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NEMI: New Ergonomic Musical Instrument

A bridge between the Human-Centred Design and Digital Musical Instrument

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Abstract

Acoustic Instruments are commonly built in shapes that emphasize their sound responses and frequently, neglect their ergonomics. This aspect is related to Repetitive Strain Injury (RSI) and other musculoskeletal disorders in instrumentalists. In this work, the ergonomics of some acoustic instruments using anthropometric measurements was considered. These measurements were applied to design a new ergonomic digital instrument with improved usability. The instrument was designed focusing on avoiding uncomfortable and forced articulation positions for the musician. The instrument can play all the notes in the chromatic scale and has its characteristic sound. This work shows the importance of ergonomics in Digital Musical Instruments (DMIs) design representing a new piece in digital lutherie.

List of Abbreviations

DMI	-	Digital Musical Instrument
DOF	-	Degrees of Freedom
HCD	-	Human-Centered Design
HCI	-	Human Computer Interaction
MIDI	-	Musical Instrument Digital Interface
NIME	-	New Interfaces for Musical Expression
OSC	-	Open Sound Control USB Universal Serial Bus
RSI	-	Repetitive Strain Injury
MSD	-	Musculoskeletal Disorder
DSP	-	Digital Signal Processing

1. Introduction

Throughout history, most musical instrument designs were music-centered and not human-centered. The design evolution of the various acoustic instruments has mostly occurred to improve the sound characteristics and almost never to improve the comfort of the musician during practice and performance [1]. This structural deficit owes its cause to various factors. One of them is the physics involved in the sound production of the instrument.

As an example, thinking on the structure of a piano and how the geometric dimensions of the strings influence the pitch of the sound emitted. Starting from the lowest octaves of a grand piano to the highest ones, the size of the strings, thickness and length, decrease in order to vibrate at ever-higher frequencies. However, the relationship between design, sound response and playability is extremely complex. Inasmuch as these connections were also influenced by socio-cultural factors, such as the expansion and the need to play one musical genre more than another. In many cases, the relationship of this triad has been influenced by manufacturing limits. Over time, technological improvements have simplified instruments making, and sometimes brought to an increase in the instrument's mechanical complexity and better expressive performance ability [2].

The concept of design and playability of the instrument will be strongly treated in this thesis under the rules of modern design, such as ergonomics, usability and user experience. The interest on traditional and acoustic instruments ergonomics came from different studies, showing the exposure of professional instrumentalists to Repetitive Strain Injury (RSI) and musculoskeletal disorders, and how this can be linked on the neglecting of a Human-centred design (HCD) [3]. Contrary to what has been said about acoustic instruments, Digital Musical Instruments (DMI) do not intrinsically present any of these limitations, since the sound generation system is split from the control system. [4]. In this way, it is possible to design a musical instrument according to the rules of HCD. More and more often, as it is already widely done for the design of tools and workplaces, the design based on the HCD exploits the standards of anthropometric measurements [5]. The correct sizing and proper arrangement of the instrument combined with a correct posture of the musician enables the activity's optimization of and greater efficiency in making music [6]. The main point of this research concerns about the possibility of creating a digital instrument based on anthropometric measurements, in order to maximize its ergonomics, attempting to avoid RSI and MSDs. For this purpose, modern technology such as microcontrollers and 3D printers have been used to create a new digital instrument. Electronics and digital tools, due to theirs versatility, allowed us to design a new ergonomic instrument, postponing problems linked to sound response, since this is not linked with the physical properties of the device.

2. Design concepts

The meaning of the word "Design" is project planning, and it is the base of the creation of any functional object. Design is made up of a series of programming and planning phases aimed at reaching a specific end.
The concept of design, unlike what one might think, is not strictly connected to aesthetic beauty factors, in fact, the final result will certainly have to present aesthetically valid forms, but above all strictly design functions.

The concept of functional design was born in relation to useful design for people, or a tool that can create favorable psycho-physical conditions ensuring excellent performance. Here comes into play the human centred design aspect that ensures the ability to meet the needs and expectations of the target audience.

2.1. Human-centered design

The Human Centred Design process, or synthetically also known by its acronym HCD, represents a process model for every phase of the design cycle, which poses the problem of understanding what users want and verifying whether the design hypotheses achieve those wishes. This approach involves the people whose products and services are aimed at. This is done in order to take into account their specific psycho-physical characteristics and to include their instances, their points of view and their ways of operating within the project. The HCD aims to change the process model that is traditionally used to manage a project by requiring the knowledge and involvement of users from the early stages of analysis and, to continue, also in those of design and implementation. This method consists of three phases:

- Inspiration
- Concept
- Implementation

According to this model, in each phase the project specifications can be verified and modified. In this way, it is possible to verify the specifications before the implementation phase, implying that even the cost becomes more contained than in the other design process, and the benefits in terms of usability and user experience are significant.

2.1.1. Ergonomics

Ergonomics derives from the Greek ergon (work) and nomos (law/norm) and was created to define the science of work, is a system-oriented discipline, which today is applied to all aspects of human activities.

Ergonomics (or human factors) is the scientific discipline that studies the interaction between people and other elements of a system, and the profession that applies theoretical principles, data and design methods (of Ergonomics) with the aim of optimizing the well-being of people and the overall performance of the system.

Ergonomics professionals contribute to the planning, design and evaluation of activities, work tasks, environments and systems with the aim of making them compatible with people's needs, abilities and limitations [7].

The term ergonomics defines the set of interdisciplinary knowledge belonging to the human being, also related to design.

"Ergonomics is the set of procedures aimed at assessing and designing the interaction of individuals with the objects and equipment they use, and with the environments in which they perform their activities.
a design philosophy that identifies in the user, and in the set of his needs and expectations, the starting point and the central objective of each intervention (evaluation and/or design)", (J. Wilson 1995).

Ergonomics is divided into several types, those taken into account in this thesis are physical ergonomics and cognitive ergonomics.

- **Physical Ergonomy**: inherent to human physiology, derives from an accurate study of the relationship between anthropology and biomechanics of the body. The posture, the material manipulation, is everything that includes skeletal and muscular movements and discomforts.
- **Cognitive Ergonomy**: inherent to how mental processes condition the interaction with the elements. Memory, reasoning and technological interaction all refer to it.

2.1.2. Usability

Usability is defined by ISO as the effectiveness, efficiency and satisfaction of certain users in achieving certain goals in certain contexts. It defines, in practice, the degree of ease and satisfaction in the interaction between man and an object.
The usability is determined by taking into account certain questions such as:

- What does the user want or need to get?
- What is the user's cultural and technical background?
- What is the context in which the user operates?
- what should be left to the machine and what should be left to the user?

In order to find the answers, an analysis of the user must be carried out following these methods:

- User-centered needs analysis
- Construction of user profiles
- Usability tests

The main features of a usable system are:

- **Effectiveness**: accuracy and completeness in achieving certain goals in particular environments for certain users.
- **Efficiency**: the resources spent in relation to the accuracy and completeness of the achieved goals.
- **Satisfaction**: the comfort and acceptability of the work system for its users and other people affected by its use.
- **Ease of learning**: A good user performance should be achieved in a short time.
- **Ease of memorization**: the user must be able to interact with an interface even after a long period of inactivity, without having to start from zero.
- **Error safety and robustness**: the impact of error must be inversely proportional to the probability of error.

2.1.3. User Experience

The user experience, or UX, is the sum of the emotions, perceptions and reactions a user experiences when interfacing with a product or service.
In other words, it is the degree of subjective adherence between expectations and satisfaction in the interaction with a system, whether it is physical (e.g. a ticket machine in the station) or digital (e.g. online shopping).
The UX is therefore a dimension of design, which places the characteristics and needs of users at the centre, focusing on their context of use.The concept was introduced by Donald Norman almost twenty years ago but the word "user experience" is still very confusing because it is often misunderstood as "usability" despite the fact that the literature, in particular the Nielsen Norman Group definition, is very clear about it.
Usability, i.e. the degree of effectiveness, efficiency and satisfaction with which man interacts with the machine, is in short only one of the components of the user experience (ex. a website can be usable without necessarily guaranteeing a pleasant user experience).

2.2. Human–computer interaction

In modern society, the interaction between man and computer is daily and takes place in different ways. The Human-computer interaction (HCI) is an interdisciplinary field covering computer science, human factors engineering and cognitive sciences, whose research has become fundamental to simplify the relationship between man and computer.

"In HCI, interaction is defined as a process of communication or information transfer from the user to the computer and from the computer to the user. The user starts an interactive process to achieve a given task" (Dix, A. J., et al. 1998. Human-Computer Interaction, 2nd ed. London: Prentice Hall Europe).

In this case, the user through the interface needs to monitor the status of the system based on the outputs, being able to manually adjust the parameters through the inputs. This interaction between the user and the system takes place through metaphors of interaction, one of the most popular paradigms in commercial systems is the WIMP (Windows, icons, menus and pointers). An interface metaphor is a concept (images, actions and procedures) that allows the user to have an instant knowledge of how to interact with the interface, based on the previous experience of the user in other real-life domains, such as the Win OS recycle bin concept.

Technological progress, particularly in specialised areas (e.g. video games), has led to interfaces based on post-WIMP paradigms, thus introducing new metaphors of interaction. The evolution is due to the fact that the WIMP paradigm offered a limited interaction compared to the multiple real-time continuous inputs used. An example of Context is in the performances of computer music. The context in HCI describes the real conditions in which the software system is used. Determining the system context means describing how the software system interacts with the user in daily situations.

HCI is often defined by the concept of Man-Machine Interaction (MMI). Nowadays, practically every computer has a graphical user interface (GUI) [8], vocal (VUI) or multimodal. The VUI is a system for speech recognition and synthesis. The emerging

multimodal user interfaces allow interaction with the virtual and physical environment through the use of natural communication mechanism, [9].
For this reason, interactions are freer and more natural, where the automated input and output system can receive different types of input and return different types of output.
These are extremely flexible environments and can interact with the user in different ways such as receiving speech input, handwriting, hand gesture and gaze, and after a process of interpretation, them return system information via output modes, such as speech synthesis, intelligent graphics and other modes. An important aspect of HCI is the end-user's satisfaction.

"Because human–computer interaction studies a human and a machine in communication, it draws from supporting knowledge on both the machine and the human side. On the machine side, techniques in computer graphics, operating systems, programming languages, and development environments are relevant. On the human side, communication theory, graphic and industrial design disciplines, linguistics, social sciences, cognitive psychology, social psychology, and human factors such as computer user satisfaction are relevant. And, of course, engineering and design methods are relevant." [10].

In the field of HCI, most of the research that is carried out to improve this interaction is related to improving the usability of these interfaces and other desirable properties such as learnability, findability, efficiency of use. [11] The difference from ergonomics is that, the main focus of the HCI is the user's specific work on the computer and not with other machines. Another point of divergence is that it focuses less on repetitive actions and physical stresses caused by work or physical shape and industrial design, but more on how the user interface with the mouse and keyboard.

The HCI develops design methodologies, tests new devices, prototypes software and hardware systems, explores interaction paradigms and develops interaction models and theories. Most design methodologies are based on a model of interaction between users, designers and technical systems. Modern models tend to focus on constant feedback and conversation between users, designers and engineers. Building technical systems to model around the experiences users want, rather than modeling the user experience around a complete system.

- Activity Theory: It is used in HCI to define and study the context in which human computer interactions take place, in order to create an activity-centric Interaction-Design. An activity is seen as a system of human "doing" whereby a subject works on an object in order to obtain a desired outcome [12].
- User-centered design (UCD): is a design philosophy in which the user is at the centre of the design of any computer system, for further details see paragraph 2.1.
- Principles of user interface design: These principles can be taken in consideration when designing a user interface in any order: tolerance, simplicity, visibility, cost-effectiveness, consistency, structure and feedback [43].
- Value sensitive design (VSD): a method used in construction technology, which takes into account the empirical values obtained directly or indirectly from the use of a technology by the user. VSD uses an iterative design process that involves three types of investigation: conceptual, empirical and technical [13].

During the test phase is evaluated the effectiveness and efficiency of the interface. For this process it is important to follow the principles of experimental design below:

1. Focus on users and their tasks: Establish how many users we need to perform a task and who is our target audience and who could benefit from this interface. Also, define what tasks users will have to perform and their frequency.

2. Empirical measurements: Test the interface daily with real users, as soon as possible. The daily evaluation avoids the different levels of user performance not representing the typical human-machine interaction. Numerically determine the usability of the interface by measuring the number of users performing the task, the time to complete the task and the number of errors made during the task.

3. Iterative design: After performing the previous steps you have to perform the next iterative design steps:

    a. Redesigning the user interface

b. Test
c. Analyze the results
d. Repeat

Repeat the iterative design process until you create a sensitive and easy-to-use interface [14].

2.3. Anthropometric Measurements

“Anthropometry is the science that measures the range of body sizes in a population”.

Anthropometric data sets compare people of different ages and occupations. Data in anthropometric databases may represent static dimensions, such as “lower leg length” or functional dimensions such as “reach.” figure 2.1 and Table 2.1 show common ranges of measurements used in office furniture design.

Measurement	Letter	Female	Male
Standing Overhead Reach	A	74.9” – 86.8”	81.2” – 93.7”
Standing Height	B	60.2” – 68.4”	64.8” – 73.5
Standing Eye Height	C	56.9” – 65.0”	61.4” – 69.8”
Standing Forward Reach	D	30.8” – 36.1”	33.8” – 39.5
Sitting Height	E	31.3” – 35.8”	33.6” – 38.3
Sitting Eye Height	F	42.6” – 48.8”	46.3” – 52.6”
Sitting Knee Height	G	19.8” – 23.2”	21.4” – 25.0”
Seat Depth	H	16.9” – 20.4”	17.7” – 21.1”

Table 2.1. Anthropometric measurements (including allowances for clothing) of small and large males and females, from BIFMA Ergonomics Guidelines, 2002. All measurements are in inches.

