TÉCNICO LISBOA

Body Perception Manipulation with Real-Time Movement Sonification of Upper Body Exercises

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Thesis to obtain the Master of Science Degree in

Computer Science and Engineering

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October 2020

Acknowledgments

First of all, I want to thank my supervisors Prof. Hugo Nicolau and Prof. Daniel Lopes for their insight, sharing of knowledge and all the support throughout the development of this dissertation. Thank you for always being so understanding.

I want to thank Fundação para a Ciência e Tecnologia for financing the necessary equipment for the development of this dissertation through the ARCADE (PTDC/CCI-COM/30274/2017) project.

To my friends from Técnico Andreia Rogério, Diana Antunes, Eduardo Janicas, Nuno Fernandes, Patrícia Lopes, Pedro Fernandes and Rui Agostinho that made this whole experience memorable and helped me grow as a person throughout my bachelor's and master's years. Thank you for always being there, despite the distance. To Miguel Renda, for all the mutual support, for the reflections and opinions and the sharing of problems and afflictions, as well as the victories.

To my hometown friends Ana Moreno, João Barreiras, Pedro Costa, Pedro Vicente, Samuel Arcadinho and Tatiana Lopes for all the words of encouragement, for always being ready to cheer me up and take me on walks and picnics.

I want to thank João Silva for all his support, for all the optimism, serenity and patience.

Last but not least, I want to thank my parents and my brother for always believing in me and supporting me over all these years. Thank you for always having encouraged and comforted me when I needed, especially during the difficult months of confinement.

To each and every one of you – Thank you.

Abstract

Recent research has shown that movement sonification is an effective way of conveying information about the movement being performed. Real-time movement sonification has been proven to have the ability to manipulate body perception and feelings, however, existent research on this field has mainly used sensors attached to the body and focused mainly on exercises of the lower limbs. Hence, we propose a prototype for real-time sonification of an upper limb exercise using a dumbbell equipped with an inertial sensor. A user study with 10 participants was conducted, with relevant findings on perceived body weight and perceived capability and promising results for future research. The developed prototype was well accepted by the users and show potential for supporting exercise practice in inactive and unmotivated people.

Keywords

Sonification; IMU; Body perception; Body feelings; Exercise.

Resumo

Investigação recente mostrou que a sonificação de movimento é um modo eficaz de transmitir informação sobre o movimento a ser feito. Foi provado que sonificação de movimento em tempo real tem a capacidade de manipular a percepção e os sentimentos relativos ao corpo, contudo os estudos existentes na sua grande maioria usaram sensores fixados ao corpo e focaram-se principalmente em exercícios dos membros inferiores. Propomos aqui um protótipo para a sonificação em tempo real de um exercício dos membros superiores usando um peso equipado com um sensor de inércia. Foi conduzido um estudo com 10 participantes com conclusões relevantes relativamente à percepção do peso corporal e percepção de capacidade/aptidão e com resultados promissores para investigação futura. O protótipo desenvolvido foi bem aceite pelos utilizadores e tem potencial para apoiar indivíduos inativos e desmotivados na prática de exercício.

Palavras Chave

Sonificação; IMU; Percepção do corpo; Sentimentos do corpo; Exercício.

Contents

1 Introduction **1**

1.1 Problem Statement 3

1.2 Approach 3

1.3 Contributions 4

1.4 Organization of the Document 4

2 Background and Related work **5**

2.1 Sound and Sonification 7

2.2 Sound in Physical Activity and Rehabilitation 8

2.3 Sound to manipulate Body Perception and Feelings 11

2.4 Discussion 14

3 System Overview **17**

3.1 Sonification Design 19

3.1.1 Dumbbell hammer curl 19

3.1.2 Sonification parameters 20

3.1.2.A Angular velocity mapped onto Amplitude 20

3.1.2.B Pitch mapped onto Frequency 20

3.1.2.C Inform limit of movement 20

3.2 Architecture 21

3.2.1 Dumbbells 21

3.2.2 Inertial Measurement Unit 22

3.2.3 Sound synthesis software 23

3.2.4 Communication protocol 24

3.3 Extending to other movements and applications 25

4 Evaluation **27**

4.1 Research Questions 29

4.2 Participants 29

4.3 Apparatus 29

4.4 Study Design 29
4.4.1 Data 30
4.5 Procedure 30
4.6 Data Analysis 31
4.7 Results 32
4.7.1 Performance time 32
4.7.2 Dumbbell weight perception 33
4.7.3 Body feelings 34
4.7.3.A Speed perception 34
4.7.3.B Body weight perception 34
4.7.3.C Strength perception 34
4.7.3.D Capability perception 35
4.7.3.E Difficulty perception 36
4.7.3.F Tiredness perception 36
4.7.4 Emotions 37
4.7.4.A Pleasure 37
4.7.4.B Arousal 38
4.7.4.C Dominance 38
4.7.5 Informal opinions 39
4.8 Discussion 39

5 Conclusions and Future Work **41**
5.1 Conclusions 43
5.2 System Limitations and Future Work 44

A Sonification code **49**

B User study forms **53**

List of Figures

2.1 Architecture and data flow of the system used in [1]. 9

2.2 COPDTrainer training approach: The smartphone app is meant to enable individual training options of a patient, besides the training with therapists. (1): Patient/therapist selects Teach-mode or Train-mode. (2): Select an exercise, here Arm extension. (3): Begin exercising after pressing start. (4): After exercising different summary screens are shown, depending on the operation mode. 10

2.3 Overview of the device developed in [2]. 12

2.4 Device attached to person's back for sonifying trunk movement during the forward reach exercise. 14

3.1 Representation of the hammer dumbbell curl exercise, here in the bilateral version. Image downloaded from [3]. 19

3.2 System Architecture of the developed prototype. 21

3.3 The tree dumbbells of our prototype and the Inertial Measurement Unit (IMU) which can be attached to any of the weights. 22

3.4 Bitalino R-IoT kit with battery and charging cable [4]. 22

3.5 SuperCollider Integrated Development Environment (IDE). 23

4.1 Participant performing unilateral hammer dumbbell curl using the developed prototype. . . 31

4.2 Performance time means in the three different conditions. 32

4.3 Boxplot of the values for performance time in the three different conditions. 33

4.4 Dumbbell weight perception means in the three different conditions. 33

4.5 Speed perception means in the three different conditions. 34

4.6 Body weight perception means in the three different conditions. 35

4.7 Strength perception means in the three different conditions. 35

4.8 Capability perception means in the three different conditions. 36

4.9 Difficulty perception means in the three different conditions. 36

4.10 Tiredness perception means in the three different conditions. 37
4.11 Pleasure means in the three different conditions. 37
4.12 Arousal means in the three different conditions. 38
4.13 Dominance means in the three different conditions. 38

List of Tables

2.1 Summary of the main features reported within the revised studies. 15

Listings

3.1 Excerpt of the SuperCollider code for the high frequency sonification. 23
A.1 SuperCollider code. 49

Acronyms

ANOVA Analysis of Variance

BPD Body-Perception Disturbances

COVID-19 Coronavirus disease 2019

CRPS Complex Regional Pain Syndrome

IDE Integrated Development Environment

IMU Inertial Measurement Unit

IP Internet Protocol

OSC Open Sound Control

WLAN Wireless Local-Area Network

1

Introduction

Contents

1.1 Problem Statement 3
1.2 Approach 3
1.3 Contributions 4
1.4 Organization of the Document 4

A sedentary lifestyle is a serious problem of our society, with the inactive and highly sedentary segment of the population being at greatest risk of poor health [5]. Globally, 23% of adults are not active enough, and 81% of the world's adolescent population is insufficiently physically active [6]. These numbers lead to an increase in the risk of noncommunicable diseases, such as cardiovascular diseases, cancer and diabetes [6]. These numbers also represent rising levels of obesity, which means higher rates of heart disease and stroke, poor quality of life, and decreased life expectancy [7]. According to the World Health Organization, regular and adequate levels of physical activity reduce the risk of several non-communicable diseases (including various types of cancer) and depression, playing also a fundamental role in weight control [8]. Hence, physical activity not only has health benefits but also attenuates the health risks of high volumes of sedentary time [5].

Resistance training is known to considerably contribute to the referred health benefits [9, 10]. While aerobic activities can be performed anywhere, resistance training is traditionally performed at the gym [11], which is richly equipped with different machines and objects for specific exercises. Inactive people tend to recur to the gym to start being more active, where they can also find counseling. Typical resistance exercises are mainly based on repetitive movements [9], which are commonly used to strengthen muscles and improve coordination [12]. Due to the repetitive nature of the activity, individuals usually perform these exercises without the need for supervision, hence without any feedback.

1.1 Problem Statement

Due to the repetitiveness of the exercises, individuals get physically and mentally tired and easily become bored with the training. People often find the exercises too difficult and feel their body is not made for exercising. They assume their body feelings as facts about their body. But can these feelings be manipulated?

1.2 Approach

Sound has the ability to give information about movement [13] and manipulate body perception and feelings [2, 14–18]. It has been proven that altering the sound of steps can make people perceive themselves as lighter or heavier if the sound has a higher or lower frequency, respectively [2]. Sonification of lower limb exercises has also been proven to make people feel less tired and more in control, being more comfortable, motivated, and happier [15]. Based on these findings, we used sound as a means for body perception and feelings manipulation but focused on a resistance exercise for the upper limbs, that have not been addressed as much as the lower limbs. Focusing on a specific upper limb exercise using a weight, we designed a movement sonification with two different ranges of sound frequency in order to manipulate users' body perception and body feelings, since body perception and feelings can influence the predisposition people have for exercising. For the sonification design, we used a sound synthesis software to map movement features into sound parameters, using an off-the-shelf inertial sensor on a "tape on and forget" approach, which can easily be attached to different objects. Based on our research, we hypothesized that higher frequency sounds would make the exercise seem easier and the user feel lighter, happier and less tired, and lower frequencies would make the exercise seem more difficult with the user feeling heavier, less happy and more tired.

1.3 Contributions

This dissertation aims to explore how movement sonification can influence body perception and feelings when performing an upper limb movement using a dumbbell. Our contributions are:

- A prototype for real-time sonification of a movement using a dumbbell.
- A user study that evaluated the effects of using the prototype.

1.4 Organization of the Document

This document is organized as follows. Chapter 2 gives the background for this work, explaining the concepts of sonification and interactive sonification. We then describe the related work relevant to our study and end the chapter discussing the articles revised. In chapter 3 we describe our solution, explaining the sonification design as well as the exercise choice, and the architecture of our system. Chapter 4 explains the evaluation process, describing the user study in detail. We present the data analysis and results obtained and end by discussing our findings. The document ends with chapter 5, where we present our conclusions and describe the limitations and future work.

2

Background and Related work

Contents

2.1 Sound and Sonification 7

2.2 Sound in Physical Activity and Rehabilitation 8

2.3 Sound to manipulate Body Perception and Feelings 11

2.4 Discussion 14

This chapter explains the advantages of using sound and the concepts of sonification and interactive sonification. Then, we present the most relevant studies that were found on the use of sound for physical activity applications and manipulating body perception and feelings. The chapter ends with a discussion on the revised studies.

