lot worse) (No difference) (Much better)

8. Do you feel any improvement in terms of the muscle strength?
1 2 3 4 5 6 7 8 9 10
(Lot worse) (No difference) (Much better)

9. How much did you enjoy the work out?

1	2	3	4	5	6	7	8	9	10
(Not at all)								(Very enjoyable)	

Open comments, please ignore if this is the first session.

10. Please specify any other differences compare to the previous session?

12. Have you done any biceps relative exercise since the last session?

Thank you!

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