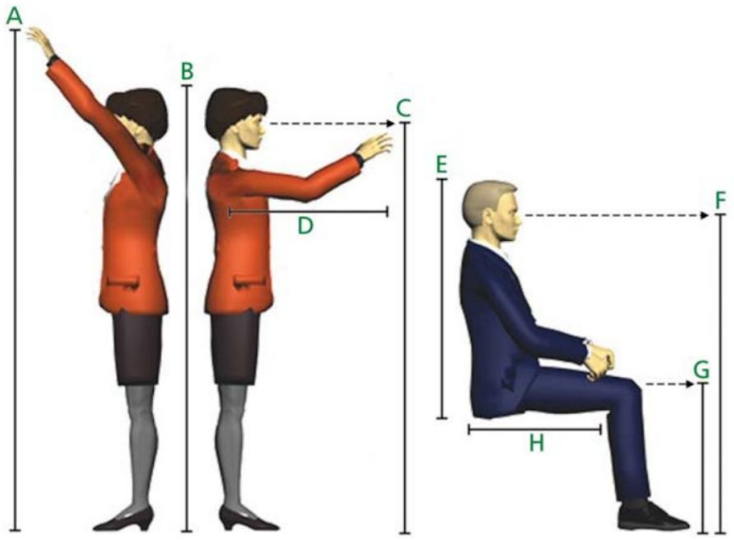


Figure 2.1. Common office environment posture measurements. Values are in Table 2.1.

The human body and its joints present a natural range of motion (ROM). All the movements that belong to the correct ROM are healthier, because they promote blood circulation and flexibility. These movements lead to increased comfort and may lead to a higher productivity. Users should try to avoid repetitive movements and some of the most extreme areas of ROM for long periods of time.

Considering both ROM and repetitive motion, the design of new products could be developed to keep user movements in the optimal ranges, helping to reduce the occurrence of fatigue and muscle disorders. ROMs are areas in which joints can move freely and are divided into zones. Zones 0 and 1 include smaller joint movements, while zones 2 and 3 represent more extreme positions. Zones 0 and 1 are preferable for most movements.

"Zones 2 and 3 should be avoided whenever possible, especially for repetitive and heavy tasks. Movement in these zones puts more strain on muscles and tendons and may lead to the development of musculoskeletal disorders" [5]. Figure 2.2 shows the ROM for common joint movements.

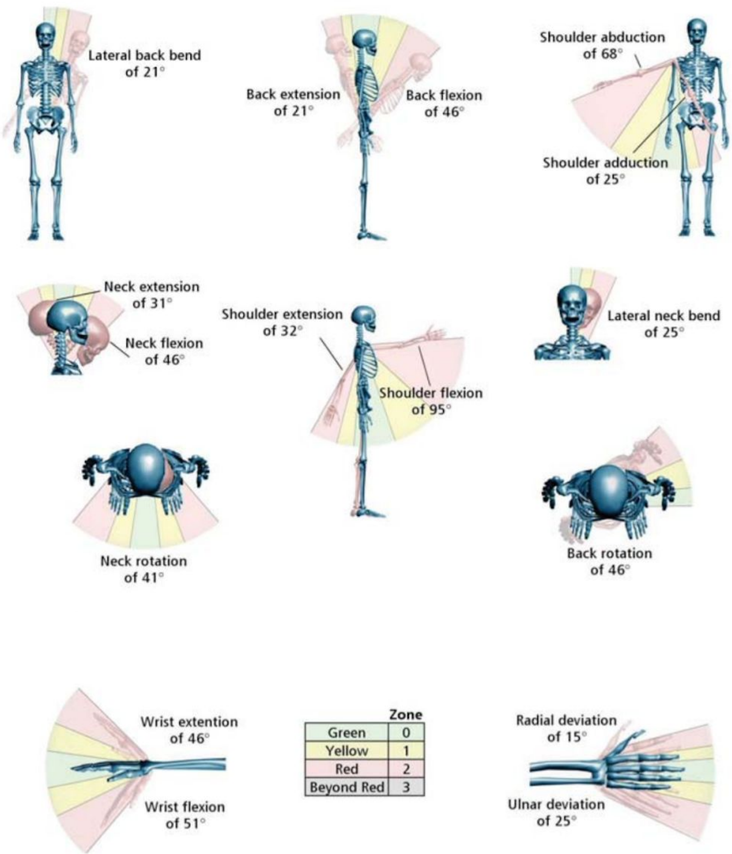


Figure 2.2. Various ranges of motion for different joints. Zone 0 is in green, Zone 1 is in yellow, and Zone 2 is in red. Zone 3 is anywhere beyond the red. Image from [5].

		Range of Motion Zones			
	Movement	0	1	2	3
Wrist	Flexion	0 – 10	11 – 25	26 – 50	51+
	Extension	0 – 9	10 – 23	24 – 45	46+
	Radial Deviation	0 – 3	4 – 7	8 – 14	15+
	Ulnar Deviation	0 – 5	6 – 12	13 – 24	25+
Shoulder	Flexion	0 – 19	20 – 47	48 – 94	95+
	Extension	0 – 6	7 – 15	16 – 31	32+
	Adduction	0 – 5	6 – 12	13 – 24	25+
	Adduction	0 – 13	14 – 34	35 – 67	68+

Back	Flexion	0 – 10	11 – 25	26 – 45	46+
	Extension	0 – 5	6 – 10	11 – 20	21+
	Rotational	0 – 10	11 – 25	26 – 45	46+
	Lateral Bend	0 – 5	6 – 10	11 – 20	21+
Neck	Flexion	0 – 9	10 – 22	23 – 45	46+
	Extension	0 – 6	7 – 15	16 – 30	31+
	Rotational	0 – 8	9 – 20	21 – 40	41+
	Lateral Bend	0 – 5	6 – 12	13 – 24	25+

Table 2.2: Range of Motion. Data for this table was modified from Chaffin, 1999 and Woodson, 1992. These are the actual angular measurements of body joints in each of the four Zones for range of motion. All measurements are in degrees.

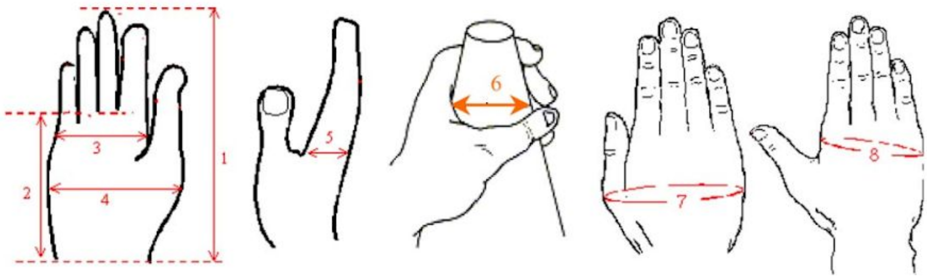


Figure 2.3. Anthropometric hand measurements for right-handed and left-handed people. the numbers correspond to: "1. Hand Length, 2. Palm Length, 3. Hand Breadth, 4. Maximum Hand Breadth, 5. Hand Thickness, 6. Grip Diameter, 7. Maximum Hand Circumference, 8. Hand Circumference" .The values are given in the 2.3 and 2.4 tables. Image taken from [15].

Hand Dimensions	Male (n = 100)		Female (n = 100)	
	Right-motor-sidedness		Right-motor-sidedness	
	Right hand	Left hand	Right hand	Left hand
1. Hand length	178.37±6.4	173.17±8.60	162.37±5.4	161.77±4.9
2. Palm length	98.47±5.3	97.37±5.8	92.17±5.1	91.27±5.4
3. Handbreadth	83.17±4.7	81.27±3.7	79.57±3.7	78.17±2.6

4. Max. handbreadth	99.77±6.3	96.47±5.6	95.77±4.1	94.97±2.3
5. Hand thickness	29.47±1.7	28.97±2.1	27.17±3.2	26.87±3.1
6. Hand circumference	196.87±8.9	195.97±9.9	191.77±6.2	189.67±4.9
7. Max. hand circumference	271.17±11.4	268.97±12.7	264.87±9.7	263.17±7.4
8. Grip diameter	54.77±3.5	53.57±2.6	51.17±2.9	50.47±3.2

Table 2.3. Mean and standard deviation of different hand dimensions in millimeters for males and females of right-handed individual participated in the study.

Hand Dimensions	Male (n = 100)		Female (n = 100)	
	Left-motor-sidedness		Left-motor-sidedness	
	Right hand	Left hand	Right hand	Left hand
1. Hand length	172.1±3.7	172.8±5.30	161.5±4.9	161.9±5.4
2. Palm length	97.8±2.8	98.3±5.1	90.3±4.9	90.8±6.1
3. Handbreadth	83.8±4.7	85.1±5.1	81.6±4.2	82.2±3.7
4. Max. handbreadth	98.2±5.8	99.1±6.1	94.1±5.2	94.9±27
5. Hand thickness	29.9±2.3	30.6±1.9	28.3±4.6	29.0±5.2
6. Hand circumference	192.8±8.6	194.8±8.6	188.5±7.1	189.9±6.2
7. Max. hand circumference	272.4±12.6	275.7±10.8	249.6±8.6	252.0±8.2
8. Grip diameter	52.3±3.8	53.1±2.7	52.1±3.7	52.3±3.1

Table 2.4. Mean and standard deviation of different hand dimensions in millimeters for males and females of left handed individual participated in the study.

3. Musculoskeletal Disorders and RSI

RSI is a particular type of musculoskeletal and nervous system disorder, the causes of which are to be attributed to highly repetitive operations. For this reason it is widely known and studied in the workplace. It also has other names such as Cumulative trauma disorders, repetitive stress injuries, repetitive motion injuries or disorders, occupational or sports overuse syndromes [40]. The most common actions that can lead to this injury are stress, vibration, mechanical compression, prolonged or uncomfortable positions [41].

Currently the correct term for these disorders according to the United States Department of Labor and the National Institute of Occupational Safety and Health (NIOSH) is musculoskeletal disorders (MSDs) or work-related musculoskeletal disorders (WMDs) [40].

A worldwide increase in these diseases has been measured in the last forty years with the advent of tools that require the use of the keyboard for extended periods, such as typewriters or computers[39].

Although, this phenomenon does not belong exclusively to the second half of the twentieth century, but the first documentation in medical literature already occurred in the sixteenth century. In 1700, the Italian scientist Bernardino Ramazzini described RSI for the first time, dividing it into the 20 categories of Italian workers who were at risk, including employees and musicians [38].

Common RSI Symptoms:

- Burning, aching or shooting pain
- Tremors, clumsiness and numbness
- Fatigue or lack of strength
- Weakness in the hands or forearms
- Difficulty with normal activities like opening doors, turning on a tap, etc
- Chronically cold hands, particularly the fingertips

According to Scott Openshaw and Allsteel Erin Taylor in their treatise *"Ergonomics and Design. A Reference Guide"*, already mentioned several times in this dissertation, there is no minimum or maximum number of repetitive movements per day but *"if repetitive activities are needed, minimizing the number of continuous movements can help reduce the risk of injury"*. Obviously this is not always possible. What can be useful, however, is the reduction of the amount of force needed to perform an activity, which will also reduce the risk of pain and musculoskeletal disorders.

3.1 RSI and Musicians

Since ergonomics, as explained in chapter 2, is the interaction between man and work, we can study the actions performed by musicians from an ergonomic point of view. Analysing the musician as a worker and its instrument and the environment that surrounds him as a workplace, it is clear that musical performance can be the subject of study in the field of ergonomics and is closely related to the design[16]. Several researches show how musicians suffer, and perhaps without their knowledge, from MSDs. In addition, numerous articles show that musicians are a vulnerable population for this kind of injury. Brandfonbrener's research [17] reports that 76% of a sample of 4000 members of the American orchestra suffered from MSDs.

As reported in the work *"Human Factors in Musicians: Design Proposals"* by Lilia R. Prado León, it is easy to find the activities performed by musicians that can contribute to the development of MSDs.

- Stress positions. Postures that are often unnatural, such as prolonged wrist flexion by guitarists or violinists.
- Overexertion. For example, it is common for pianists to have to press the piano keys more forcefully to emphasize certain parts of the composition.
- Overuse. During musical performances the repetition of movements and the long duration are an obligo. For example, a pianist can perform 760 finger movements per minute [18].

- Static load on the muscles. Sedentary positions or asymmetrical such as those held during performances or rehearsals holding instruments of various kinds and weights, can be an example.
- Contact stress. Vibrations of strings rubbing against fingers during a guitar performance is one of these risk factors.

The seriousness of the problem was demonstrated by several authors over time. Although, the quantity and quality of the work published so far in the area of musicians' medicine is far behind that of other fields of occupational medicine. The authors Frank and Von Mühlen in the article *"Queixas Musculoesqueléticas em Músicos: Prevalência e Fatores de Risco"* of 2007 make it a resume, reporting the results in the table:

Authors	**Year**	**Target Audience**	**Prevalence Rate**	**n**	**Prevalence**	**Observation**
Fry	1986	Orchestra musician	Life Time	485	42%	
Caldron e Calabrese	1986	Professionals, amateurs, teachers and college students	Life Time	250	38,6%	No wind instrument
Lockwood	1988	Under 18s	Life Time	113	49%	
Fishbein e Middlestadt	1989	Professional Orchestra musician	Life Time	2.212	76%	
Mathews e Mathews	1993	Professional Orchestra musician	Punctual	29	55%	
Larsson *et al.*	1993	Professionals and college students	Life Time	660	67%	
Shoup	1995	Under 18s	Life Time	425	33,2%	
Blum	1995	Professional Orchestra musician	Life Time	1.432	86,3%	Strings
Salmon e Shook	1995	Professionals, teachers and	Life Time	154	29%	

		college students				
Zetterberg e Blacklund	1998	Universitários	Yearly	227	38,8%	
Yeung e Chan	1999	Professional Orchestra musician	Yearly	39	64,1%	
Shields e Dockwell	2000	College students	Life Time	159	25,8%	Piano
Guptill *et al.*	2000	College students	Life Time	108	87,7%	
Rigg *et al.*	2003	Professionals, amateurs, and college students	Yearly	261	61,3%	Guitar
Kaneko *et al.*	2005	Professional Orchestra musician	Punctual	241	68%	

Table 3.1. Prevalence of musculoskeletal complaints among musicians.

This studies show that there is a general prevalence of musculoskeletal complaints of 55% to 86% in professional musicians of orchestras and between 26% and 87% of the general population of musicians. This percentage is high compared to other professions, such as office workers, where studies indicate 37% prevalence of work-related complaints in the system [19]. Pianists, trumpeters and string musicians are subjects prone to dystonia, as supported by various studies. In particular, trumpet players would suffer from facial dystonia, while in string instrument performances carpal tunnel is more common, thoracic outlet syndrome and neck pain are associated, instead, with the specific position of the violinists' necks. The bent thumb of stringed instrument musicians is associated with the development of Quervain's disease [16].