2.1 Sound and Sonification

Sound can be conveyed in different ways such as music, speech and ambient sounds. For a long time, sound was neglected by interface engineers and designers in favor of graphics, however, it has an important role in conveying information [19]. We can have knowledge of what is surrounding us by listening to the environment, or know what to do by listening to instructions given through speech. Another significant aspect of sound is its emotional expressiveness, which is one of the most important methods of human communication. Emotional information is carried not only in human speech but also in music and ambient sounds. Modulation of the acoustics enables the transmission of this information, which is then decoded by the receiver, which can be the audience of a concert or a human conversation partner [20].

In physical activity such as sports or rehabilitation treatments, sound is particularly useful for providing feedback on the performance, with speech being the most widely used way of conveying this type of information. Recently, technology evolution enabled opportunities for different ways of providing feedback for individuals doing exercise. Sound represents several benefits when chosen as the way of providing information in physical activity, such as the fact that it does not interfere with movement and allows delivering several streams of information simultaneously and continuously [21, 22]. Another advantage is that audition operates relatively well even in noisy environments, it offers high temporal resolution and high sensitivity for the detection of structured motion (rhythm) and rapid changes [21, 23], with this detection being faster than the observed for the visual system [24]. Hence, beyond being enjoyable and entertaining, sounds are also beneficial to trigger intuitive, fast and accurate responses in users, and to continuously give information about the performance.

One method for conveying information through sound is sonification, which can be defined as the use of non-speech audio to convey information [22]. More precisely, sonification can be described as a mapping of multidimensional datasets into an acoustic domain, which can then be used to obtain a deeper understanding of the data or processes under investigation [25]. It can be seen as the auditory equivalent of data visualization [26]. Interactive sonification in particular is defined by Hermann et al. [25] as ”the use of sound within a tightly closed human-computer interface where the auditory signal provides information about data under analysis, or about the interaction itself, which is useful for refining the activity”.

2.2 Sound in Physical Activity and Rehabilitation

By applying the powerful technique of interactive sonification to sensor data recorded during physical activity, it is possible to turn a rhythmic activity into a sonic rhythm so that the listeners can understand the coordination during the movement [13]. Human-computer interaction research has already works on the physical exercise context using sound. Hermann et al. [13] introduced a new system for the interactive sonification of sports movement involving arm and leg movements. With the aim of enabling visually impaired users to participate in aerobics exercises, and also enhancing the perception of movements for sighted participants, this system allowed listeners to identify features of the underlying coordinated movements. After some learning time, visually impaired users were expected to conduct the exercises with much less verbal explanations or corrections. In this article, the authors showed a prototype for the aerobics sonification for the restricted case of knee and elbows sensing, dedicated to exercises performed at a fixed location. For sensing motion-relevant information, arm and leg postures were tracked using self-made goniometers, and data were then streamed to a computer via Bluetooth while the sonification was implemented using SuperCollider [27]. The first sonification approach used the real-time data of elbow and knee angles for a basic continuous parameter mapping sonification, modified so that the sonification was excitatory – if there are no changes in the posture, there is no sound. The second approach was an event-based sonification, which aimed to "reduce the sound as much as possible so that it becomes sparser to free the auditory space for more specific and articulated sonic cues that identify critical or significant events." It was concluded that despite being coarser (may not be sufficient to reproduce the movement accurately), the event-based sonification was perhaps superior to recognize the pattern and to emphasize the detailed synchronization between joints.

Effenberg et al. [28] described a new method of movement sonification to enhance motor learning on the practice of indoor rowing. For the sonification, the data collected were grip force, bilateral footrest forces, grip pull-out length and sliding seat position. Each data stream was transferred to the sonification software MLmini[1] and was used to modulate the frequency and partially amplitude of a certain sound. Normalization was used to enable users to generate the same sound pattern as the model, independently of individual physical abilities and strengths. The study included forty-eight novices with no rowing experience, divided by three samples: Visual condition (only treated with video information); Natural audiovisual condition (treated with video and natural motion attended sounds of the rowing machine); Sonified audiovisual condition (treated with video and 4-channel movement sonification). The distance values between the model's technique and participants' technique were calculated using dynamic time warping (a general time alignment and similarity measure for two temporal sequences [29]), and it was possible to conclude that the sonified audiovisual condition resulted in faster and more precise learning compared to both other samples.

[1] Software MLmini, University of Bonn, Institut of Computer Graphics, Prof. Andreas Weber.

Dance sonification has been addressed by Landry et al. [1], which described a process of designing and testing a dancer sonification, with the end goal of having dancers generate aesthetically pleasing music in real-time based on their movements, instead of dancing to pre-recorded music. The authors adopted a participatory design research methodology, having recruited expert dancers and musicians. The system used included a Vicon tracking system with twelve infrared cameras and the sonification algorithm was programmed in PureData, a real-time graphic dataflow programming environment. Figure 2.1 shows the architecture of the system. Three sonification scenarios were evaluated with twenty-

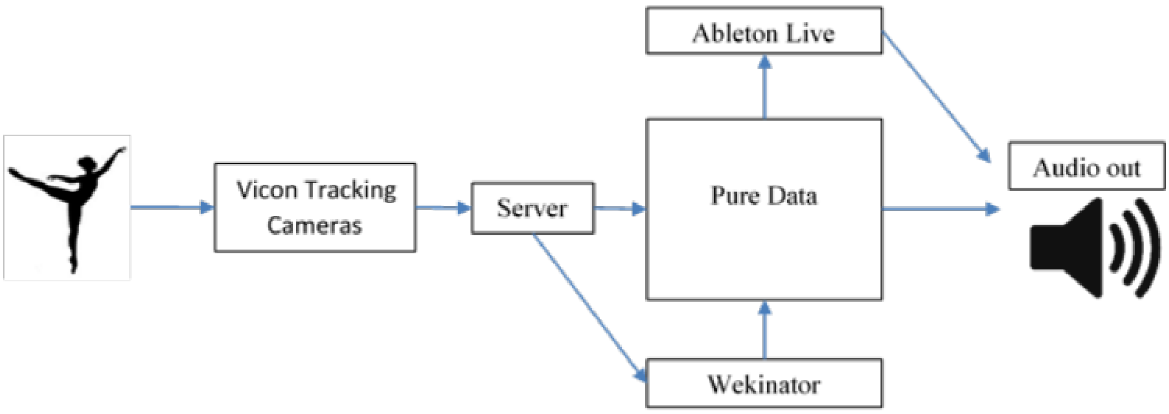

Figure 2.1: Architecture and data flow of the system used in [1].

three novice dancers, and one of the scenarios was described as pleasant and gratifying. In all scenarios, users perceived they could control more aspects of the sound than they actually could. It was concluded that domain expert feedback is really valuable and it is difficult to achieve a good balance between user control and system automation.

A physical rehabilitation tool named PhysioSonic was presented by Groß-Vogt et al. [30] to provide exact feedback in real-time, without the subjective filter of the therapist. This study focused on the kinematics of the shoulder joint, which was transformed into an auditory feedback used to correct false postures or coordinate a therapeutic exercise for the shoulder joint. The tracking system data were used to synthesize sound and transform sound files (music or text), which composed the auditory feedback. Sounds of nature, music and texts were used, and all metaphoric sounds and sonification designs allowed to hear the correct sound only if the movement was correctly performed. Patients positively accepted PhysioSonic, which has enriched the therapeutic offer according to their statements.

COPDTrainer is a smartphone-based training system that was presented by Spina et al. [31]. The system used the smartphone built-in sensors for movement detection and provided real-time audio feedback (verbal). The smartphone was attached to one of the limbs, and during the execution of exercises, the user was provided with acoustic feedback on the counted repetitions and notified when errors occurred with notes such as “move slower” or “move faster and higher”. All instructions were provided in the smartphone app (fig. 2.2). The system was evaluated with healthy users and also with a group of chronic pulmonary obstructive disease patients, and the viability of the prototype was demonstrated, with high accuracy on repetitions count and high trainee performance classification rate.

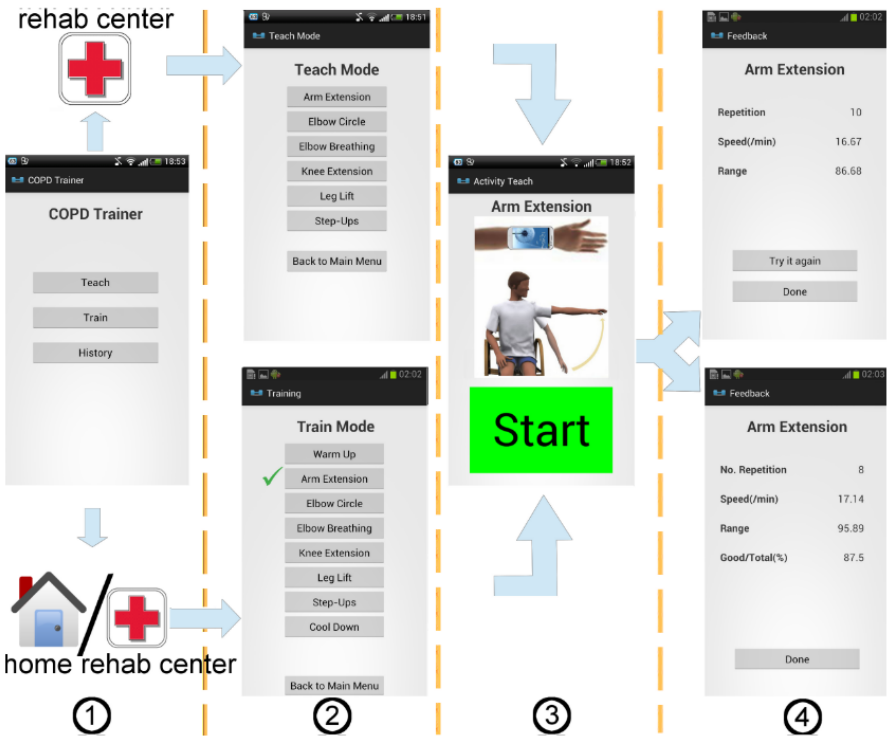

Figure 2.2: COPDTrainer training approach: The smartphone app is meant to enable individual training options of a patient, besides the training with therapists. (1): Patient/therapist selects Teach-mode or Train-mode. (2): Select an exercise, here Arm extension. (3): Begin exercising after pressing start. (4): After exercising different summary screens are shown, depending on the operation mode.

Horsak et al. [32] described a prototype of a pair of instrumented insoles for real-time gait sonification. The instrumented insoles were equipped with seven force sensors, and data were streamed via Bluetooth to the PureData audio generation software. Five different sonifications were evaluated and results suggested that sonification had an effect on gait parameters, however, further investigation was needed in order to understand the benefits of such effect for gait rehabilitation.

The goal of Newbold et al. [33] was to investigate how musically informed movement sonification could be used to avoid overdoing and facilitate progress during stretching exercises. The approach was based on harmonic stability. This means that when a sound was stable, it would give the idea of conclusion, while when the sound was unstable, it would give the idea of continuity, making users behave according to these perceptions. This approach was tested with a bending trunk exercise, where a smartphone was placed on the participant’s lower back. A smartphone application was used, taking advantage of the built-in gyroscope for the bending measure. This measure drove the sonification. It was showed that ending of different stabilities can be used to either encourage movement (unstable) or provide a definite endpoint (stable). These definite endpoints were also seen as more rewarding.