The growing interest in the subject can also be observed through the creation of associations dedicated to it, such as the American Performing Arts Medicine Association (PAMA) and the Deutsche Gesellschaft für Musikphysiologie und Musikermedizin (DGfMM), in addition to a specialized magazine, the "*Medical Problems of Performing Artists*" (FRANK & VON MÜLHEN, 2007), and centers specialized in the treatment of musicians, such as the Brazilian *"Exerser - Núcleo de Atenção Integral à Saúde do Músico"*, in Belo Horizonte.

The most epidemiologically elaborated studies include the University of North Texas Musician's Health Survey (2000), which was able to isolate some symptomatic foci according to the instrument used, the results of which are shown in the table:

	Double-Bass	Cello	Bassoon	Transverse flute	Transverse flute	French horn	Piano	Piano	Low Brass	Oboe	Trombone	Trumpet	Viola	Violin
Nr. Lit. (n)	7 (1.378)	7 (1.378)	30 (135)	28 (1.639)	31 (369)	32 (739)	15 (455)	28 (1.639)	32 (739)	30 (135)	32 (739)	32 (739)	7 (1.375)	7 (1.375)
Fingers D	3	6	21,3	-	-	12	25,1	-	19	25	7,8	14,8	5	4
Fingers E	12	16	30,7	-	-	21	21,1	-	13,3	10	15,5	8,3	11	10
Hand D	5	7	28	-	31,7	13,2	24,4	-	17,1	25	8,8	13	5	6
Hand E	11	12	37,3	-	28,5	16,2	21,8	-	10,8	8,3	20,7	9,6	12	13
Fist D	7	8	33,3	-	38,2	14,4	34,5	-	22,8	45	10,4	13,5	6	6
Fist E	7	7	48	-	35,2	16,2	29,7	-	10,8	18,3	20,2	12,2	12	5
Forearm D	4	3	22,7	-	22	7,2	-	-	8,2	21,7	6,7	7,8	6	5
Forearm E	5	6	26,7	-	19	9	-	-	4,4	13,3	11,4	6,1	7	6
Elbow D	5	9	2,7	-	12,2	1,8	-	-	4,4	8,3	4,7	4,8	8	7
Elbow E	6	5	8	-	11,4	4,2	-	-	5,1	1,7	10,9	2,6	5	4
Shoulder D	14	16	26,7	-	30,1	15	-	-	10,1	15	14	13,5	16	16
Shoulder E	8	11	26,7	-	28,2	18	-	-	8,9	11,7	22,8	8,3	18	15
Cervical spine	16	25	42,7	73,7	53,7	31,2	-	71	25,3	31,6	24,4	29,6	33	31
Back column	8	10	-	21,1	14,1 (re)	20,4	-	31	19,6	-	11,4	16,2	12	10
Lumbar spine	40	26	29,3	27,6	21,1 (re)	41,4	-	35,2	46,9	33,3	32,2	36,8	21	23

Table 3.2.Prevalence of Musculoskeletal Complaints by body region and instrument[1]. This table was taken from the article: "Queixas Musculoesqueléticas em Músicos: Prevalência e Fatores de Risco. Annemarie Frank, Carlos Alberto von Mühlen".

[1] Results as a percentage of total musicians with musculoskeletal complaints for each instrument.

As demonstrated by the same study of Lilia R. Prado León in "Human Factors in Musicians: Design Proposals" the use of ergonomics in music can be an excellent contribution and prevention for the MSDs, helping to reduce risks. This type of approach is effective but not enough. Because in the same work, the statistical analysis shows that musicians perceive the shape and material of the instrument as a factor of minor responsibility for these injuries. Showing a certain reluctance to change these aspects. This is an interesting issue from the point of view of cognitive psychology and design. It limits the possibility of generating interventions to make the instruments more ergonomic. It is important to properly inform musicians of the risk they run, especially for young people, so that they can take timely preventive action as necessary.

4. Traditional Acoustic Instruments

A musical instrument is an object designed with the intent to produce sounds, whose purpose is to meet cultural needs of various kinds. Originally, musical instruments at the dawn of human culture, but not only (many cultures continue to this day), were used in rituals and ceremonies, secular or religious. The most common use in today's Western culture is to produce music with them. Primarily, anything that produced sounds could be used as a musical instrument, while today the term tends to define only those objects that have obvious musical design.
The different cultures developed on them the composition and execution of melodies for entertainment, and with the evolution of their application changed the same tools. [44].

What do we mean by acoustic[2] instruments?

It is those instruments that produce sound by acoustic resonance, rather than by the use of electrical or electronic means. Acoustic resonance is nothing more than a particular case of mechanical resonance.
An object is resonant if it vibrates for a certain period of time when stimulated by an energy impulse. The frequency of the vibration is determined by the size and material of the resonator. The vibration pattern can be a simple harmonic movement or a more complex action. If the resonator is estimated by a repeated series of pulses, the vibrations will be sustained over time if the frequency of the pulses corresponds to a certain extent to the natural frequencies of the resonator.
Resonance is of fundamental importance in musical instruments because almost all of them are composed of three main elements [20]:

[2]Acoustic music is a retronym, which appeared after the diffusion of electronic or electromechanical musical instruments, such as the electric guitar, the Hammond organ and the synthesizer.

Acoustic music players often use electronic amplifiers to increase the volume produced. However, these devices remain separate from the amplified instrument and faithfully reproduce its natural sound [45].)

1. Sound source, characterized by a vibrating element (the source of the oscillations, for example the strings of a violin or the lips of a trumpeter)

2. Real acoustic resonator which has the function of amplifying and characterising the sound emitted by the vibrating element (for example, the resonance box of the violin or acoustic guitar, or the cannon of a trumpet), which vibrates with the same characteristics as the sound source

3. Any acoustic impedance adapters, i.e. elements that favour the transmission of vibrating energy between the sound source and the resonator, the different parts of the instrument, and between the instrument and the surrounding environment (e.g. the bridge and the soul of the violin or the bell of a trumpet).

An acoustic resonator produces amplification because a series of vibrations are produced internally, whose typical frequencies depend on the geometric and mechanical properties of the resonator itself. The phenomenon of resonance affects both the vibrating element and the resonator. The way in which it starts this interaction can be more or less complex depending on the shape of the instrument. For example, in the case of cords, standing waves are formed in the vibrating element itself (the strings) and the resonance occurs freely in the resonance box; instead, in the case of brass, the sound waves are confined to the tube, which is not a sound source but a tuned resonator, and as such the vibrating element has its own characteristics.

Resonators can be divided into free resonators, which respond to a wide range of frequencies of the sound source (such as chordophone resonance boxes) and tuned resonators, which enter into resonance at certain frequencies [21]:

the most intense is the fundamental frequency, while the other frequencies are higher harmonics at a lower intensity; all the different frequencies are "filtered" and will not cause the body to vibrate (for example, the cannons of almost all wind instruments) [46].

Acoustic instruments also require a kind of driver, a mechanism that applies energy to the resonator in the appropriate form. The driver can be of various kinds from a

simple stick, a bow, pick or bare hand, etc. or it can be an additional resonant structure.
The majority of instruments also have a sort of tone control mechanism. The pitch is controlled at two levels, tuning and performance. Tuning an instrument determines the intonation possibilities that the artist can exploit during the performance. Pitch controllers can change the functioning of the resonator, the driver or both [47].

When in this research we talk more specifically about traditional acoustic instruments, we refer mainly to instruments used by Western cultures, i.e. all those instruments used in symphony orchestras. In this conception we can classify them as:

- Stringed instruments
- Wind instruments
- Percussion instruments
- Keyboard Instruments
- Pinch Instruments

4.1.1. STRINGED INSTRUMENTS

The driver or sound generating device of the stringed instrument is a tight string. When the string is stimulated, which can be done by a hammer, pinch or continuous scratch, it is set in motion at a speed determined by its length, mass and tension. The movement is complex and contains energy at many harmonically correlated frequencies. This movement is transmitted to the resonator through the bridge, a piece of light wood that supports one end of the string.
Tensioned strings, which characterize the chordophones such as piano, violin and guitar, when plucked, beaten or rubbed act as a means of propagation of standing waves, which are confined between two knots (the ends to which they are attached) and whose frequency is correlated with the mass, tension and length of the string.
The fundamental wavelength will be twice the length of the string, while the higher harmonics will be characterized by submultiple wavelengths whole of the

fundamental wavelength. The corresponding frequencies (f) are related to the velocity v of the stationary wave:

$$f = \frac{nv}{2L} \qquad (4.1)$$

where L is the length of the string (2L is therefore the fundamental wavelength) and n is an integer = 1, 2, 3... when n = 1 the frequency corresponds to the basic frequency, the fundamental, the upper integers correspond to the harmonic frequencies. The speed of a wave through a string is correlated to the voltage T and to the mass per unit of length ρ:

$$v = \sqrt{\frac{T}{\rho}} \qquad (4.2)$$

From which it can be deduced that the frequency is connected to the properties of the string according to the following equation:

$$f = \frac{n\sqrt{\frac{T}{m/L}}}{2L} \qquad (4.3)$$

where m is the total mass of the string.

If, on the other hand, the string is excited continuously by means of a bow, an antinode is formed at its central point (i.e. a belly, a point where there is maximum oscillation of the string), so that the frequencies that would have a knot at that point are excluded (i.e. the even frequencies) and only the harmonic sounds of an odd order (corresponding to the submultiples L/1, L/3, L/5...) will be present. This mechanism allows you to adjust the timbre that a string can emit. For example, in string instruments, if you want to obtain a soft and round sound, you place the bow at about half the length of the string ("at the keyboard") to eliminate the even order harmonics; if, on the other hand, you want to obtain a penetrating and metallic sound, you place the bow "at the bridge", towards the end of the vibrating portion of the string, so as to obtain a sound with numerous harmonics.

As for the resonator of a stringed instrument is commonly a box of different shapes or an acoustic board. The resonator responds to wide frequency bands and radiates the sound at these frequencies throughout its surface. The response of the body or soundboard is not flat within these bands, so it acts as a frequency band-pass filter altering the amplitude of the various harmonics. These response peaks are called formants and play a very important role in establishing the timbral identity of an instrument.

Since the sound box is tuned to different frequencies, what produces tone control in instruments of this type is the string. In this case the string itself acts as a tuned resonator. The frequency produced by the string is controlled by adjusting the tension and manipulating the length during the performance.

4.1.2. WIND INSTRUMENTS

With wind instruments, the resonator usually has the shape of a pipe and the energy is supplied as an airflow into the pipe. The resonance produced by the airflow entering the pipe is correlated with its geometric shape (the length and shape of the pipe) and is also dependent on factors such as the presence of holes. By convention, open tubes are defined as cylinders if both ends are open; a cylinder closed on one side and open on the other is defined as a closed tube. Wind instruments can be considered, in the first approximation, as resonant cavities; for example, the transverse flute behaves like an open cylindrical tube, the clarinets [37] and the brasses behave like closed tubes, the saxophones and the oboes behave like closed conical cavities. The drive mechanism in wind instruments is a kind of valve that periodically interrupts or modulates the airflow. The pipe of some winds and the lips of the musician are examples of modulating valves. The resonance frequency of a tube is determined by its length:

For open tubes

$$f = \frac{nv}{2L} \qquad (4.4)$$

for closed tubes

$$f = \frac{nv}{4L} \qquad (4.5)$$

Tone control on wind instruments is typically regulated by the length of the resonator.

In woodwinds the length of the tube is changed by opening or closing the holes along the side of the instrument.

In brass instruments the length of the tube is manipulated directly, adding sections by using valves or pulling in or out of the slides. Much of the brass stamp is attributable to the bell, which is frequency selective as it is the open air sound impedance adapter. The sound is drastically modified if the shape of the bell is modified with the addition of mute.

4.1.3. PERCUSSION INSTRUMENTS

The percussion instrument is a musical instrument whose sound comes from beating, rubbing or shaking.

The common characteristic of all percussion instruments is that the energy of the impulse is applied directly to the resonator, whose response is a vibration for a short period of time. The resonator can be a Helmholtz resonator, also called as air chamber, or a variety of tubes, or it can simply be a particularly resonant piece of metal or wood. Air chamber resonators have spectra to some extent similar to those of the harmonic model, whose tone is quite defined. For these instruments it is possible to obtain the proper frequency of the resonator, as already said, using the model of the harmonic oscillator. For resonators with cylindrical or rectangular neck the resonance frequency is proportional to:

- The square root of the inverse of the volume of the cavity;
- The square root of the inverse of the length of the outlet of the cavity;
- The square root of the area of the opening of the cavity.

The following formula for the resonance frequency can therefore easily be derived:

$$f_h = \frac{v}{2\pi}\sqrt{\frac{A}{VL}} \qquad (4.6)$$

where v is the speed of sound in air or propagation medium expressed in m/s, fH is the resonance frequency in Hz, A is the area of the transverse section of the neck in square metres, L is the length of the neck in metres, V is the volume of the cavity in cubic metres.

Whereas solid body resonators vibrate more complexly, whose resulting spectra are not harmonic or even similar to broadband noise. It is difficult to distinguish the tone on these instruments, the only possible perception is that of the overall pitch.

The main classification of percussion instruments divides them into two sets: those with a determined sound, capable of emitting notes of defined pitch (for example, the vibraphone or the timpani), and those with an indeterminate sound, which produce sounds that can be defined as "high" or "low", but of a pitch that cannot be measured precisely (for example, the snare drum or the bass drum).

To adjust the pitch of instruments having membranes, they are equipped with systems to modify the tension of the membranes themselves.

Percussion instruments also follow a classification by category or type:

- Membranophones (e.g. drums, timpani) emit sound by means of the vibration of a stretched membrane.
- Idiophones (e.g. triangles, xylophones, cymbals) emit sound by vibrating the instrument body.

4.2. Instruments and Ergonomics

Each instrument has a specific shape that produces its own typical sound. In general, they have undergone very few considerable morphological changes in the last century, with the exception of electrical and electronic instruments. As explained in the previous paragraphs, acoustic, historical, artistic and aesthetic causes have influenced the shapes of these objects, giving each of them the characteristics so well recognizable today. This has made them so intrinsic to modern society that their modification is complex and not always welcome [16].