Scholz et al. [34] presented a musical sonification therapy, designed to retrain gross motor functions after stroke. The prototype was composed of two inertial sensors (attached to the forearm and upper arm), and the sonification was generated so that the use of the system was compared to playing the theremin. The study included twenty-five stroke patients randomly assigned to each of two groups – music group and control group. Patients in the music group were encouraged to actively play and create music by moving their arms. The music group showed significantly reduced joint pain, a trend to improve hand function, and also significantly better movement smoothness.

2.3 Sound to manipulate Body Perception and Feelings

Sound is known to contribute with information about movement, being capable of altering people's body feelings and perception when listening to their "body sounds". These sounds can be the real sounds produced by the body (that can be altered) or can be artificially produced (sonification). Tajadura-Jiménez et al. [35] showed that the perceived tactile distance is affected by the sound of one's actions. The study had participants tapping on a surface while progressively extending the right arm, and in synchrony with each tap users listened to a tapping sound that was spatially manipulated for three different conditions. The results showed that exposure to the tapping sounds with double auditory distance resulted in a significant increase in participants' perceived tactile distance on the test arm, while with the quadruple auditory distance the users reported that they did not feel the tapping and the sound originated at the same location. These results pointed to the limitations of the plasticity of body-representation in response to auditory manipulations, with body-representation being manipulable only by nearby auditory sources that convey adequate spatial information allowing participants to effectively locate their own action sounds.

In a similar context, a prototype for sonification of surface tapping was presented by Tajadura-Jiménez et al. [36], delivering sounds in real-time in response to a user's taps on a real or virtual surface (tapping in the air). To evaluate this system, authors quantified changes in perceived surface hardness, tapping behavior and emotional responses. The sonification was achieved by having the tapping action trigger the playing of prerecorded tapping sounds in real-time. The tapping action was detected by a piezoelectric transducer attached to the real surface and an accelerometer attached to the middle finger of the user's hand. A within-subjects design was followed, with all participants experiencing all sound conditions, presented in randomized order. It was showed that audio feedback could effectively manipulate perceived and subsequent motor behavior, emotional state, and perceived material properties.

In the physical exercise context, Fritz et al. [16] modified fitness machines, equipping them with sensors to modulate the musical audio-feedback. The objective was to explore the effects of musical agency on perceived exertion during a physically strenuous task. The movement data of the fitness machines were sent to a musical composition software (Ableton Live 8), where it was mapped to musical parameters. The study included physiological and behavioral measurements and it was shown that musical agency resulted in a significantly lower perceived exertion than passively listening to music while working out.

Relying on previous reports suggesting that listeners can extract properties of the body of an unknown walker just from the acoustic features of the walking sounds [37–39], Tajadura-Jiménez et al. [2] altered walking sounds in order to manipulate the perception that the users had of their own body. The authors investigated the influence of people's perception of their own body in the moment of exercise, following the previous study by Tajadura-Jiménez et al. [17]. A shoe-based prototype was built, allowing the dynamic modification of footstep sounds, as people walked, and measurement of walking behavior changes. Each foot was equipped with a 9-axis motion-tracking sensor and two force-sensitive resistors that were used for the gait pattern analysis, and a microphone that allowed the caption of the steps sound. The captioned sounds were then altered and fed back to the users via closed headphones. The prototype is represented in fig. 2.3. It was shown that, overall, low frequency sounds led to a heavier

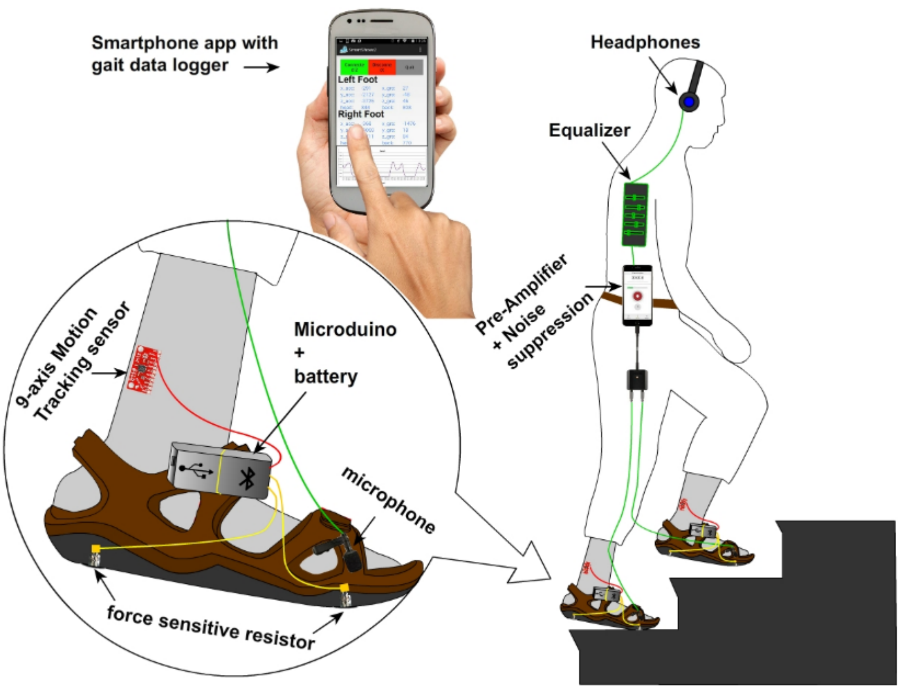

Figure 2.3: Overview of the device developed in [2].

body perception and lower foot acceleration, making participants feel more masculine and find exercise more difficult. High frequency sounds led participants do perceive themselves as lighter, feel quicker and more feminine than in the other conditions. This type of technology can be used to support people who suffer from low self-efficacy when exercising.

Following a similar approach for the sound feedback design, Tajadura-Jiménez et al. [14] used a similar prototype in a physical rehabilitation related context and investigated the potential value of using sound feedback for altering Body-Perception Disturbances (BPD) and its related emotional state and motor behavior in those with Complex Regional Pain Syndrome (CRPS). In a study that included twelve patients with CRPS who were exposed to real-time alteration of their walking sounds, results suggested that sound feedback may affect the perceived size of the affected limb and the pain experienced. Sound feedback affected CRPS descriptors and other bodily feelings and emotions including emotional dominance, limb detachment, position awareness, attention and negative feelings toward the limb. It was also suggested that the effects depend on the type of BPD, which leads to the need for future studies to phenotype patients and explore their particular BPD, bodily feelings and emotions in order to better understand how to utilize sound feedback optimally.

More recently, Ley-Flores et al. [15] followed a similar methodology, but this time tried the sonification of movement rather than modifying the sound naturally produced by one's actions. The exercises chosen were walking and thigh stretch, and the prototype consisted of a pair of shoes, each composed of a wireless emitter with an Inertial Measurement Unit (IMU) connected to two force-sensitive resistors. The data from the sensors were sent wirelessly to a computer, and the sonification was generated using the software Max/MSP (Cycling'74). Different metaphors (including wind, water and gear sounds) were taking into account to develop the sonifications, and the study showed a link between the different metaphors and body perception, with changes in body feelings and emotional state.

Ghai et al. [40] assessed the effect of real-time auditory feedback on knee proprioception. A study with thirty healthy participants was conducted, having a control group and an experimental group. The participants performed a knee reposition task, with the experimental group receiving real-time auditory feedback that consisted of knee joint angle and angular velocity being mapped onto pitch and amplitude of the sound, respectively. This sonification was generated using Python and Csound. The real-time auditory feedback showed to be beneficial, with significant enhancement in knee reposition accuracy. However, once the auditory feedback was removed, the benefits were no longer observed, which might be linked with over-dependency of the participants with the feedback.

Singh et al. [18] presented a sonification framework, Go-with-the-flow, for physical rehabilitation in chronic pain. The system was focused on psychological capabilities, worrying about what the patients felt they could perform. Designed to build confidence in movement and reduce anxiety, the authors conducted studies to evaluate two devices: a smartphone-based wearable device (fig. 2.4), that made use of the smartphone sensors and two respiration sensors, and a Kinect home-based system. For all sonification conditions tested, people found that sound feedback was always preferable to no sound feedback, on all aspects considered (awareness, performance, motivation, and relaxation). The system could be used by patients to become more confident in activity and to transfer those benefits to everyday lives. Following this work, the authors conducted a one-two week-long home study with people with chronic pain [41]. People were asked to use the device in everyday activities. It was showed that real-time sonification of functional activity movements could increase awareness of capabilities, self-efficacy and confidence.

Figure 2.4: Device attached to person's back for sonifying trunk movement during the forward reach exercise.

2.4 Discussion

In this section, we discuss the articles that represent relevant work for our design and development process. We focus on the works within the physical exercise context (including sports/physical activity and rehabilitation) that used sound to either support the activity or manipulate body perception. A summary of these studies is shown on table 2.1. The studies we include in this discussion are balanced in terms of the context to which they apply. Physical activity and physical rehabilitation have both been approached and both have already works that use sound as the main feedback method.

As tracking mechanism, the most used method is the use of inertial sensors, with eight of these studies using some form of inertial sensors on their systems. Smartphone sensors are a popular choice, due to its availability and low price. However, a smartphone is not a very small object, which might be uncomfortable for the user in some aspects. IMU's are a good choice in terms of size and usually can be chosen in terms of what is needed from them, which can make affordable choices when the system does not require a very complex set of sensing data. Other studies used different sensing mechanisms such as goniometers or force sensors and two studies used the VICON motion tracking system, which captures movement making use of infrared cameras that track markers attached to the human body. This type of tracking system is much less affordable and is not portable, despite being a reliable and accurate method of tracking movement.

The sensing units are mostly attached to the human body, as most of the solutions studied do not

Table 2.1: Summary of the main features reported within the revised studies.

Article	Context	Tracking method	Location of sensors	Sound	Software
Hermann et al. [13]	Physical Activity	Goniometers	Arm and leg	Sonification	SuperCollider
Effenberg et al. [28]	Physical Activity	Inertial sensors (not specified)	Fitness machine	Sonification	MLmini
Landry et al. [1]	Physical Activity	VICON motion tracking mechanism	-	Sonification	PureData
Groß-Vogt et al. [30]	Rehabilitation	VICON motion tracking mechanism	-	Sonification	SuperCollider
Spina et al. [31]	Physical Activity	Smartphone sensors	One of the limbs	Spoken	-
Horsak et al. [32]	Rehabilitation	Force sensors	Insoles	Sonification	PureData
Newbold et al. [33]	Rehabilitation	Smartphone sensors	Lower back	Sonification	Not specified
Scholz et al. [34]	Rehabilitation	IMU	Wrist and upper arm	Sonification	Synthesis Toolkit
Fritz et al. [16]	Physical Activity	Inertial sensors (not specified)	Fitness machine	Sonification	Ableton Live
Tajadura-Jiménez et al. [2]	Physical Activity	-	-	Alter natural sounds	-
Tajadura-Jiménez et al. [14]	Rehabilitation	-	-	Alter natural sounds	-
Ley-Flores et al. [15]	Physical Activity	IMU and Force Sensors	Ankle and insoles	Sonification	Max/MSP
Ghai et al. [40]	Rehabilitation	IMU	Leg	Sonification	Csound
Singh et al. [18]	Rehabilitation	Smartphone sensors and Respiration sensors	Trunk	Sonification	Not specified

use objects for the performance of the exercises. From the studies that used sensors, only two of them did not place the sensing objects on the human body, placing them in fitness machines instead. When attaching the sensors to the body, the system becomes less versatile, as the sensor has to be moved depending on the exercise being performed. When the sensors are fixed to the objects in use, the users only use them when performing the exercise, and do not need to have any devices attached to them when resting. Not having the sensors attached to the body results in a more comfortable solution for the user.