The shape of the instrument is not the only determining factor for the occurrence of injury or not, but it is a variable in the equation that determines the risk factors described in chapter 3. Other factors are weight, instrument quality and the musician's technique itself. It is easy to deduce that each instrument determines the typical posture. Brandfonbrener [22] confirms this thought and as seen in table 3.2 the location of symptoms and diseases is often correlated with the surrounding environment, with the posture required by each instrument and by the parts of the body most frequently stressed during the activity.

Therefore, for example: the movements required to play stringed instruments mainly concern the upper joints, from the shoulders to the fingers. There is also an overload on the neck and back.

In wind instruments, the muscles of the face, neck and upper limbs are more stressed. Back pain and discomfort are also often indicated.

In percussion instruments the activity required to play them can be constant or may have physical and muscular overloads for shorter periods, localized in the upper limbs and neck, trapezium and back [22].

In the same way, the format of the instruments can, for example, impose an asymmetrical posture on the instrumentalist, as in the case of the flute and the violin. Moreover, the characteristics of the instrument can impose an excess of weight on a part of the body (e.g. oboe, tuba, electric bass) or concentrate its weight in certain points of support.

Other acoustic instruments require a posture that compensates for the lack of body support caused by the use of pedals (e.g. organs and batteries). After this general overview, through qualitative measurements[3] compared to the tables in section 2.3, the ergonomics of three traditional instruments are evaluated: Piano, Guitar and Violin.

4.2.1. Piano

The piano is an instrument that requires the musician to perform a very wide repertoire of movements. Some of which lead the musician into positions of great discouragement. In this work some of these situations have been taken into account as examples. Analyzing the three figures 4.1a, 4.1b and 4.1c, the musician has to play in a very low ergonomic position, where his joints are working in critical zones[4]. The joints highlighted in the photo are: shoulder, neck and back. In particular, the musician has a shoulder abduction, a neck flexion and a back rotation in "zone 3", which is a position of the limbs that should be avoided, especially for repetitive or heavy tasks. There is also a shoulder flexion, whose criticality is minor. We refer to table 2.2 in paragraph 2.3, where the measured values can be compared with anthropometric measurements, demonstrating what has been said previously.

Musician joint	Value	ROM	Zone
Shoulder abduction	60	35 - 67	2

[3] Measurements were obtained from static images using image editing software. Only the critical angles of the joints are evaluated. As they are indirect measurements, the angles can differ by several degrees from reality.
[4] This refers to the ROMs, which are explained in the paragraph on anthropometric measurements.

Shoulder abduction	54	35 - 67	2
Shoulder flexion	39	20 - 47	1
Neck flexion	40	23 - 45	2
Back rotation	35	26 - 45	2

Table 4.1. Comparison between the results of measurements (piano) and anthropometric table 2.2. Measurements are expressed in degrees.

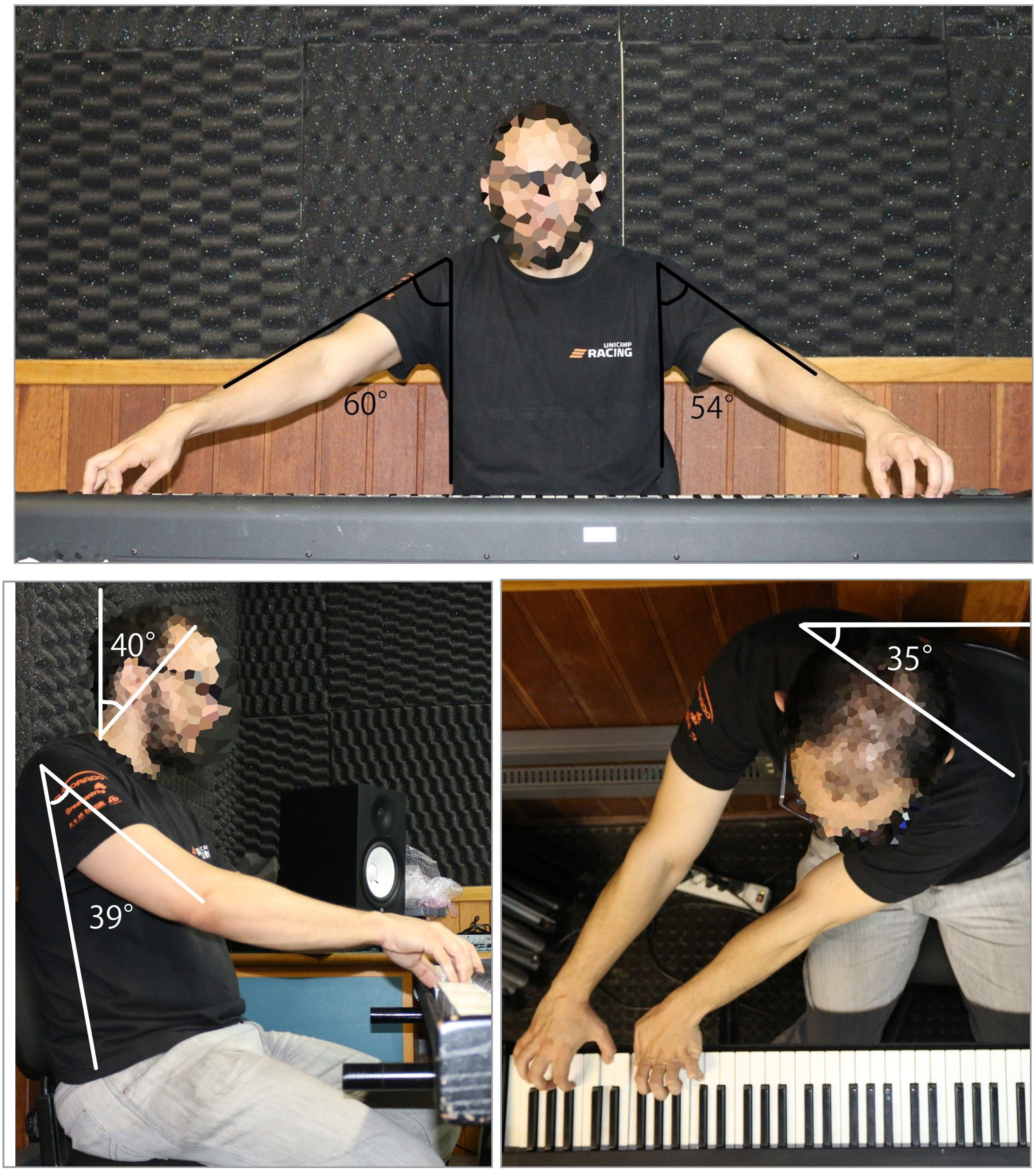


Figure 4.1. Front a, lateral b and top c view of a musician playing piano (keyboard). All angles are expressed in degree. the angles can differ by several degrees from reality.

4.2.2. Guitar

Figure 4.2. Front c, lateral b and top a view of a musician playing acoustic guitar. All angles are expressed in degree. the angles can differ by several degrees from reality.

The classical guitar compared to the piano is a much more static instrument, with a number of movements concentrated mainly in the musician's wrists. However, as can be seen from the 4.2a, 4.2b and 4.2c images, there are several critical areas that can lead the musician to injuries. Especially in the neck. The junctions to consider are: back, neck, shoulder and wrist.
The shoulder abduction of the right arm will not be taken into account, because the weight of the movement and the arm itself is supported by the body of the guitar.

Musician joint	Value	ROM	Zone
Shoulder abduction	24	14 - 34	1
Neck rotation	33	21 - 40	2
Neck flexion	38	23 - 45	2
Wrist flexion	43	26 - 50	2
Back rotation	22	26 - 45	2

Table 4.2. Comparison between the results of measurements (guitar) and anthropometric table 2.2. Measurements are expressed in degrees.

4.2.3. Violin

The violin, as already mentioned in this work, is a notoriously unergonomic instrument. Like the guitar, it is an instrument played almost statically. The areas subject to the greatest stress are the shoulder of the arm in which the bow is held and the wrist of the hand that supports the neck. From the 4.3a and 4.3b images, it is easy to see that another stressed part is the neck, even if it is not subjected to repetitive movements, it has to assume a not optimal position for a long time. In this case there is a Neck flexion and rotation in a critical zone while a back rotation, a shoulder abduction and flexion in less critical zones.

Musician joint	Value	ROM	Zone
Shoulder abduction	28	14 - 34	1

Shoulder flexion	25	20 - 47	1
Neck flexion	27	23 - 45	2
Neck rotation	32	21 - 40	2
Back rotation	14	11 - 25	1

Table 4.3. Comparison between the results of measurements (violin) and anthropometric table 2.2. Measurements are expressed in degrees.

Figure 4.3. Front, lateral and top view of a musician playing violin. All angles are expressed in degree. the angles can differ by several degrees from reality.

5. Digital Musical Instruments

A digital musical instrument is a digital music composition and performance system, consisting of three basic parts, a user interface, a digital sound synthesis system and an output system.

When we talk about digital musical or computer music, we have to define the concept of digital signal and compare it to the analog signal.

A signal is a function of time that transmits information about a phenomenon, in the specific case of music, an analog signal is a one-dimensional electrical signal whose amplitude variation over time and time itself vary in a continuous domain, following proportionally the variations of the acoustic phenomenon.

A digital signal is a binary numerical vector, where time and amplitude are discrete values. Each sample can be mapped by a single bit or more common case by multiple bits, characterized by a sampling rate (sampling rate Fs, Hz) and a resolution (N, bit).

Once we have defined what a digital audio signal is, let's see how it can be generated by an electronic system. The basic principle of digital acoustic synthesis is that random numerical series sound like noise, periodic sinusoidal numerical series sound like tones, while complex sounds can be approximated by multiple sinusoids of different amplitudes, frequencies and phases.

Over time, various methods have been developed to ensure that an electronic system could produce digital sound synthesis. Most of the time, these methods owe their fortune to the technological limitations imposed by the time.

5.1. Digital Music Synthesizers

The first methods used, borrowed from analogue synthesis, were additive synthesis, where a complex spectrum is recreated as a set of discrete "lines" corresponding to sinusoids, and subtractive synthesis, starting from a spectrum rich in harmonics, obtains the desired spectrum through filtering operations.

According to Fourier theory, the waveform of a signal and its envelope over time can be mathematically obtained as a combination of sine waves of multiple frequency of the fundamental (harmonics) and partial sine waves of different frequency, phase and amplitude.

$$f(t) \;=\; a_0 + \sum_{n=1}^{\infty} a_n cos(2\pi f t n) - \sum_{n=1}^{\infty} b_n sen(2\pi f t n) \qquad (5.1)$$

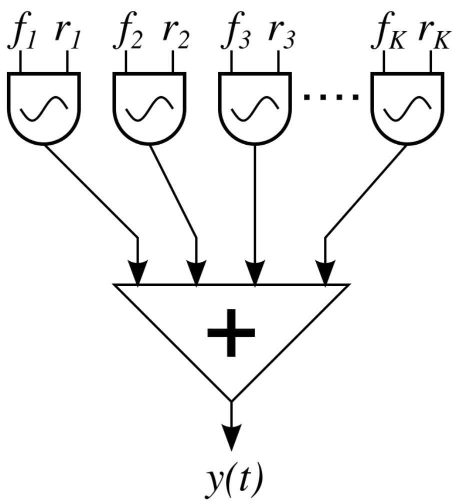
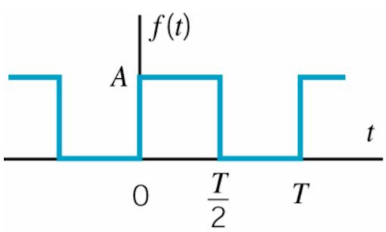


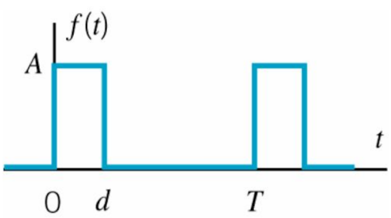
Figure 5.1. Additive synthesis diagram. (https://creativecommons.org/licenses/by-sa/3.0)

Additive synthesis uses exactly this mechanism to imitate the sound of any musical instrument. The output of several oscillators, modulated and adjusted according to the Fourier decomposition is combine to generate the final output [36]. In this way it is possible to reproduce the waveform corresponding to the timbre of the specific instrument, thus emulating its sound.



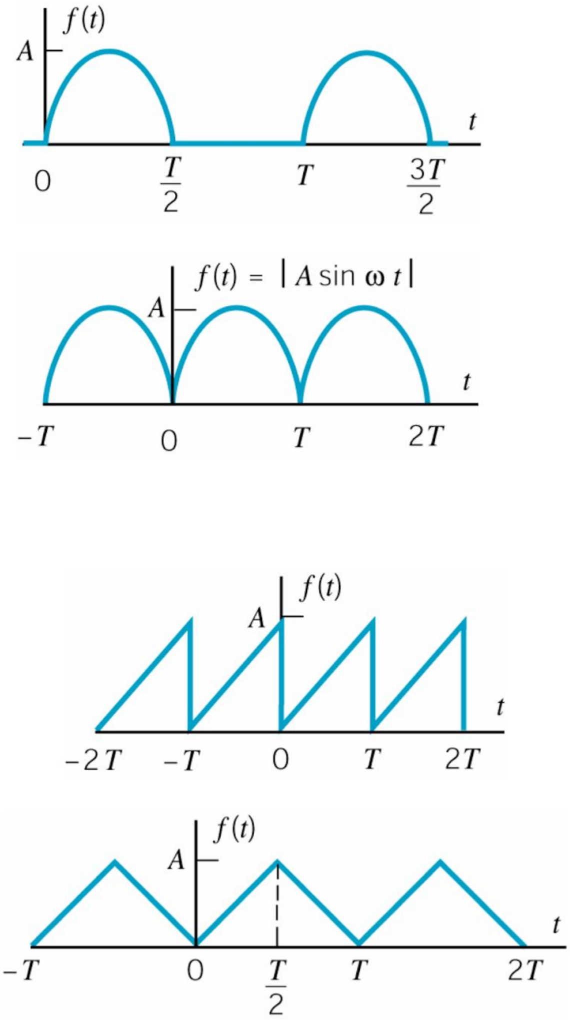
Square wave: $\omega_0 = \frac{2\pi}{T}$

$$f(t) = \frac{A}{2} + \frac{4A}{\pi}\sum_{n=1}^{\infty}\frac{\sin\left((2n-1)\omega_0 t\right)}{2n-1}$$



Pulse wave: $\omega_0 = \frac{2\pi}{T}$

$$f(t) = \frac{Ad}{2} + \frac{2Ad}{\pi}\sum_{n=1}^{\infty}\frac{\sin\left(\frac{n\pi d}{T}\right)}{\frac{n\pi d}{T}}\cos\left(n\omega_0 t\right)$$



Half wave rectified sine wave: $\omega_0 = \frac{2\pi}{T}$

$$f(t) = \frac{A}{\pi} + \frac{A}{2}\sin\omega_0 t - \frac{2A}{\pi}\sum_{n=1}^{\infty}\frac{\cos(2n\omega_0 t)}{4n^2-1}$$

Full wave rectified sine wave: $\omega_0 = \frac{2\pi}{T}$

$$f(t) = \frac{2A}{\pi} - \frac{4A}{\pi}\sum_{n=1}^{\infty}\frac{\cos(n\omega_0 t)}{4n^2-1}$$

Sawtooth wave: $\omega_0 = \frac{2\pi}{T}$

$$f(t) = \frac{A}{2} + \frac{A}{\pi}\sum_{n=1}^{\infty}\frac{\sin(n\omega_0 t)}{n}$$

Triangle wave: $\omega_0 = \frac{2\pi}{T}$

$$f(t) = \frac{A}{2} - \frac{4A}{\pi^2}\sum_{n=1}^{\infty}\frac{\cos((2n-1)\omega_0 t)}{(2n-1)^2}$$

Figure 5.2. Examples of the fourier series. Six common time domain waveforms are shown, along with the equations to calculate “a” and “b” coefficients.

The first additive synthesis in the musical field seems to have been the analysis and synthesis of trumpet tones with Music V by Jean-Claude Risset in 1964 [23].

The MUSIC-N series started in 1957 by Max Mathews at Bell Laboratories was the first family of computer programs to generate digital audio waveforms through direct synthesis. Music V, was one of the most used sound synthesis programs at the time, created in 1967-68.

Music V consists of computer models of oscillator and amplifier modules, as well as procedures for establishing interactions between modules [48].

The real turning point came in 1973, [24] when the Japanese company Yamaha patented the frequency modulation synthesis algorithms of John Chowning, who had been experimenting at Stanford University since 1971 [25]

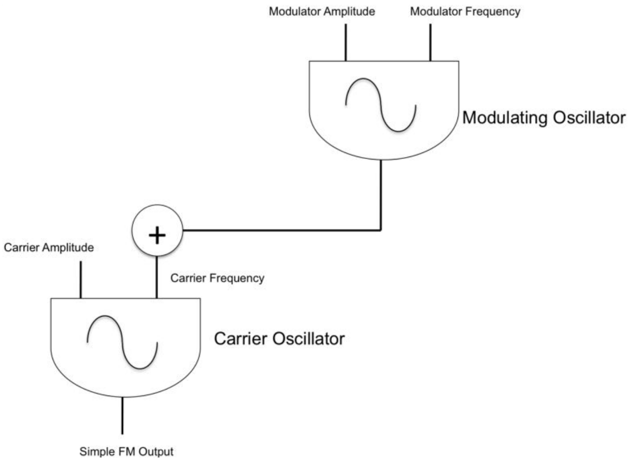
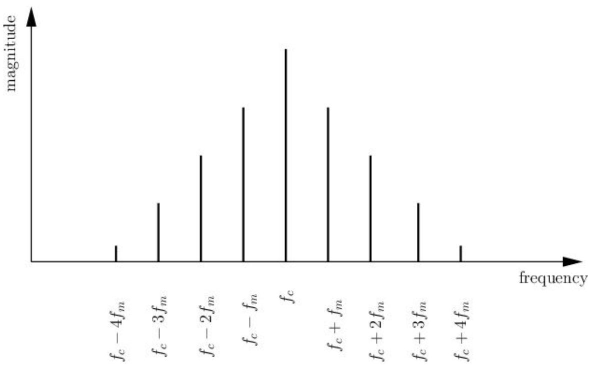


Figure 5.3. Rappresenta due oscillatori in configurazione sintesi FM, in cui l'oscillatore Modulante, modula la frequenza del Carrier.

Frequency modulation is achieved by coupling two oscillators, the Carrier (Osc1) and the Modulator (Osc2). The modulating oscillator will modify with its output the frequency of the Carrier fc, so the signal resulting in output from Osc1 has a variable frequency in time fc(t). The Modulator frequency fm must be greater than 20Hz, otherwise the result is a simple Vibrato effect. The resulting spectrum has theoretically infinite harmonics with decreasing amplitude.

If the two oscillators are sinusoidal, the transfer function is expressed in this way:

$$FM(t) = A \sum_{k=-\infty}^{\infty} J_k\left(\frac{B}{\omega_m}\right) sin((\omega_c + k\omega_m)t) \qquad (5.2)$$



and the frequency of the resulting signal is:

$$freq(t) = f_c + k_f m(t) \qquad (5.3)$$

Figures 5.4. Resulting spectrum of frequency modulation.

where:

- *A* is the input value of the Carrier amplitude,
- *B* is the input value of the Modulator amplitude,
- J_k is the k-th Bessel function of the first kind
- $\omega = 2\pi f$,
- *m(t)* is the modulating signal
- k_f is a constant, called the
- Modulator frequency sensitivity factor.

The inverse of the Harmonicity ratio fm/fc, called C:M ratio, define the harmonics characteristic of sounds. If the C:M ratio can be expressed as a reduced fraction N1:N2 where Ni are integers, the spectrum of the sound is harmonic.
The amplitude of each sideband depends on Modulation index:

$$I = \frac{B}{\omega_m} \qquad (5.4)$$

Yamaha engineers applied the Chowning algorithm to a commercial digital synthesizer, adding improvements such as key scaling. This avoided the distortion that normally occurs in analog systems during frequency modulation.
And when the same company launched the Yamaha DX7 in 1983, there was a revolution in the world of digital synthesizers, which for innovation and cost, defined the decline of analog synthesizers. The instrument had a five-octave range of sensitive keys and offered a wide choice of timbres.
The other techniques we are going to talk about became commercially viable only after an improvement in performance of microprocessors and digital signal processing (DSP).

The Sample-based synthesis technique involves sampling and the subsequent use of sounds, to which it is possible to apply transformations to obtain completely new ones. It is perhaps a legacy of the tape-based *"musique concrète"* developed by Pierre Schaeffer at the beginning of 1940 [26]. This technique, required a large

amount of available memory. Today, it is one of the most used techniques by VSTi to recreate real instrument sounds.
For example, the first commercial sampling instrument was the Fairlight Computer Musical Instrument (CMI), introduced in 1979. the Fairlight CMI was a general purpose computer that presented peripherals useful for the musician to record, digitize and reproduce the sounds he created, with the help of a piano keyboard. It also gave the possibility to the musicians to control the volume, the attack and decay of the sound, and the use of an effect that simulated the vibrato.

Wavetable synthesis is a technique in which a stored or drawn arbitrary waveform is read over and over again at each cycle to create a periodic sound. Digital interpolation between adjacent waveforms allows fluid and dynamic changes in timbre. This kind of synthesis is also applied to the frequency domain. In this case, a desired harmonic spectrum is created and with the use of the inverse of Fourier series the period of the table is created. Normally, the wavetable stores N values sampled at sampling rate fs over one single period, so the output frequency of the synths is:

$$f_0 = fs/N \tag{5.5}$$

This technique was developed by Wolfgang Palm of Palm Products GmbH (PPG) at the end of the 1970s [27].
The technique of physical model synthesis involves the use of equations and algorithms designed to reproduce exactly the sonority of an instrument. In simpler versions such as linear-predictive-coding (LPC), it normally consists of two phases, the creation of the excitation signal and the creation of a filter that recreates the sounds of the instrument. LPC was mainly used in telecommunications for low bit-rate speech synthesis. Physical modelling is not a novelty in the field of acoustics, but its use was only possible after the development of the Karplus-Strong algorithm. An improvement of this technique was implemented by Julius O. Smith III, with the use of Digital waveguide synthesis, an extension of the Karplus-Strong algorithm [26]

Digital waveguides are an important part of most modern physical modeling synthesizers. The quality and speed of physical modeling improves as processing power increases. The first tool to use the waveguide synthesis technique was the Yamaha VL1 in 1994.

In the table 5.1 there is an interesting summary on the taxonomy of digital synthesis techniques. This table is reported by Julius O. Smith III in his article "Viewpoints on the History of Digital Synthesis" [26].

Processed Recording	**Spectral Model**	**Physical Model**	**Abstract Algorithm**
Concrète	Wavetable F	Ruiz Strings	VCO,VCA,VCF
Wavetable T	Additive	Karplus-Strong Ext.	Some Music V
Sampling	Phase Vocoder	Waveguide	Original FM
Vector	PARSHL	Modal	Feedback FM
Granular	Sines+Noise (Serra)	Cordis-Anima	Waveshaping
Prin. Comp. T	Prin. Comp. F	Mosaic	Phase Distortion
Wavelet T	Chant		Karplus-Strong
	VOSIM		
	Risset FM Brass		
	Chowning FM Voice		
	Subtractive		
	LPC		
	Inverse FFT		
	Xenakis Line Clusters		

Table 5.1. A taxonomy of digital synthesis techniques [26].

5.2. HCI in Digital Musical Instruments

When we talk about DMI, a WIMP type model of HCI is often not adequate. Currently, post-WIMP interaction models are taken into consideration, and one of these is called Instrument interaction (Beaudouin-Lafon 2000), it is a GUI model but expands the WIMP metaphors. In such a model, the interaction with the computer takes place in the domain of objects with the use of tools. In order to be clearer, this approach is based on how we use tools to manipulate objects in the physical world.The name given to the object of interest which is manipulated is called domain objects and the way it is manipulated through the computer is called interaction instruments. This method is very evocative of the way musical performance occurs with the use of gestural controllers. Therefore, the interaction that takes place in computer music can be seen as a high specialization of HCI in the field of music. Where the interaction between computer and man requires the use of motor skills and different complex cognitive abilities.In this case, the goal of the performance, is of a bidirectional the interaction between the performer and the computer. The movement of the performer is the input of the system, but it can also be part of a choreography and the output of the system is audible both to the public and to the person who is performing, obtaining information about the state of the system. An important difference from generic HCI is the fact that interaction with a DMI takes into account several control parameters simultaneously and includes the relationship with timing, rhythm and training. Here follows a list of contexts where the interactions with DMI could take place, from traditional to modern [28]:

- **Note-level control**, or musical instrument manipulation, i.e. the real-time control of synthesis system parameters. The parameters that we can modify are for example:
    - Pitch
    - Loudness
    - Timber

- **Score-level control**, like a conductor's baton, controlling the characteristics applied to a previously generated sequence, or possibly generated on the computer.
- **Sound processing control**, or post-production activities, digital control of real-time effects, audio effects or spatialization, often used in live electronic music.
- **Contexts related to traditional HCI**, such as drag and drop, scrubbing (Wessel and Wright 2001) or navigation; some of these contexts are used for different metaphors, such as timbre control in a multidimensional space.
- **Interaction in multimedia installations**, are spaces where one or more people can act through sensors to manipulate audio, video or haptic systems. In this context, contrary to the others, no previous skills are required to interact with the interface, since the main goal in this case is the exploration of physical space.
- **Interaction in the context of dance/music interfaces**, where the emphasis is given mainly to the choreographic movements performed by the dancer, who is typically monitored by various types of sensors. In this case, the generation of music is not the primary goal.
- **Control of computer games**,or , the manipulation of a computer game input device, although in this case the primary objective of the interaction is fun rather than performance.

Therefore, once established the instrument interaction context associated to the computer interaction, in this particular case the interaction with the DMI, it is necessary to understand which are the tools that manipulate our objects domain and which are the most appropriate metaphors to use. Speaking of tangible instruments, which have a physical body, in the literature the interfaces have been classified according to their relationship with the acoustic traditions instruments, as follows [29]:

- **Instrument-Like** are DMI whose peculiarity is to tend to be a replica as faithful as possible to their acoustic references, both in the interaction, both in the metaphors that the musician will use. Even though they try to offer an experience as similar as possible to the acoustic ancestor, their control capacity is reduced. Instead, they offer a wide sound palette [30]. One of the most famous examples is the digital keyboards that emulate a grand piano, but over time, the MIDI version of a large number of acoustic instruments has been developed.

- **Instrument Inspired**, are instruments that in a certain form are inspired by their acoustic reference, but whose characteristics do not make it a true representation in the interaction and metaphors used.
- **Augmented Instrument**, this family of instruments is based on acoustic instruments whose capabilities and possibilities of interaction are amplified by the use of sensors.
- **Alternate instruments** are all instruments that do not belong to any of the previous classifications and in no way follow patterns of existing acoustic instruments. For example, they may be a non-physical interfaces based on the performer's body itself, or whose forms, interactions and metaphors in no way evoke traditional musical instruments. Others, may be based on existing objects, e.g. a video game controller, etc. For this reason, such instruments are often under-classified in two ways. For the type of sensors used (wearable or not) and by the parts of the body exploited (hands or whole body). In the first category, we can observe those that can be weared, such as: gloves, biosignal detectors, sticks; not wearable such as: systems of movements and body position monitoring.

5.3. Digital Lutherie

"Digital Lutherie is quite a broad subject, which includes highly technological areas (e.g. electronics and sensor technology, sound synthesis and processing techniques, computer programming), human-related disciplines (associated with psychology, physiology, ergonomics and human-computer interaction components), plus all the possible connections between them (e.g. mapping techniques), and the most essential of all, music in all of its possible shapes.” this is the definition given by

Sergi Jordà in 2005 in his dissertation "Digital Lutherie - Crafting musical computers for new musics' performance and improvisation".

Whenever a new digital instrument is designed with the intent to produce a “good” instruments, capable of virtuosity and also that “hook” novice users, these are the questions that need to be asked: *“How do we create controls and interactions that feel inevitable to expert and amateur users?”*, and *“How do we create interactive situations that stimulate rather than placate, leading the participant beyond the surface and into thoughtful consideration of rich, expressive, meaningful experiences?”*. These questions were asked for the first time in 2002 by Machover [35].

So in this chapter, we will try to give an answer to these questions and try to understand what are the parameters that, in letterature, lead to the production of a "good" DMI. In addition to more abstract concepts related to humanistic disciples to define what a "good" DMI is, such as playability, physicality and virtuosity, this chapter examines in detail more technical aspects of HCI as the sensitive electronic part and the type of connection between the sensing system, the gestures and the output.