We focused mainly on studies that worked with movement sonification, however, we include here some works that did not develop a sonification, due to its relevance in terms of body perception manipulation, especially [2] and [14] that are strong inspirations for the present work. The authors altered natural sounds of footsteps in order to manipulate body perception and feelings. Following that approach, our work aims to follow a similar methodology but closer to the one followed in [15], where body perception manipulation is attempted with movement sonification.

Multiple software packages were used in the revised studies. MLmini, Ableton Live and Max/MSP are not open-source, thus will not be further considered. PureData is a visual programming language for multimedia, while SuperCollider, Synthesis Toolkit and Csound do not have a visual interface and imply code writing. The choice of either of them is mainly personal since the three of them are adequate for receiving sensor data and sonify movements.

There is still a lack of literature on the field of movement sonification. We could find some research regarding the use of IMU's to track movement and develop sonifications to explore how that can manipulate body perception and feelings. However, research dedicated to upper limb movements is still scarce, with the upper limbs having received much less attention than the lower limbs, and very few articles showed a placement for the sensors different than the body. Our aim is to explore how a dumbbell equipped with an IMU can be used to sonify an upper limb exercise and manipulate body perception and feelings. Most revised studies developed sonification designs based on simple mappings between movement features and sound parameters. Since we are trying to address a specific case that to the best of our knowledge has not been explored, we will stick to a simple mapping too. More complex designs may mask the effects of a simple sonification, which effects must be known in order to inform the development of more complex designs.

3

System Overview

Contents

3.1 Sonification Design 19
3.2 Architecture 21
3.3 Extending to other movements and applications 25

This chapter describes the sonification design and the architecture of the system, explaining the development work.

3.1 Sonification Design

This section covers the reasons for our exercise choice and the sonification design process, explaining the different parameter mappings.

3.1.1 Dumbbell hammer curl

Resistance training implies an external resistance, and that is why it is so common to use weights, such as dumbbells. Being one of the most common equipment used in this type of activity, we decided to choose an exercise that would make use of a dumbbell (to which we attach the sensing unit). The chosen exercise is the dumbbell hammer curl, which is a simple exercise that works the upper limbs, with a special impact on the biceps. It is performed by holding the dumbbell as if it was a hammer, and flexing the elbow while having the upper arm in a vertical position and static (fig. 3.1). The type of movement performed in the dumbbell hammer curl is very relatable to other exercises that use a dumbbell, making it simple to adapt the sonification for other types of exercises. The simplicity of the exercise also makes testing less complex. With more complex exercises, we would need a specialist to explain the exercise to users and check the performance.

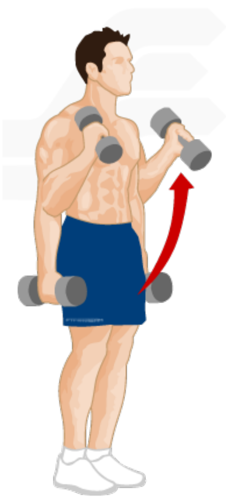

Figure 3.1: Representation of the hammer dumbbell curl exercise, here in the bilateral version. Image downloaded from [3].

3.1.2 Sonification parameters

The real-time auditory feedback was inspired by the designs developed by Ghai et al. [40] and Ley-Flores et al. [15] and was generated using SuperCollider [42], which is a free and open-source software for audio synthesis and algorithmic composition. We chose to use SuperCollider as sonification software mainly due to the resources freely available online.

Our sound synthesis was based on a sine wave oscillator, with amplitude and frequency being modulated by angular velocity and pitch angle, respectively. Amplitude and frequency were chosen because they represent sound features easily identified by the listener, with amplitude being perceived as the loudness of the sound, and frequency being perceived as the pitch (to not be confused with the pitch angle mentioned in 3.1.2.B). At the limit of the elbow flexion, a different sound is played, indicating the contrary movement is to start. Following the studies that showed that different frequencies would influence body feelings in different ways [2, 17], our sonification has two versions, that differ in frequency ranges.

3.1.2.A Angular velocity mapped onto Amplitude

Angular velocity was derived from the 3-axis gyroscope as shown in the equation below, where ω represents the angular velocity.

$$\omega = \omega_x^2 + \omega_y^2 + \omega_z^2 \ (^\circ/s)$$

Angular velocity was then directly mapped onto sound amplitude, which represents the volume.

3.1.2.B Pitch mapped onto Frequency

Euler angles (yaw, pitch and roll) can describe the 3D orientation of an object using a combination of three rotations about different axes. When moving the arm as it is moved in the dumbbell hammer curl, that movement corresponds to changes in the pitch. Pitch values are mapped onto the frequency of the sound, by modulating the values into a range of frequencies. In the low frequency sonification, the frequency ranges from 100 to 1000 Hz, while in the high frequency sonification, the frequency ranges from 200 to 2000 Hz.

3.1.2.C Inform limit of movement

When the arm reaches the limit of elbow flexion in each repetition, a different sound is heard, which is also based on a sine wave oscillator, but its frequency is controlled by a low frequency noise generator at a specified rate and range of frequencies. As previously explained for the pitch mapping, the difference between the two sonifications here is also the frequency. The function that defines this sound is freed once it is played, and is called each time the arm reaches the limit of elbow flexion. This limit is controlled by observing the pitch angle, when it is higher than a defined threshold (which is defined for each user through initial calibration), the function is called.

3.2 Architecture

This section presents the architecture of the developed prototype and describes each of its components and processes. Figure 3.2 shows a diagram of the architecture. The prototype is composed of a dumbbell to which can be attached a Bitalino R-IoT IMU [4] which collects data from the movement being performed; these data are wirelessly transmitted to the sound synthesis software SuperCollider [42] running on a personal computer, and the produced sound is fed back to the user via headphones. In order to establish the wireless communication between the IMU and the computer, the hotspot functionality of a smartphone was used to create the network.

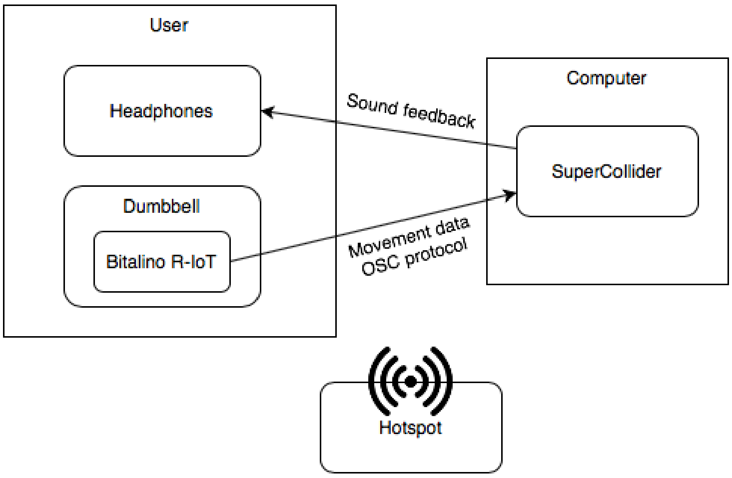

Figure 3.2: System Architecture of the developed prototype.

3.2.1 Dumbbells

For purposes of the user study design (see chapter 4), our prototype is composed of three dumbbells instead of only one. Although they have different colors, they all have the same weight of 1 kg. Figure 3.3 shows the three dumbbells with a fixing system that allows easily attach the IMU to any of them. The dumbbells originally had the same color and were wrapped up in colored lamination paper. This adhesive lamination paper was used to attach a small piece of an elastic to each of the dumbbells. The elastic allows a tight attachment of the IMU to the dumbbell.

Figure 3.3: The tree dumbbells of our prototype and the IMU which can be attached to any of the weights.

3.2.2 Inertial Measurement Unit

The sensing unit used was Bitalino R-IoT [4] (fig. 3.4), which includes a triaxial accelerometer, a triaxial gyroscope and a triaxial magnetometer and transmits at a sampling rate of 200 Hz. The IMU sensor data are locally processed (sensor fusion), analyzed and streamed in an Open Sound Control (OSC) message (see section 3.2.4 for OSC protocol description) wirelessly by the module using its firmware. Each OSC message has a list of 21 values that includes the sensor's data and also the computed values for quaternions and Euler angles.

Figure 3.4: Bitalino R-IoT kit with battery and charging cable [4].

3.2.3 Sound synthesis software

SuperCollider [42] is a free open-source platform for sound synthesis and algorithmic composition. This powerful software allows real-time analysis of external data and sound synthesis based on those data. SuperCollider has its own Integrated Development Environment (IDE) (Figure 3.5) and allows the fluid combination of many known and unknown audio techniques [27]. Through OSC protocol (see section 3.2.4), SuperCollider can receive the IMU data in real-time, analyze it and use it as input for the sonification generation.

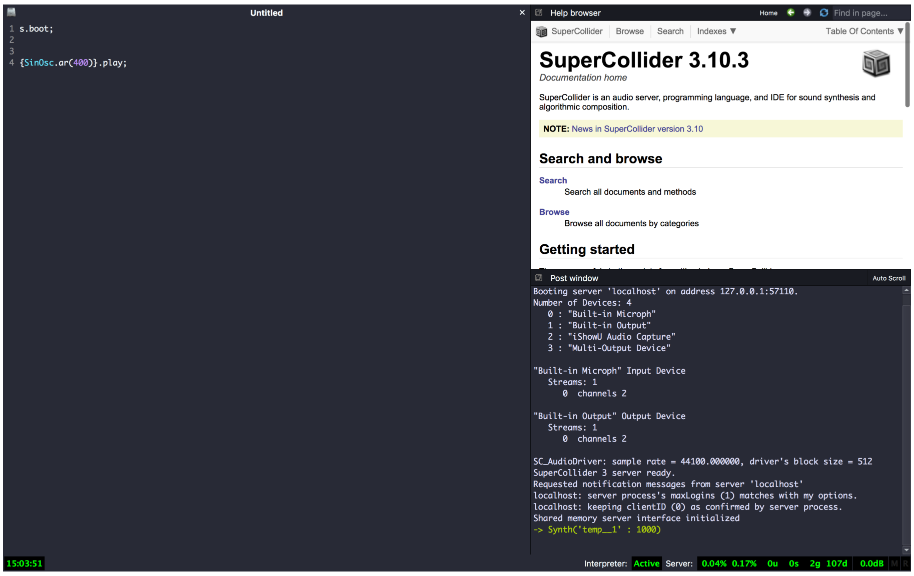

Figure 3.5: SuperCollider IDE.

As an example of the parameter mapping that can be done in SuperCollider, an excerpt of the code is showed below, where z represents the function holding the sine wave oscillator that is the basis of this sonification. After evaluating this function, an OSC function has to be evaluated to receive the OSC messages (argument msg), analyze their content, and use it to change the amplitude and frequency of the sine wave oscillator (using the set method).

Listing 3.1: Excerpt of the SuperCollider code for the high frequency sonification.

```
//Sine wave oscillator which amplitude and frequency is modulated by OSC functions
(
z = {
    arg amp=1, freq=400;
    var sig;
    sig = SinOsc.ar(freq) * amp;
}.play;
```

```
)

//High frequency sonification
(
OSCdef.new(
    \sinOscFinal,
    {
        arg msg, time, addr, port, freq;

        //angular velocity -> amplitude
        x = ((msg[4]).squared) + ((msg[5]).squared) + ((msg[6]).squared);
        x = x.sqrt;
        z.set(\amp, x); //sets new amplitude of sine wave oscillator

        //pitch -> frequency
        freq = msg[20].linexp(-180,180,200,2000);
        z.set(\freq, freq); //sets new frequency of sine wave oscillator
    },
    '/0/raw'
);
)
```

3.2.4 Communication protocol

Open Sound Control (OSC) is a protocol for communication among computers, sound synthesizers, and other multimedia devices that is optimized for modern networking technology [43]. OSC's advantages include interoperability, accuracy, flexibility, and enhanced organization and documentation and brings the benefits of modern networking technology to the world of electronic musical instruments [43].

Making use of a smartphone hotspot functionality, it is possible to create a Wireless Local-Area Network (WLAN), to which the Bitalino R-IoT connects once it is switched on. The hotspot must create a wi-fi network with the name that the IMU is expecting ("riot" by default, but can be reconfigured). In order to establish the communication protocol, the personal computer must be connected to the same network and its Internet Protocol (IP) address has to be set to the same as of the IMU. Once this is done, SuperCollider has to open the port to which the IMU is set to send data, and then we can finally receive OSC messages in SuperCollider.

3.3 Extending to other movements and applications

The prototype has been developed with the intention of integrating different environments, such as fitness our rehabilitation gyms, or even support home-based training sessions. With resistance training being widely practiced as a physical exercise style or as part of rehabilitation treatments, the uses of this system can be highly versatile with the appropriate adjustments. By simply switching the Euler angle being used in the sonification design, this prototype can be used for different exercises. By adding a graphical user interface to the prototype, these adjustments could be done by the users themselves. The system can be part of an interactive environment such as an interactive gym fully equipped with smart objects for the practice of exercise.

4

Evaluation

Contents

4.1 Research Questions . . . 29
4.2 Participants . . . 29
4.3 Apparatus . . . 29
4.4 Study Design . . . 29
4.5 Procedure . . . 30
4.6 Data Analysis . . . 31
4.7 Results . . . 32
4.8 Discussion . . . 39

The fourth chapter presents the user study we designed and carried out in order to evaluate our prototype. After explaining the user study in detail, we present the data analysis performed and the results obtained. This chapter ends with a discussion on the results.

4.1 Research Questions

Our study aimed to address the following research questions:

1. Does sonification affect body perception and feelings when performing unilateral hammer dumbbell curl?
2. How do high/low frequency sounds affect body perception and feelings in the performance of unilateral hammer dumbbell curl?

4.2 Participants

Ten participants (mean age 28.1 $\pm$ 9.6 years, seven male and three female, normal hearing) naïve to the study aim, took part in the study. Their mean body weight and height were 70.2 $\pm$ 11.37 Kg and 173.2 $\pm$ 8.98 cm. Six participants reported they exercised once or twice a week, two participants reported they exercised three or more times a week, and two participants answered they did not exercise at all. The only two participants that reported they used weights to exercise the upper limbs were the ones that exercised three or more times a week, with one of them using weights once or twice a week, and the other one using weights three or more times a week.

4.3 Apparatus

A Bitalino R-IoT [4] was used to capture movement data that was mapped into sound. The Bitalino was attached to one of three different colored dumbbells (one for each condition) and connected wirelessly to a personal computer running SuperCollider [27]. While performing the exercise, the sound was fed back to participants through headphones. For each trial of the exercise, the performance was timed using the stopwatch functionality of a smartphone. Each session was video and audio recorded.

4.4 Study Design

We adopted a within-subject approach, where each participant tested all three sound conditions: Control (No Sound); Low Frequency Sonification and High Frequency Sonification. In each condition, participants performed two trials of the exercise, with the exercise being performed by both arms in each trial. In total, we had 10 participants x 3 conditions x 2 trials = 60 trials.

4.4.1 Data

The performance of each trial was timed (each arm was timed, and then we used the mean of both arms), in order to assess how fast a subject performed the exercise in the different conditions. Perception of the dumbbell weight was assessed by including an open question in the post-questionnaire. Changes in body feelings were quantified using a questionnaire based on the one used in [2], comprised of 6 statements (7-point Likert-type response items), ranging from:

- “I felt slow” to “I felt quick” (Speed);
- “I felt light” to “I felt heavy” (Body Weight);
- “I felt weak” to “I felt strong” (Strength);
- “I felt very incapable” to “I felt very capable” (Capability);
- “I found the exercise very easy” to “I found the exercise very difficult” (Difficulty);
- “I found the exercise not tiring at all” to “I found the exercise very tiring” (Tiredness).

To assess changes in emotional state, the self-assessment manikin [44] was used, which assesses Pleasure, Arousal and Dominance. Each participant had to answer the post-questionnaire six times (after each trial).

4.5 Procedure

Due to the Coronavirus disease 2019 (COVID-19) pandemic, some extra measures had to be taken. All materials that were to be used by the participants were disinfected with a suitable product before each session, no more than two people (the participant and the person responsible for the tests) remained in the room during each session, and social distancing has been fulfilled. The person responsible for conducting the tests used a mask, but because the spaces used were ventilated and were not public (use of mask mandatory in closed public spaces [45]), the use of a mask by the participants was optional during the tests.

Participants filled in a pre-questionnaire about their demographic data and level of activity and signed a consent form. Subjects were then informed about the experiment procedure and how to perform the exercise – unilateral hammer dumbbell curl.

In order to avoid the surprise effect, participants practiced the exercise with all sound conditions until they felt comfortable hearing the sounds. After practicing the exercise, they completed three trials (Low Frequency, High Frequency and Control) in a randomized order (Repetition 1), and then they repeated the three trials in another randomized order (Repetition 2). The reason for the two repetitions with trials in a randomized order was to compensate for practice bias. In each trial, participants performed the unilateral hammer dumbbell curl 10 times with each arm at the pace they felt comfortable. The different conditions used a dumbbell of a different color, but all with the same weight, with participants being unaware of the weight. Dumbbells had different colors in order to avoid that participants would assume they all weighed the same. After finishing each trial, participants completed the questionnaire about their emotional state and body feelings. Figure 4.1 shows a participant using the prototype during the user study session.

Figure 4.1: Participant performing unilateral hammer dumbbell curl using the developed prototype.

4.6 Data Analysis

Statistical analysis was performed in order to assess the data obtained in the study. One-way repeated measures Analysis of Variance (ANOVA) [46] was used to assess performance time (continuous variable) while the Friedman test [47] was used for all the other variables (ordinal variables). Each of the ten participants repeated the three conditions twice, which gave us two repetitions per participant and twenty repetitions in total to analyze. Data are mean $\pm$ standard deviation unless otherwise stated.

4.7 Results

In this section, we describe the statistical tests performed for each of our eleven dependent variables: Performance time; Dumbbell weight perception; Speed perception; Body weight perception; Strength perception; Capability perception; Difficulty perception; Tiredness perception; Pleasure; Arousal; Dominance.

4.7.1 Performance time

Performance time corresponds to the mean time between the two arms in the performance of the exercise for each trial. Mean performance time was 24.34 $\pm$ 6.57 s for the control condition, 24.85 $\pm$ 5.89 s for the low frequency condition and 24.24 $\pm$ 5.38 s for the high frequency condition as can be seen in fig. 4.2. No pattern was identified between these values and the demographic information about participants, with many of them not being consistent between repetitions.

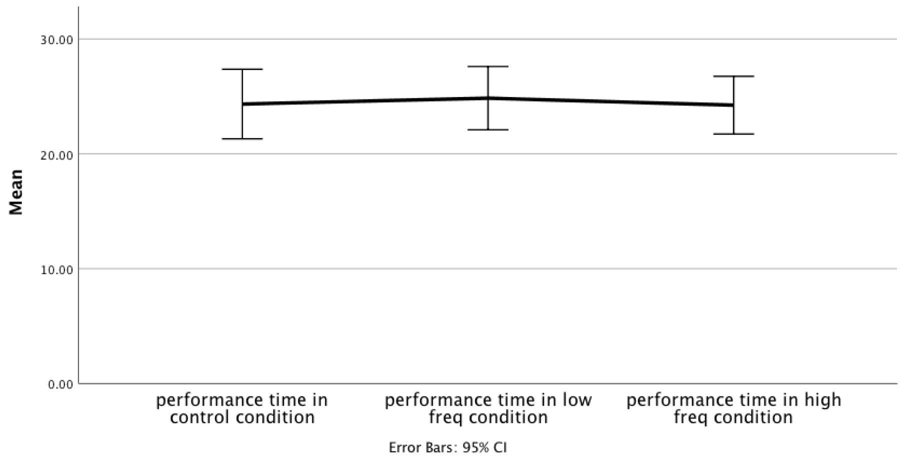

Figure 4.2: Performance time means in the three different conditions.

A one-way repeated measures ANOVA test was run to determine the effect of the different sound conditions on the performance time of the unilateral hammer dumbbell curl. There were no outliers in the data, as assessed by inspection of the boxplot showed in fig. 4.3. Performance time was normally distributed in each condition, as assessed by Shapiro-Wilk's test (p $>$.05). Mauchly's test of sphericity indicated that the assumption of sphericity had not been violated, χ^2(2) = .115, p = .944. The different sound conditions did not represent any statistically significant differences in performance time, F(2, 38) = 1.075, p = .351, partial η^2 = .054.

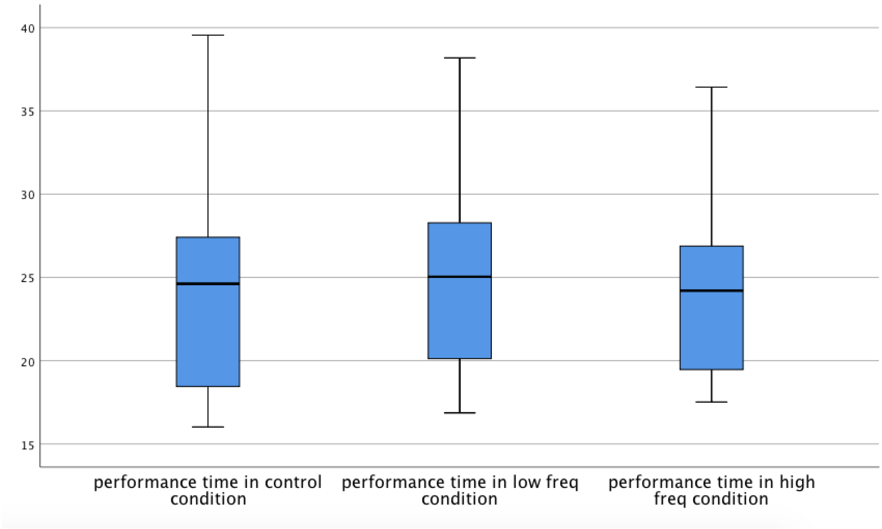

Figure 4.3: Boxplot of the values for performance time in the three different conditions.