5.3.1. Sensing System

The sensing system is the organ used to detect an action of the performer, in terms of HCI it is the system that allows the machine to receive input from the user. More specifically in the field of digital musical instruments, the system is capable of capturing the event of a gesture by the performer and sending it to the processing system. Sensors are nothing more than transducers capable of transforming a physical phenomenon into a proportional electrical signal, linear or not, usable by a processing system. This apparatus is fundamental in DMIs, since there is no mechanical system directly connected between the performer's action and the sound production, as in traditional acoustic instruments, it is the only way to react to the user's gestures. The types of sensors are varied and can be integrated with each other to create more complex sensitive organs. Currently, no research indicates a better type of sensors to be used in this area, it certainly depends on the needs of the musical instrument craftsman. It is not the objective of this thesis to determine which are the best systems to use, but only to give an in-depth overview of the possibilities. It is easy to understand that to translate same physical phenomenon it is possible to use different sensors belonging to the same family, but depending on the intrinsic characteristics of the sensor, which can be defined as quality, different performances will be offered. Now let's try to understand what kind of sensor we have to choose for our DMI.

In order to choose the type of sensitive organ we need, we should ask ourselves the following questions:

1. Which physical phenomenon should be measured?
2. What technical specifications do we need?

In the first question the answers can be varied, here an example of the most conventionally used is given:

- **Acceleration sensors**: accelerometers
- **Biometric sensors**: detect a characteristic of an area of the human body.
- **Electrical resistance sensors**: ohmmeters, multimeters.
- **Force sensors**: load cells, strain gauges.
- **Light sensors**: photocells, photodiodes, phototransistors, CCD and CMOS
- **Orientation sensors**: gyroscopes, laser gyroscopes, position sensors, rotation sensors
- **Proximity or distance sensors**: switches, optical proximity sensors (made by a combination of photocell and LED or with a laser), or ultrasonic sensors.
- **Sound sensors**: microphones, speakers
- **Temperature sensors**: thermometers, thermocouples, temperature-sensitive resistors, thermistors.

A different type of classification, more oriented to the field of digital instruments, is proposed by Sergi Jordà (2005):

- **Muscle-action sensors**
- **Blowing sensors**
- **Voice sensors**
- **Other sensors**

The latter (other sensors) include all the sensors previously mentioned under the name of biometric sensors (which detect changes in the state of the body). These include factors that are under the direct control of the user (such as bio-electricity from muscle movements) and those that are not (such as blood pressure, temperature, etc.).

The second question can be divided into additional questions such as:

1. What precision, accuracy and range do we need?
2. In which and how many directions do we need to detect the phenomenon (degrees of freedom)?
3. In which field of application should it work, with the parameters described above?

While it is not always necessary to use sensors that have a very large range, because maybe we have to measure small scale variations of a phenomenon, or we do not always need a measurement that is very accurate and precise, because maybe we are not interested in knowing the true value of measurement but we are interested in understanding only if the phenomenon has varied qualitatively, a greater number of degrees of freedom is often desirable because physical phenomena occur in three-dimensional space and maybe being able to know the variations along a single direction is not enough. A very simple and intuitive example is the measurement of the position variation of an object, when we only have one degree of freedom, we are taking into account its variation only in a single direction. With two degrees of freedom we are already measuring its movement on a plane and with three degrees of freedom in space. With four degrees of freedom, we are also considering its rotation on an axis and in order to avoid dragging it out long, with 6 degrees of freedom we are measuring its translation and rotation in 3D space. It is also possible to have more than 6 degrees of freedom, but usually these last three are used to correct past measurements with the integration of additional data, so that any drift errors can be corrected.

When we define the scope of our sensor system we need to define the conditions under which our sensor must work. For example, we need our instrument to operate at temperature, pressure or other characteristics outside of commercial standards. Of course, taking these situations into account also allows us to create a tool that faithfully meets our expectations.

5.3.2. Mapping

"The connection between gestural parameters (input) and sound control parameters or audible results (output) is called mapping. The most direct kind of mapping, which associates each single sound control parameter (e.g., pitch, amplitude, etc.) with an independent control dimension, has proved to be musically unsatisfying, exhibiting a toy-like characteristic that does not allow for the development of virtuosity." , Sergi Jordà (2005).

The digital instrument designer, after considering which sensors should be used, which HCIs will occur between the musician and the DMI and which sounds the instrument will emit, then he still has to decide which sensor(s) will control which aspect(s) of the sound. This task, known as mapping, is an integral part of the process of creating a new musical instrument. We can then define mapping as the act of taking data in real time from an input device that measures the user's performance and use this data to control the parameters of a synthesis engine. In the music literature different mapping strategies are described and classified by different authors such as Rovan, Wanderley, Dubnov and Depalle (1997). These take different names according to who describes them, but they can be summarized in three types of mapping:

- One-to-one, where a synthesis parameter is driven by a performance parameter,
- One-to-many, where a performance parameter can influence several synthesis parameters at the same time ,
- Many-to-one (Divergent), where a synthesis parameter is driven by two or more performance parameters.

The classification of the mapping into these three basic types provides a general method of "*how two groups of parameters can be related to each other*". A further possibility derives from the combination of these three previous three strategies, called basic strategies. It leads to a many to many strategy. An example of a many to many mapping strategy is presented in Figure 5.5.

A.HUNT and M. WANDERLEY (2000) deal with these basic mapping strategies from a psychological point of view. They use experiments to demonstrate which of these structures was best suited to the design of new digital musical instruments. These experiments, unconsciously, took into account parameters such as learning curve, usability, user fun. These experiments, as also reported by Sergi Jordà (2005), demonstrated the effectiveness of complex mapping strategies to the detriment of the simpler ones, which caused dissatisfaction on the user's side. This is because interfaces that used complex mapping led the user to think of sound as the product of a gesture, as is common in acoustic instruments, and not as the variation of a single parameter. This process makes the user more involved in the tasks to be performed.

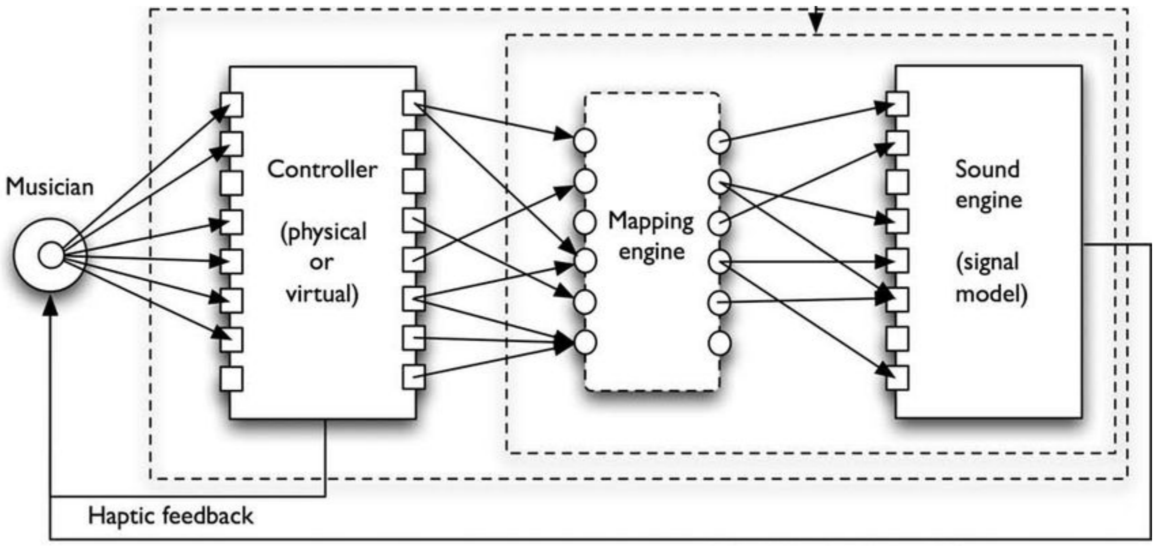


Figure 5.5. Typical structure of a DMI interface (Wanderley 2000; Leman 2008; Wessel and Wright 2001), divided into gesture controllers, sound engine and mapping. Figure taken from "Designing Constraints: Composing and Performing with Digital Musical Systems" by Thor Magnusson.

A. HUNT and M. WANDERLEY, in the same work, draw up guidelines (reported below), also taking inspiration from the world of traditional acoustic instruments, to design a mapping strategy that makes a digital instrument attractive to users and that can be more durable over time.

- **Energy is required for amplitud**: As already shown in the chapter on acoustic instruments, the excitation of the system before it vibrates is provided by the musician, who must continue to provide energy to keep it vibrating. The output amplitude of the system is mostly directly related to the energy supplied as input. Once the system is stimulated, the mechanical energy is dissipated as acoustic energy.
- **Two hands are used**: In most acoustic instruments, the excitation and damping operations described above are performed using different limbs. A classic example is the string instrument, which is excited by one hand and the modulation of the tone is done through the fingering of the other hand.
- **Complex mappings**: Changes in one parameter are reflected in the others. Let's consider the correspondence of each input control to the audible parameters in the acoustic instruments. For example, where can we find a

violin volume control? As is easy to imagine, this control is not present in acoustic instruments. Rather, this control is given by a combination of inputs such as the speed of the bow, the pressure of the bow, the choice of string and even the position of the finger. In terms of mapping strategy this can be defined as "many-to-one" or " convergent", since it requires several inputs to control a parameter. Always taking the violin as an example, it can be shown that the bow influences more than one parameter of the sound (volume, timbre, articulation and pitch). This is therefore an example of "one-to-many" mapping. This is the kind of interaction users are familiar with when playing an instrument and therefore they expect the same complexity of interaction with DMIs.

- **Timbre is controlled in a non-direct manner**: Most acoustic instruments do not have a specific timbre control system. The timbre is given by the nature of the instrument as already explained in chapter 4, it is controlled by almost all the input parameters of the instrument. This is a particular case of point (3) (described above) where many input parameters combine to influence a particular characteristic of the system.

An important result reported by Hunt and Wanderley, obtained as the conclusion of this analysis on mapping strategies, is the need for a multi-layer topology. As the authors write in "Mapping performance parameters to synthesis engines" three layers are needed [31].

1. The first layer represents the specific mapping of the device between technical control parameters and gestures.
2. In the second layer, there is the mapping between the names of the parameters that carry the gesture and the semantics of the sound. This layer is referred to as the "semantic layer", as described in figure 5.6.
3. In the last level there are specific mappings between the technical control parameters and aesthetically significant "sound parameters", such as brightness or position.

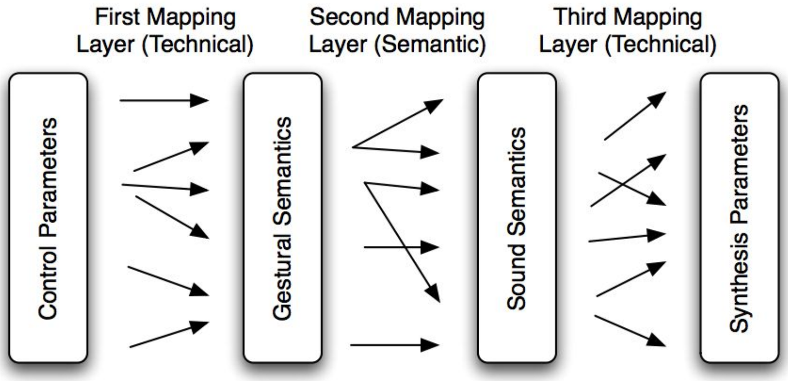


Figure 5.6. A 3-layer mapping diagram adapted from [31].

5.3.3. Virtuosity

The ability of an instrument to be a virtuous one, is defined by Sergi Jordà (2004) as the junction of two properties that we define as Variability and Reproducibility.

The Reproducibility component of an instrument is described as that property that guarantees to execute two performances in a very similar way by the musician. This characteristic is closely linked to western music of the last 500 years. This property is also described by Wanderly and Orio (2002) as controllability.

When discussing Variability, it is more complex and takes its cue from acoustic instruments. We can divide Variability into three subtypes of diversity, Micro-diversity (Performance nuances), Mid-diversity (performance contrasts) and Macro-diversity (Stylistic flexibility) [30].

- **Micro-diversity (MicD)** - this parameter identifies the differences allowed by an instrument between two performances of the same piece of music, or how much a performance can influence the characteristics of a song. In acoustic instruments these micro differences are given by the richness and the fine control that the musician has over the sound, but it can also be linked to the structural variation that the instrument allows as variation of time, tempo, and number and density of voices.

- **Mid-diversity (MidD)** - Unlike MicDs, this feature is an indication of how much two performances or two musical pieces can differ using the same instrument. Most traditional instruments allow great control from this point of view, except for the unpitched percussion instruments which have a low MidD value.

- **Macro-diversity (MacD)** - the last feature refers to the flexibility and adaptability of the instrument. We can also describe it as the ability of an instrument to be general purpose, thus adapting to multiple genres or musical contexts.

This last characteristic is the one that influences less the virtuosity of an instrument, since for example among the traditional instruments there are many instruments that allow the musician to be a virtuoso without being general purpose.

5.3.4. Physicality

"All human communicatory systems produce concrete visual, auditory and/or tactile products that in their own respective forms of transmitting the energy used in their production are models of the act of production on the parts of their producers", (Seeger, 1977: 23) [32].

One aspect that might have been underestimated in recent decades of electronic music is the concept of the physicality of the electronic/digital instrument.

When in this work the physicality is mentioned, we refer to two bi-directional concepts, the action performed by the performer (gesture) and the action of the instrument towards the musician (feedback).

In the first instance, the introduction of complex gestures that allow the performer to inject energy into the instrument during its use through movement, guarantees a better performance experience. This interaction may affect performance factors such as fun and immersion.

The instrument's feedback can be sonic and haptic. A direct physical conduction of the sound/sound vibration in the body of the performer, as happens in traditional acoustic instruments, greatly increases the " feel " and intuitive control of the instrument as an extension of the body.

The two concepts of Gesture and Feedback are bidirectional, in other words, the performer's action must correspond to one or more actions returned by the instrument, creating a loop in which each one responds to the other.

In this way the performance can stimulate emotional sensations in the musician and improve the effectiveness.

The development of gesture performance interfaces such as sonic and tactile displays that are equally responsive is therefore essential.

"Instrumental “touch,” the sensitivity to a subtle haptic/sonic feedback loop in acoustic instrumental technique, is an essential aspect of the development of a musician. The instrument conducts touch, amplifies it and sonifies physical gesture. In return, the body responds to the “feel” of the instrument and its resulting sound. A resonating feedback loop between touch, sonic result and feel, is formed. Much of the physicality of musical performance is a result of these mediations between feel and ear." [33]

5.3.5. Playability

The concept of playability is usually part of the gaming world, but it is important to discuss this topic also for digital musical instruments. This concept is based on the concept of usability. Playability is not limited to evaluating the fun and entertainment experienced while playing a DMi, which are subjective and difficult to measure, but extends to a larger dimension to evaluate the Player Experience (Px). Playability is a set of properties that are described from a specific system to measure not only fun and entertainment but also the credibility and satisfaction of the musician. The set of attributes to characterize playability are: Satisfaction, Learnability, Effectiveness, Immersion, Motivation, Emotion and Socialization [34].

- **Satisfaction**: We define this as the gratification or pleasure that comes from playing a digital instrument. Satisfaction can come from different aspects of the instrument such as:

  Learnability: This is defined as the ability of the musician to understand and master the mechanics of the system (how to interact with the instrument, its gestures, and its sound characteristics), which in our opinion is strongly linked to the balance of these three characteristics Challenge, Frustration and Boredom, which are discussed later.
  Difficulty: it can be greater or lesser depending on the learning curve and in relation to the musician's skills. A high level of difficulty can cause a greater stress on the player in order to learn how to play. For all these reasons, an instrument with different levels of difficulty can be helpful.
  Frustration: This property is often part of the learning process and is produced by feelings of being unable to achieve a particular goal.
  Discovery: An instrument with different features requires more time for the musician to learn its full characteristics, but the discovery of new possibilities to improve his skills on the instrument and the achievement of new goals, creates more satisfaction.
  Fun: One of the main goals of any instrument is to entertain, so a DMI that is not fun to play could never satisfy the musician.

- **Effectiveness**: Define it as the time of practice and resources needed by the musician to achieve satisfactory goals, with all its characteristics described above.
  Immersion: We define this as the ability of the instrument to be credible, so that the performer is directly involved in the performance. To characterize Immersion we propose the following properties:

Awareness: the degree to which the musician is aware of the consequences of his gestures, understanding each action as he modifies the performance helps the musician to imagine what to do next, it is highly related to the concept of Predictability. Absorption: a completely absorbed user is involved in the performance enough to concentrate all his skills and attention on it.
Realism: Realism can be more easily described for instrument-like DMIs, but more generally, sound and haptic feedback helps to maximize realism. The greater the realism is, the greater is the immersion of the player.

- **Motivation**: This is the set of characteristics of the DMI that drives performers to continue its practice until the completion of their goals. We define Motivation as having the following properties:
  Encouragement: the degree of encouragement of musicians is influenced by the level of confidence they feel in front of the instrument and the possibility of achieving new skills. This may also be related to the popularity of the instrument.
  Curiosity: it derives from the concept of discovery defined in the satisfaction property.
  Self-improvement: occurs when the user develops his own skills and abilities to improve the way he interacts with the DMI.
  Diversity: linked to what has already been expressed in the paragraph on Virtuosity.

- **Emotion**: Refers to those involuntary responses the instrument performance stimulates the musician. Emotion is characterized as having the following properties:
  Reaction: the performer reacts because the system is a source of different stimuli. The reaction can then trigger different types of emotions.
  Sensory appeal: the instrument must stimulate different sensorial channels, for example the auditory and haptic perceptual channel.

5.3.6. What a "Good" DMI is

According to Sergi Jordà (2004) a "good" musical instrument is such only, if it is balanced in the three regions of Challenge, Frustration and Boredom. Since professional musicians are very easily bored of the most common simple tools, while in amateurs comes easily the frustration for instruments too sophisticated. For example, let's take two acoustic instruments that perfectly represent these two opposite characteristics, the violin and the kazoo. The first instrument from a beginner's point of view is a very frustrating one, because just emitting a note is extremely complex, and being a fretless instrument, emitting this note in tune is even more difficult. Contrary to what happens with the kazoo as it is very simple to start playing, but you can not develop any skill as a virtuoso, becoming a simple toy for a professional musician [30]. So, ideally, when we design a new digital instrument we want its learning curve to be such that a beginner can quickly learn to play the instrument satisfactorily and the curve itself has no upper limit to allow a professional musician to become a virtuoso of the instrument.

Unfortunately, the term learning curve is not an official technical parameter due to its extreme difficulty in being calculated, but it is an expression commonly used in any educational field. This learning curve strongly depends on the learning ability of a user, who is subjective. An approximation of this curve in the field of digital music is expressed by Sergi Jordà (2004) as:

$$Musical\ Instrument\ Efficiency = \frac{Music\ Output\ Complexity}{Diversity\ Control}$$

- **Music Output Complexity**: is a parameter that depends on all possible characteristics of the output sound and its variations.
- **Diversity Control**: is the parameter that expresses how and how much the performer's actions affect the music he is producing. It is a parameter that serves to distinguish a CD player from a musical instrument. Without this parameter it might seem that CD Player, having a very large musical

complexity in the output and very simple input controls, is the perfect instrument.

“A good instrument should not impose its music on the player. A good instrument, for example, should not be able to produce only good music. A good instrument should also be able to produce “terribly bad” music, either at the player’s will or at the player’s misuse.” [30].

- **Control Input Complexity**: This parameter depends on the relationship between the degrees of freedom of the controller and the mapping. It can also be expressed as "explorability", i.e. the number of gestures that are recognized, the precision with which it is possible to control them and includes the mapping strategies (Orio, 1999) [42].

5.4. Digitals vs Acoustics Instruments

Inspired by the 2007 article *"The acoustic, the digital and the body: A survey on musical instruments"* written by Thor Magnussone and Enrike Mendieta [43], this section deals with the concept of how users approach these two types of instruments mentally and psychologically. The intrinsic differences of the two categories, which have already been extensively explained in the previous chapters, will not be discussed.

This article makes it clear that acoustic instruments, as objects strongly rooted in human culture, are seen as products of nature to which the performer must "shape" himself around. Where the limits of the instrument, are seen as cues for more creative space and expressiveness. These limitations, according to the authors, change and evolve constantly in relation to the levels of the musician's ability, who has the will to overcome the limits of the instrument itself. On the other hand, the limits found in digital instruments are viewed critically and once learned they are perceived as errors or limitations of the design. The creative challenge from this point of view, in digital instruments, is perceived as the ability to select and refine a task, more than expanding one's knowledge of the instrument. It is interesting how one of the participants in this study defined the use of digital instruments as "making them work" rather than playing them.

From this concept it is easy to understand the two psychological responses of the users in the interaction with these two types of musical instruments, often at the antipodes. In the case of acoustic instruments there is an emotional response from the musician, who feels an affinity with his instrument, feeling at ease even in the limitations of the object itself. The musician who plays an acoustic instrument, as a result of sound and tactile/vibrational feedback, feels immersed in his performance. Another observation that emerged from the article is that "not being able to play correctly" an acoustic instrument is seen as a defect of the musician and not as an imperfection of the design of the instrument itself.

What has been shown, in contrast, is a performer's response to digital instruments that is more rational than emotional, where performance limitations are seen as frustrating. Participants in the experiment have often expressed frustration with technology also because of the limitations due to software environments and the dissatisfaction with the hardware that needs constant updating, fixing and the use of electricity. In this case, a reduced immersion in the performance is due to a typical lack of any kind of tactile feedback and a sound response affected by latency and almost always not coming from the instrument but from loudspeaker systems.

Other interesting aspects are reported by T. Magnussone and E. Mendieta in the article, as a greater versatility for acoustic instruments, even if more tied to traditional repertoires and a design for more specific purposes for DMI. Other aspects that differentiate user experiences between the two categories are summarized in table 5.2.

	Acoustic Instrument	Digital Instrument
Positive	Tactile feedback Limitations inspiring Traditions and legacy Musician reaches depth Instrument becomes 2nd nature Each instrument is unique No latency Easier to express mood Extrovert state when playing	Free from musical traditions Experimental – explorative Any sound and any interface Designed for specific needs Freedom in mapping Automation, intelligence Good for composing with Easier to get into Not as limited to tonal music
Negative	Lacking in range No editing out of mistakes No memory or intelligence Prone to cliché playing Too much tradition/history No experimentation in design Inflexible – no dialog No microtonality or tunings No inharmonic spectra	Lacking in substance No legacy or continuation No haptic feedback Lacking social conventions Latency frequently a problem Disembodied experience Slave of the historical/acoustic Imitation of the acoustic Introvert state when playing

Table 5.2. It presents the differences between acoustic instruments and DMI reported by the studies of T. Magnussone and E. Mendieta. Magnusson, Thor & Mendieta, Enrike. (2007).

In conclusion, we could say that there are many reasons to explain the perceptual differences by users between these two types of instruments, but what seems most relevant to us is that acoustic instruments have had centuries of improvement, while digital music softwares/instruments are a new and naturally experimental field, which still have a lot to learn from acoustic predecessors to attract users more.

6. NEMI: New ergonomic musical instrument

The New Ergonomic Musical Instrument (NEMI) project was born from the desire to create a musical instrument that was unique, discovering how the digital world could enrich the musical world. An important point to work on in the design of DMI is the will of creating it something not completely foreign to the user. From here, evolves the concept of re-using mechanisms that for a general user, musician or not, were in a certain way familiar. A striking aspect of DMI, as already explained in the chapter concerning digital musical instruments, is the possibility of separating the control system, whether it is tangible or not, from the sound synthesis produced by digital systems.

This seemed to be an important clue to give uniqueness to the musical instrument. Therefore, we started working on HCI without worrying about the synthesis part. In our case the HCI had to follow some precise guidelines which we traced. These guidelines came from the fact that NEMI should be a tangible object whose HCI followed the terms of usability and human experience, in a few words, human-centred design.
A tangible user interface increase the user involvement, since the possibility of reproduce a physical feedback on it.

Starting from these, we focussed our analysis on two points: the shape of the object (DMI) and the way to play it. Subsequently, we focussed our attention on a more general concept: the creation of an ergonomic DMI.
The idea of shaping the instrument according to the human-centered design came from different studies, showing the exposure of professional instrumentalists to Repetitive Strain Injury (RSI) and musculoskeletal disorders after hours of practicing, and how this can be linked on the neglecting of a Human-Centred Design (HCD). Therefore, it has to fit perfectly in one hand. For this reason, anthropometric measurements standards was used to design its shape.

To shape the DMI we were inspired by common life objects; from the most traditional video game controllers, up to fruits and vegetables.

In a day life of a general user, one of the most common things used is a any kind controllers (ex. from the remote controllers of a TV or a gate, to the one for playing a video game or even the generic midi controller). One thing that most of these controllers have in common is the use of various kinds of buttons. So, obviously, the use of buttons to play our DMI seemed to be an interesting choice.
During the design phase, planned to define how the instrument should be used, a technological limit, became a salient feature of our instrument. The normal and cheap push buttons can return only the two logical values 1 and 0 (respectively indicating short and open circuit) so, the problem of how to generate one of the three fundamental parameters of the MIDI protocol, namely Velocity, came up.

Velocity is a midi parameter assigned to a midi note that keeps its constant value for the duration of the note up to the note off event. This parameter does not simply control the amplitude of the note volume but in most digital instruments or VSTs it is associated with the dynamics of the sound being emitted. For example, in VST that simulates acoustic instruments, it could control which samples to send in streaming, at high Velocity values it chooses samples in which the instrument has been played with more emphasis during the sampling phase. Looking at acoustic instruments, give an easier understanding of how this parameter works. For example, hitting a drum with more or less force not only changes the volume of the sound, but also changes the timbre and its resonances.

To add a Velocity variable into emitted sound, the insertion of a system that reacted in some way to the user will of manage the dynamic, is needed. Moreover, this system also influences the way the instrument is played by musician. For this reason an accelerometer was used to let user shake the device with the desir strength, to modulate the velocity. Furthermore, the way of playing the instrument was defined by the previous sentences: the variation of acceleration is used to manage the dynamics of the sound and the use of buttons is used to select the pitch and definition the notes up and the notes off.

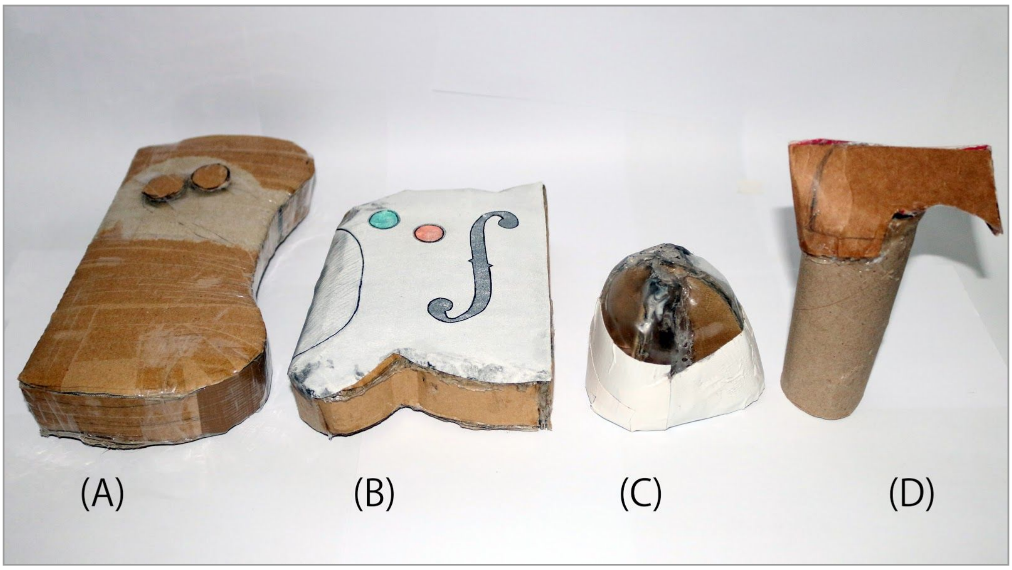
This new instrument has to guarantee the maximum musical expressiveness, meaning being comfortable to play for most music genres: the DMI has to play in all chromatic scale, solo notes and chords. One handed-use allows the performer to play with two different controllers, one in each hand, granting polyphonic and homophonic music textures. Moreover, one handed-use permits the beginner to start practicing on each hand separately.