4.7.2 Dumbbell weight perception

Dumbbell weight perception showed a mean of 1.21 $\pm$ .38 Kg for control condition, 1.08 $\pm$ .44 Kg for low frequency condition and 1.14 $\pm$ .33 Kg for high frequency condition (fig. 4.4). No pattern was identified between these values and the demographic information about participants. A Friedman test was run to determine if there were differences in dumbbell weight perception between the three sound conditions. The differences between conditions were not statistically significant, $\chi^2(2) = 3.160$, $p = .206$. The median had a value of 1.00 Kg in all conditions.

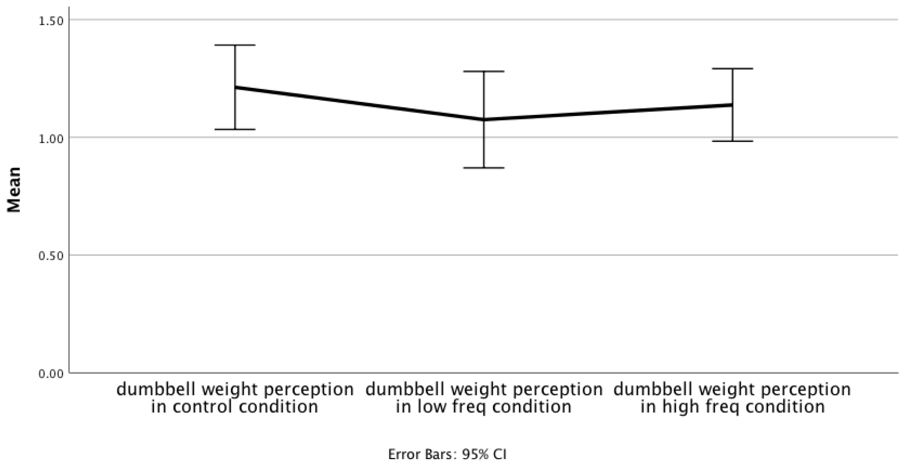

Figure 4.4: Dumbbell weight perception means in the three different conditions.

4.7.3 Body feelings

Data about body feelings were obtained by the answers to six 7-point Likert type questions on perceived speed, body weight, strength, capability, difficulty and tiredness. Given their ordinal nature (with values from 1 to 7), all these variables were analyzed by running a Friedman test.

4.7.3.A Speed perception

Speed perception means showed to be slightly different in the three conditions (fig. 4.5), with control representing a mean of 4.90 ± 1.07, low frequency a mean of 4.80 ± .95, and high frequency a mean of 5.10 ± 1.16. However, these differences are not statistically significant, $\chi^2(2) = 2.138$, $p = .343$, with median values of 5.00 for all conditions.

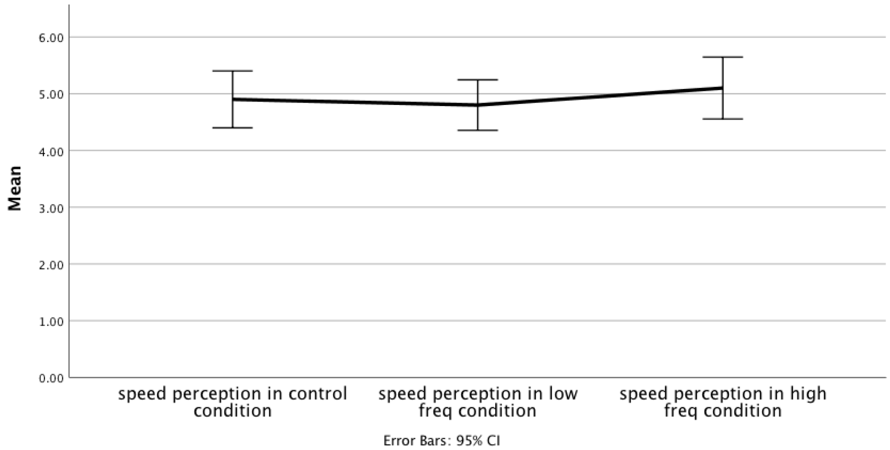

Figure 4.5: Speed perception means in the three different conditions.

4.7.3.B Body weight perception

Body weight perception was statistically significantly different in the different sound conditions, $\chi^2(2) = 8.759$, $p = .013$. Pairwise comparisons were performed with a Bonferroni correction for multiple comparisons, which did not reveal additional conclusions, with results not being statistically significant. Nevertheless, we could see that the mean body weight perception was 2.85 ± 1.42 for the control condition, 3.25 ± 1.55 for the low frequency condition, and 2.95 ± 1.64 for the high frequency condition (fig. 4.6), with medians of 3.00, 3.50 and 3.50 respectively.

4.7.3.C Strength perception

Strength perception had a mean of 5.75 ± 1.16 for control condition, 5.50 ± 1.40 for low frequency condition and 5.75 ± 1.25 for high frequency condition (fig. 4.7). These differences are not statistically

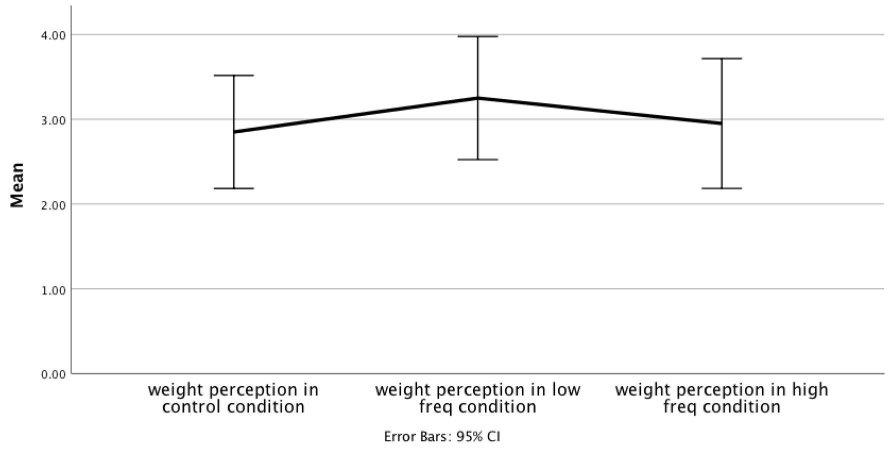

Figure 4.6: Body weight perception means in the three different conditions.

significant, $\chi^2(2)$ = 3.161, p = .206, with median values of 6.00, 5.50 and 6.00 for control, low frequency and high frequency conditions, respectively.

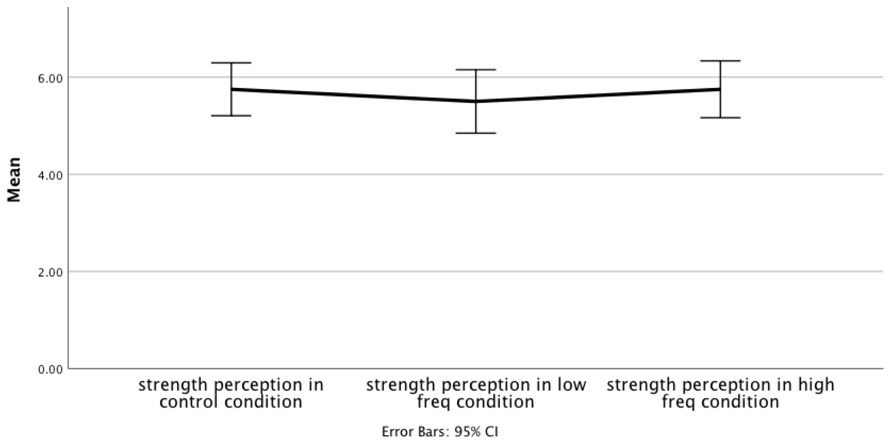

Figure 4.7: Strength perception means in the three different conditions.

4.7.3.D Capability perception

Capability perception was statistically significantly different in the different sound conditions, $\chi^2(2)$ = 9.333, p = .009. Pairwise comparisons were performed with a Bonferroni correction for multiple comparisons, which did not reveal additional conclusions, with results not being statistically significant. Mean capability perception was 6.75 $\pm$ .55 for control condition, 6.35 $\pm$ 1.04 for low frequency condition and 6.65 $\pm$ .59 for high frequency condition (fig. 4.8), with median values of 7.00 for all conditions.

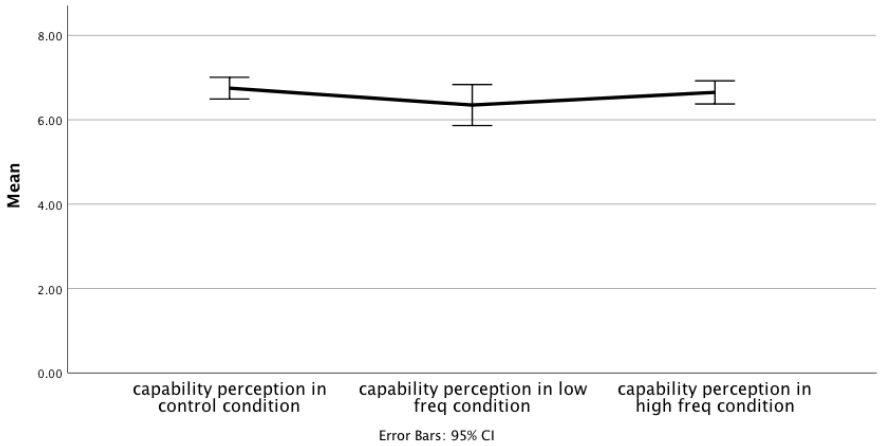

Figure 4.8: Capability perception means in the three different conditions.

4.7.3.E Difficulty perception

Difficulty perception had a mean of 1.40 $\pm$ .82 for control condition, 1.60 $\pm$ 1.27 for low frequency condition and 1.40 $\pm$ .82 for high frequency condition (fig. 4.9). These differences are not statistically significant, χ^2(2) = 3.600, p = .165, with median values of 1.00 for all conditions.

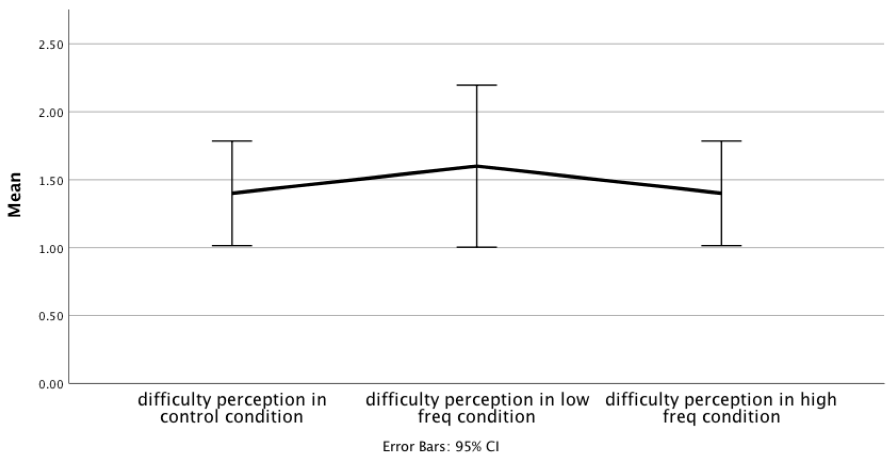

Figure 4.9: Difficulty perception means in the three different conditions.

4.7.3.F Tiredness perception

Tiredness perception had a mean of 1.55 $\pm$ .89 for control condition, 1.90 $\pm$ 1.33 for low frequency condition and 1.60 $\pm$ .82 for high frequency condition (fig. 4.10). These differences are not statistically significant, χ^2(2) = 3.263, p = .196, with median values of 1.00 for all conditions.

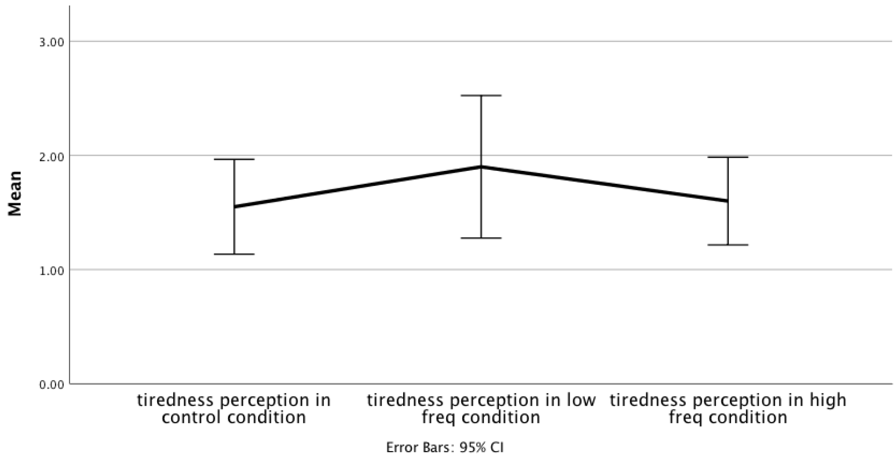

Figure 4.10: Tiredness perception means in the three different conditions.

4.7.4 Emotions

Data about emotions were obtained by showing a sequence of five images for each category (Pleasure, Arousal and Dominance) [44] and participants had to choose the image that better suited their emotional state for each category. Each image sequence has an order and images can be numbered from 1 to 5, thus all these variables were analyzed by running a Friedman test.

4.7.4.A Pleasure

Pleasure assessment showed a mean of 4.25 $\pm$ .91 for control condition, 4.20 $\pm$ .95 for low frequency condition and 4.25 $\pm$ .91 for high frequency condition (fig. 4.11). These differences are not statistically significant, $\chi^2(2)$ = .667, p = .717, with median values of 4.50 for all conditions.

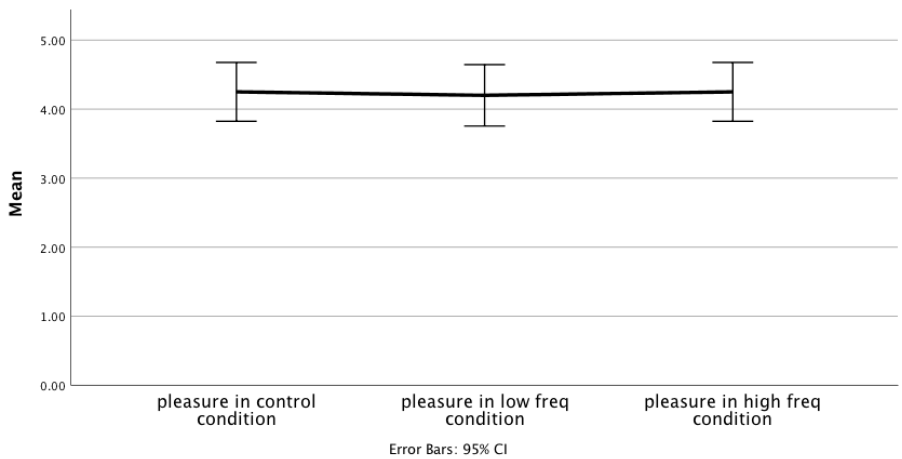

Figure 4.11: Pleasure means in the three different conditions.

4.7.4.B Arousal

Arousal assessment showed a mean of 1.20 ± .41 for control condition, 1.30 ± .47 for low frequency condition and 1.15 ± .37 for high frequency condition (fig. 4.12). These differences are not statistically significant, $\chi^2(2) = 4.667$, p = .097, with median values of 1.00 for all conditions.

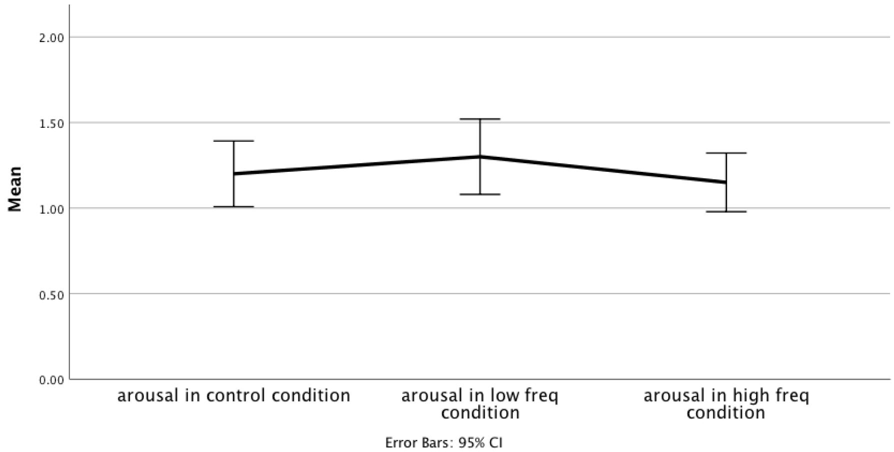

Figure 4.12: Arousal means in the three different conditions.

4.7.4.C Dominance

Dominance had a mean of 3.95 ± 1.00 for control condition, 3.80 ± 1.00 for low frequency condition and 5.00 ± .92 for high frequency condition (fig. 4.13). These differences are not statistically significant, $\chi^2(2) = 3.895$, p = .143, with median values of 4.00 for all conditions.

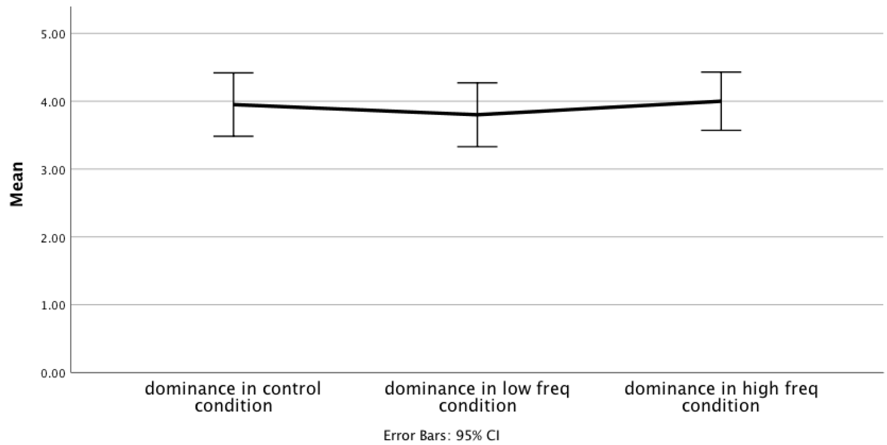

Figure 4.13: Dominance means in the three different conditions.

4.7.5 Informal opinions

Some users had the initiative of giving their opinion about the system after finishing the study session. One of the users expressed that the sound gave them conscience about the movement and it helped them not getting lost in the exercise. Another participant also expressed they preferred the sound conditions as opposed to the control condition because the sound made them feel more focused when counting the repetitions, especially the low frequency condition that also made them feel calmer. Another participant reported that the low frequency sound was less rewarding and they felt slower when being fed back with that sound. One participant reported they preferred the no-sound condition because it made them feel more autonomous and the sound conditions made them feel more pressured, especially when hearing the different sound at the end of each arm repetition, that made them feel they had to quickly proceed with the exercise. Overall, four participants explicitly expressed they enjoyed using the system with sound feedback.

4.8 Discussion

Previous findings [2, 15, 17] suggested that real-time movement sonification can alter users' behavior, body feelings and emotions when performing physical activity. These findings showed that high frequency sounds can make people move more dynamically and perceive themselves as faster, lighter and happier. In contrast, low frequency sounds can make people perceive themselves as slower and heavier. Based on these findings, we wanted to explore the effects of real-time sonification in an upper-limb exercise and using an object as the base for the IMU, instead of attaching it to the body.

To assess if the users would move faster or slower in the different sound conditions we timed each trial of the exercise and found that no statistically significant differences could be observed. A slight difference might suggest that the users tend to move faster in the high frequency condition and slower in the low frequency condition when compared to the control condition, however, no clear conclusions can be found.

We also wanted to explore if the different sound conditions would affect the perception of the dumbbell weight. To accomplish this, we designed the prototype to include three different colored dumbbells without informing the participants of their weight nor telling them they all weighed the same. Although there are no statistically significant findings, the results on the dumbbell weight perception suggest that the users perceived the dumbbell as lighter in the two sound conditions and heavier in the no-sound condition.

Our results show that our prototype can alter body perception, with the low frequency condition representing lower mean values for perceived speed, strength and capability, and higher mean values for perceived body weight, difficulty and tiredness. Nonetheless, the statistical analysis only showed statistically significant results for the body weight and capability variables.

Emotion assessment does not show differences in pleasure when using the system in the different conditions, with almost all participants answering consistently the same in all trials. Arousal assessment suggests that users might feel more aroused in the low frequency condition. Although these differences are not statistically significant, they can be linked to the tiredness results. By feeling more aroused in the low frequency condition, participants also felt more tired. By assessing dominance, we can see that low frequency sonification made users feel overall less dominant, however, the differences are not significant.

Addressing our first research question - Does sonification affect body perception and feelings when performing unilateral hammer dumbbellcurl?-, we can observe by our results that real-time sonification could influence body weight perception and capability perception. By observing the mean values for all the other variables, we can also see a certain tendency that might suggest the influence of sonification in body perception and feelings. Although these differences do not represent statistical relevance, they open a door for future research on the field.

Our second research question goes further and aims to explore how the different frequencies of sound can affect body perception and feelings. By analyzing our results, we could find some evidence to support what was concluded by the above-mentioned studies [2, 15, 17]. We hypothesized that high frequency sounds would make people perceive themselves as faster, lighter, stronger, more capable, less tired, and the exercise as easier. In contrast, low frequency sounds would make people perceive themselves as slower, heavier, weaker, less capable, more tired, and the exercise as more difficult. Our results show that users felt heavier and less capable when listening to the low frequency condition. However, no differences could be seen for the high frequency condition.

With the informal feedback we gathered from the participants, we believe this system has the potential of bringing benefits to its users and motivating them to exercise. However, the results obtained do not suggest such benefits. Observing our results, we can only conclude that real-time movement sonification could influence body feelings negatively, which might have other implications in different fields, such as gaming. Further studies are needed in order to validate our findings and find new conclusions that could not be found due to the sample size.

5

Conclusions and Future Work

Contents

5.1 Conclusions 43
5.2 System Limitations and Future Work 44

In this final chapter, we present our conclusions regarding the work developed. We end with a reflection on the limitations of our work and the future work that can be done to improve this work and advance the research on the field.

5.1 Conclusions

This dissertation focus on the problem of a high rate of inactive adults in the world, which brings threats to a long and healthy life and decreases the quality of life around the world. In order to address this, we identify a very common type of exercise - resistance training -, that represents some issues regarding motivation and adherence. This type of physical activity is repetitive and people get easily bored and mentally tired.

The developed work resulted in a prototype for real-time sonification of movement that leveraged on the previous findings that sound can manipulate body perception and feelings [2, 14–18]. We used an IMU for movement data collection and attached it to a dumbbell without any change to the natural usage of the object. The IMU was wirelessly connected to a computer running the sonification software and the sound was fed back to the user through headphones.

We conducted a user study on a within-subject approach and tested the performance of a dumbbell exercise in three conditions: Control (no sound); Low Frequency Sonification and High Frequency Sonification. Even though our findings suggest that sonification can indeed alter body perception and feelings, we did not obtain statistical significance for all studied measures, with only perceived body weight and perceived capability representing statistically significant differences between the conditions. Users felt heavier and less capable when listening to the low frequency sonification. These findings do not support our main goal of motivating people to exercise by manipulating their body feelings. Nonetheless, influencing body feelings negatively might have other applications, such as games, virtual reality applications, and other immersive experiences.

Our work was well accepted by the users, with some of them expressing the use of the system as an enjoyable experience. By their comments we could also conclude that the system can bring benefits to the practice of resistance training, adding more conscience to the movement and facilitating the concentration. We believe by our results that the developed prototype can be a starting point for the development of a useful tool for improving motivation to exercise. Our findings also represent benefits for other applications that may take advantage of influencing body feelings and perception.

5.2 System Limitations and Future Work

Our prototype has the potential for being a flexible tool that can be used for different types of exercises using a dumbbell and this methodology can even be applied to other objects. However, at the moment the prototype is only suitable for the practice of a specific exercise and needs a specialist to alter the system to make it suitable for other exercises. This represents a limitation and also an opportunity for improvement. A user interface can be developed in order to allow the users to make these adjustments themselves by simply choosing the exercise they want to perform. This can be a starting point for the development of an interactive gym based on this prototype and other versions of it, creating an interactive experience for unmotivated users that need a push to become more active.

The sound created is simple and can benefit from the contribution of sound artists and specialists to make it more complex and enjoyable. Nonetheless, our design was suitable for the type of investigation we intended to do and a more complex sound could have masked the effects of a simple sonification, which effects must be known in order to inform the development of more complex designs.

Finally, our work needs further evaluation, which must include a study with more users in order to find significant findings and validate the developed solution. The present conclusions represent a starting point for further research on the use of sonification for perception manipulation when exercising using objects.

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A Sonification code

Listing A.1: SuperCollider code.

```
//Boot server
s.boot;

//Check which ports are open
thisProcess.openPorts;

//Open port 8888, which is the port to which Bitalino will send data by default
thisProcess.openUDPPort(8888);


//Sine wave oscillator which amplitude and frequency
//is modulated by OSC functions
(
```

```
z = {
    arg amp=1, freq=400;
    var sig;
    sig = SinOsc.ar(freq) * amp;
}.play;
)


//Sound indicating end of movement (High frequency)
(
h = {
    arg freq = 600;
    SinOsc.ar(LFNoise0.kr(10).range(freq, freq), mul: Env.perc.kr(doneAction: 2))
}
)

//Sound indicating end of movement (Low frequency)
(
l = {
    arg freq = 350;
    SinOsc.ar(LFNoise0.kr(10).range(freq, freq), mul: Env.perc.kr(doneAction: 2))
}
)


//High frequency sonification
(
OSCdef.new(
    \sinOscFinal,
    {
        arg msg, time, addr, port, freq;

        //angular velocity -> amplitude
        x = ((msg[4]).squared) + ((msg[5]).squared) + ((msg[6]).squared);
        x = x.sqrt;
        z.set(\amp, x); //sets new amplitude of sine wave oscillator

        //pitch -> frequency
```

```
        freq = msg[20].linexp(-180,180,200,2000);
        z.set(\freq, freq); //sets new frequency of sine wave oscillator


        //checks end of movement
        if(((msg[20] >= 20).and(msg[20] <= 50)), {
            h.play; //calls function
        }, {

        })

    },
    '/0/raw'
);
)

//Low frequency sonification
(
OSCdef.new(
    \sinOscFinal,
    {
        arg msg, time, addr, port, freq;

        //angular velocity -> amplitude
        x = ((msg[4]).squared) + ((msg[5]).squared) + ((msg[6]).squared);
        x = x.sqrt;
        z.set(\amp, x); //sets new amplitude of sine wave oscillator

        //pitch -> frequency
        freq = msg[20].linexp(-180,180,100,1000);
        z.set(\freq, freq); //sets new frequency of sine wave oscillator


        //checks end of movement
        if( ((msg[20] >= 20).and(msg[20] <= 50)), {
            l.play; //calls function
        }, {

```

```
            })

        },
        '/0/raw'
);
)
```

B

User study forms

Declaração de consentimento informado

O atual estudo decorre no âmbito da realização da dissertação de mestrado em Engenharia Informática e de Computadores pela aluna Maria Filipa Gonçalves Matilde Oliveira e tem como objetivo testar um protótipo para a sonificação em tempo real de movimento do corpo.

O resultado do estudo será incluído no documento da dissertação e será apresentado no Instituto Superior Técnico aquando da defesa oral da dissertação podendo, se desejar, contactar a aluna para se inteirar dos resultados obtidos.

Este estudo não lhe trará nenhuma despesa ou risco. As informações serão recolhidas através de questionários, gravação de dados sobre o movimento e filmagem dos procedimentos.

Todos os dados serão anonimizados e utilizados apenas para fins de investigação científica.

A sua participação neste estudo é voluntária e pode retirar-se a qualquer altura, ou recusar participar, sem que tal facto tenha consequências para si.

Depois de tomar conhecimento das explicações acima referidas, declaro que aceito participar neste estudo.

Participante: ____

Data: ___________________, _____ de _____________ de 2020.

Aluna responsável: ____

Pré-questionário

Participante nº _____

1. Idade:

   ____

2. Género:

- O Mulher
- O Homem
- O Outro (especifique) ________________________

3. Peso (kg):

   ____

4. Altura (cm):

   ____

5. Quantas vezes por semana faz exercício?

- O Nenhuma
- O 1 a 2
- O 3 ou mais

6. Quantas vezes por semana usa pesos para trabalhar os membros superiores?

- O Nenhuma
- O 1 a 2
- O 3 ou mais

Questionário sobre percepção corporal e emoções pós-exercício

Participante nº _____ Repetição nº _____ Condição: _________________

Por favor, responda às seguintes questões com a máxima sinceridade. Pode fazer questões sempre que precisar de alguma clarificação.

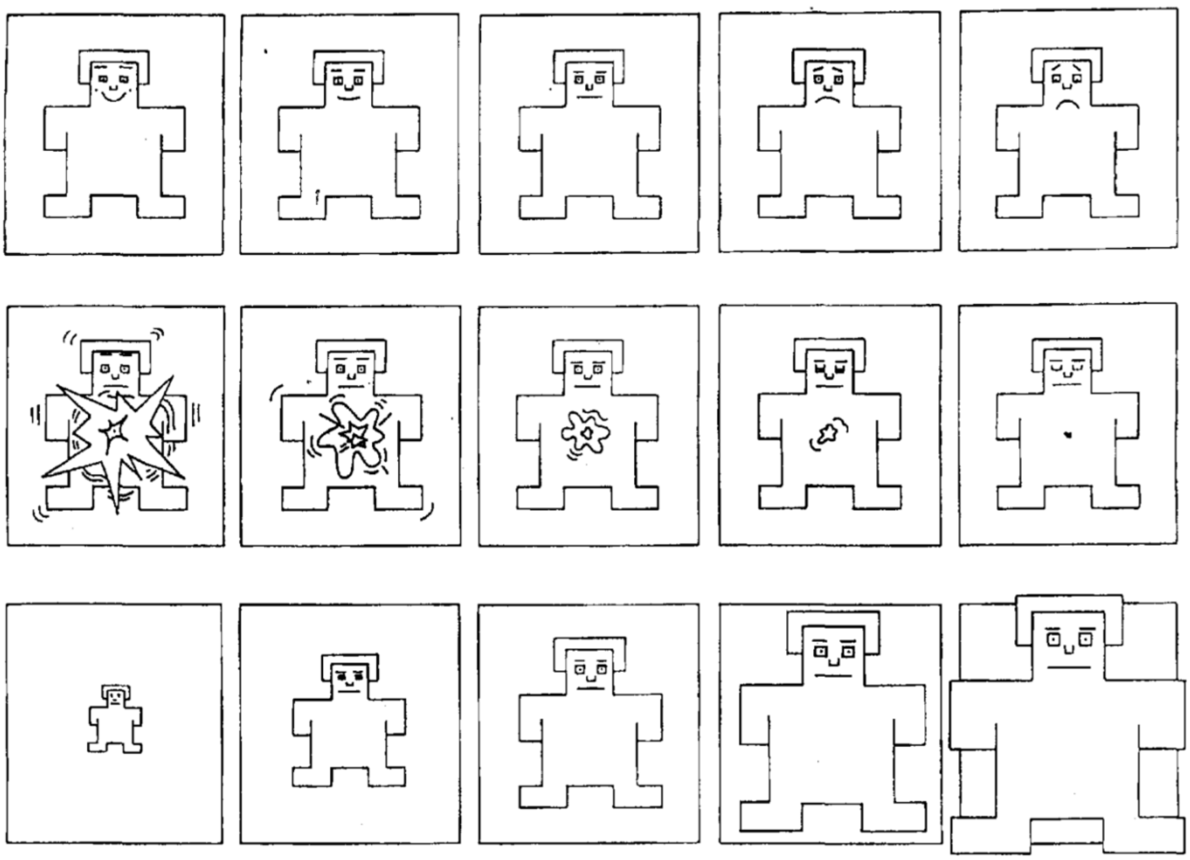
1. Na sua percepção, qual o peso do halter que usou neste exercício?

   __________ kg.

2. Em relação às características abaixo referidas, por favor assinale com uma cruz o valor da escala que melhor se adequa à sua percepção, em que 1 corresponde à descrição à esquerda, e 7 corresponde à descrição à direita.

	1	2	3	4 (neutro)	5	6	7	
Senti-me lento(a)	O	O	O	O	O	O	O	Senti-me rápido(a)
Senti-me leve	O	O	O	O	O	O	O	Senti-me pesado(a)
Senti-me fraco(a)	O	O	O	O	O	O	O	Senti-me forte
Senti-me muito incapaz	O	O	O	O	O	O	O	Senti-me muito capaz
Achei o exercício muito fácil	O	O	O	O	O	O	O	Achei o exercício muito difícil
Achei o exercício nada cansativo	O	O	O	O	O	O	O	Achei o exercício muito cansativo

3. Abaixo encontra três linhas distintas com imagens. Para cada linha, por favor selecione com uma seta a imagem que melhor representa como se sentiu durante a execução do exercício.



Obrigada!