6.1. Design

During the design of the shape and appearance of the DMI, both the guidelines set in the previous paragraph and hardware needs have been taken into consideration. The device size has to be large enough to accommodate a microcontroller, a battery, a three-dimensional motion sensor and buttons. The type of microcontroller, the sensor and the size of the battery, are not taken into consideration. Micro-controllers and batteries are available in different models, sizes and characteristics on the market. The crucial part in the Hardware Design is the amount, the type and position of the buttons used to play. To play all the notes in the chromatic scale, twelve keys, that correspond to the twelve notes of the chromatic scale are needed. However, this approach, despite the simplicity from a beginner point of view, is not applicable due to lack of ergonomics and usability. The best setting for the DMI is one button for each finger.
Since five buttons don't allow the musician to play all the notes in the chromatic scale, a finite state structure has been introduced, allowing to play all the notes with only six buttons:

$$N_1 = B_1,\ N_2 = B_2,\ N_3 = B_3,\ N_4 = B_4,\ N_5 = B_1 + B_A,\ N_6 = B_2 + B_A,\ N_7 = B_3 + B_A,$$
$$N_8 = B_4 + B_A,\ N_9 = B_1 + B_B,\ N_{10} = B_2 + B_B,\ N_{11} = B_3 + B_B,\ N_{12} = B_4 + B_B\ .$$

Where B_A and B_B are the State Buttons, while B_1, B_2, B_3 and B_4 are the Note Buttons. Hence, the thumb has to be able to press two distinct buttons. This is possible since the thumb is opposable, reaching two separate buttons more comfortable than the other fingers without the loss of comfort for the musician. Once the number of buttons are chosen, the positioning and the shaping of the instrument are exploited.



Figures 6.1. The four designs considered for this research. Mockups made of cardboard. (A) First design taken into account, (B) second design taken into account, (C) third mockup evaluated, (D) mockups related to the last design.

Four designs were considered, all four prototyped through a cardboard mock-up to evaluate the pros and cons and consider a possible implementation scenario. The fabrication of all the mockups have the main conceptual ergonomics features, previously described, the possibility of being held in one hand and having six buttons, two of which are designed to be pressed only by the thumb. These models have been used purely to define the shape, therefore no anthropometric corrections have been made.

The first prototype, reminds of the idea of a TV remote control, while its shape follows the curves of a guitar body. It had only two buttons at the top and four at the bottom. Physical ergonomics in this type of controller was almost absent, while cognitive ergonomics persists, keeping the same product idea, Figure 6.1(A).

The physical ergonomics problem was dictated by an extremely large object, where the weight of the cardboard model alone created problems for one-handed use.
In addition, the sinusoidal shape was not properly shaped around the hand.

The second attempt using an ergonomic design has produced a DMI shaped like a video game controller. This results have not been considered as successful. Despite its ergonomic shape, the DMI can not be held and played at the same time using one hand, since no external supports are provided, Fig. 6.2, as in the previous design. Moreover, this object does not provide an optimal grip due to the large size, even if the DMI is divided into two symmetrical controllers. Differently, this design approach is preferable when there is a two-handed use of the object. One possibility is that one hand hold the instrument and the other plays it or, hardly, that both hands keep the two joined pieces and playing together.

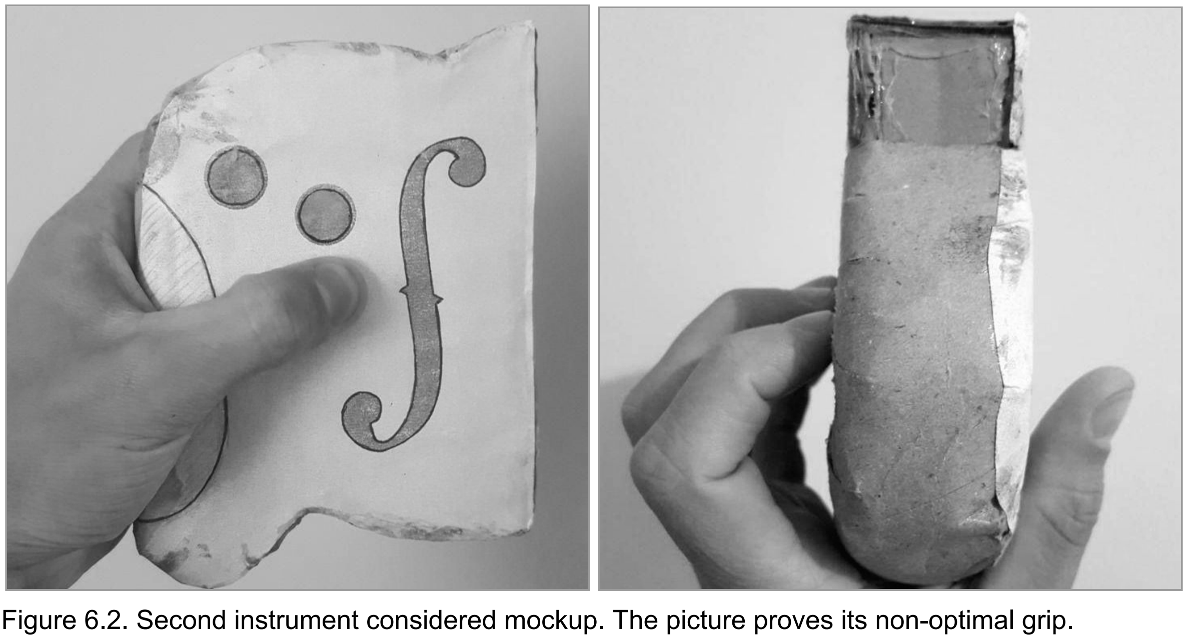


Figure 6.2. Second instrument considered mockup. The picture proves its non-optimal grip.

The third design, was inspired by a Brazilian instrument, the Caxixi. The design reminded a computer mouse that was used in reverse, Figure 6.1(C).

The cognitive and physical ergonomics characteristics of the object were very positive, it had a shape that fit perfectly into a hand. But since it was a musical instrument that the performer would have to interact with, the fingers had to be moved to press the various buttons, and this did not ensure a secure and stable grip on the object anytime. This led to the problem of designing a support structure in which the musician's fingers or hand could be clamped. This type of method did not seem to be ideal, as it would restrict the mobility of the fingers of the hand or could create blood circulation problems, as the support had to be clamped on the back of the hand to ensure a stable grip.

The latest prototype design, is extremely minimal, did not present any factor of adaptation to the hand, except for the hook holder, which drew the back curvature of the hand. Since it allowed a more efficient mobility of the fingers without limiting the performer by external supports, it is the one that was chosen for the realization. Even if it did not present the best physical ergonomics of the four proposed.

6.2. Hardware and Software Implementation

The implementation process started with the installation of the necessary hardware in the protoboard, figure 6.3. The hardware in question was an MPU 6050 accelerometer and six buttons linked to a NodeMCU ESP8266 . The first idea was to use the ESP8266 generated network to communicate the status of the sensor and buttons to the computer via UDP protocol.

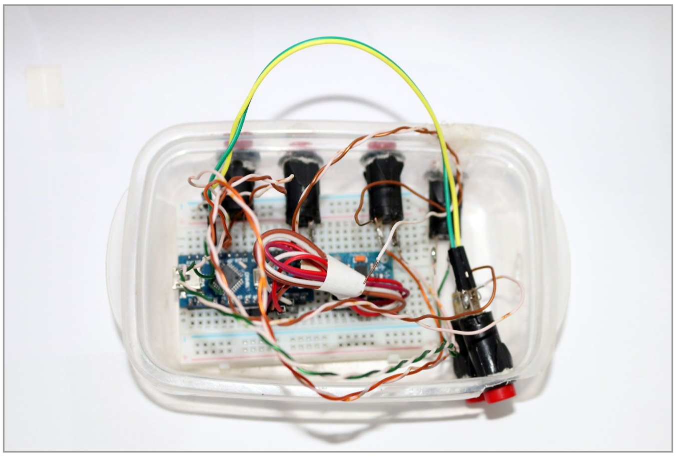


Figure 6.3. The protoboard prototype

Unfortunately, this type of setup was abandoned due to a problem with the number of input pins offered by the NodeMCU. Because, for convenience and miniaturization of the electronic board, external pull-up resistors were not used to connect the buttons to the microcontroller, but internal resistors were used, which are limited in number.

This led to problems with some NodeMCU pins, whose operation was linked to its own microprocessor functions, making it extremely unstable. The code written for NodeMCU, in Arduino language, consisted in an OSC message exchange between the microcontroller and the Pure Data software.

The next step was to transpose all the code to work in serial mode and no longer via UDP protocol, allowing in this way the use an Arduino Nano, which in previous research had proved more stable in managing a large number of inputs with integrated pull-up resistors.

Once the workability of electronics had been evaluated, the focus moved on modeling the instrument body. From the cardboard mockup, the corrections provided for the anthropometric measurements, reported in table 2.2 of paragraph 2.3, have been applied to the digital version. The corrections taken into consideration were Palm length, Hand length and Grip diameter.

The first anthropometric measurement used during 3D modelling was Grip diameter (52.3), which was used to define the bottom diameter of the cylinder of our instrument. The other two were used in the second correction process, happen after 3D printing.

The modeling of the components was performed in the 3D modeling software, Blender.
In order to obtain a correct arrangement of all the components inside the case, before printing the 3D device, the PCB was produced through the KiCAD software.

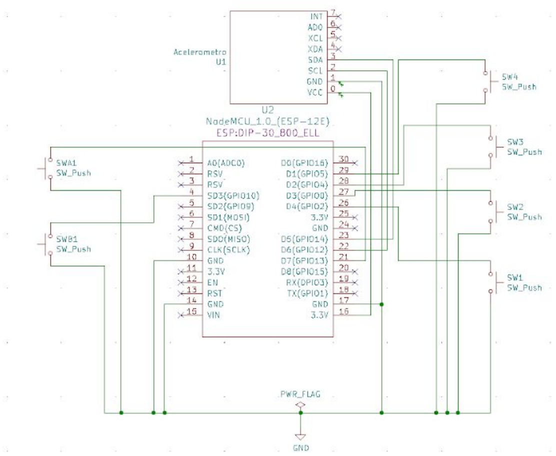


Figure 6.4. Wiring diagram of the components, Image created from the KiCAD software. From the top left the selection buttons SWA1 and SWB1, from the top right the note buttons SW4, SW3, SW2, SW1.

As shown in figure 6.4, all connections between the microcontroller pins, the accelerometer and the six buttons were made in order to produce the design of the electrical circuits on a PCB, Figure 6.5. SWA1 and SWB1 are the buttons that correspond to the Status Buttons, which are those buttons that, depending on the state in which the instrument is operating, modify the intonation of the four Note Buttons.

The SW4, SW3, SW2 and SW1 buttons are called Note Buttons. Each of these buttons represents a note of the chromatic scale, depending on the state in which the instrument is, the pitch of each button changes.
The next step after the creation of the electrical scheme is the arrangement of the conductive tracks, in order to allow the PCB to be printed. The tracks are located only on one side of the electronic board for technological requirements of the CNC milling machine used to create the copper tracks and holes.

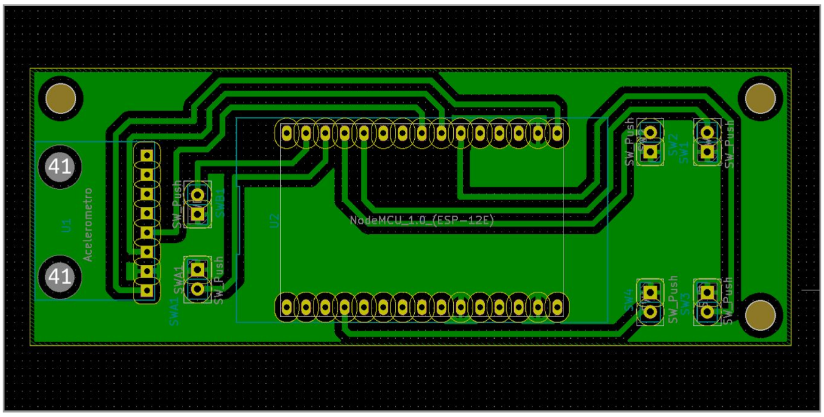


Figure 6.5. PCB tracks, designed in KiCAD.

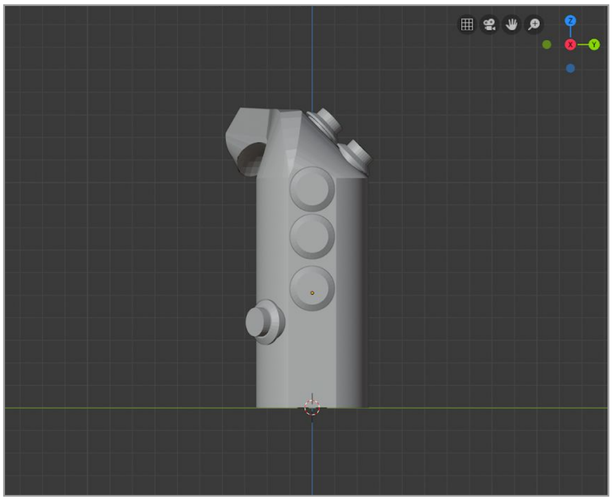


Figure 6.6. Full 3D model of the instrument. Image generated by Blender.

Il The virtual PCB model allowed us to recreate a 3D model in Blender with all the components that would be part of the electronic board, such as connectors, accelerometer, and the microprocessor, Figure 6.7. This step was crucial to designing the internal spaces of the instrument. The buttons were also modelled in Blender and placed to get a preview of the finished instrument, ready to be printed, Fig. 6.6.

In Figure 6.6, the buttons are arranged as follows, from top to bottom, SWB1, SWA1, SW1, SW2, SW3, SW4.

Once the instrument was 3D printed, the other two anthropometric measurements, Palm length and Hand length, were used to design a hump which could be positioned at the back of the instrument, in order for the instrument to fit perfectly into the hand. This hump keeps the buttons at a right distance from the palm of the hand, giving more comfort during the grip, Figure 6.8. It was made as a cross section of a cylinder of 4 cm in diameter. This element has been designed to be variable, allowing people who have to play the DMI to replace it with one that fits better in their hand.

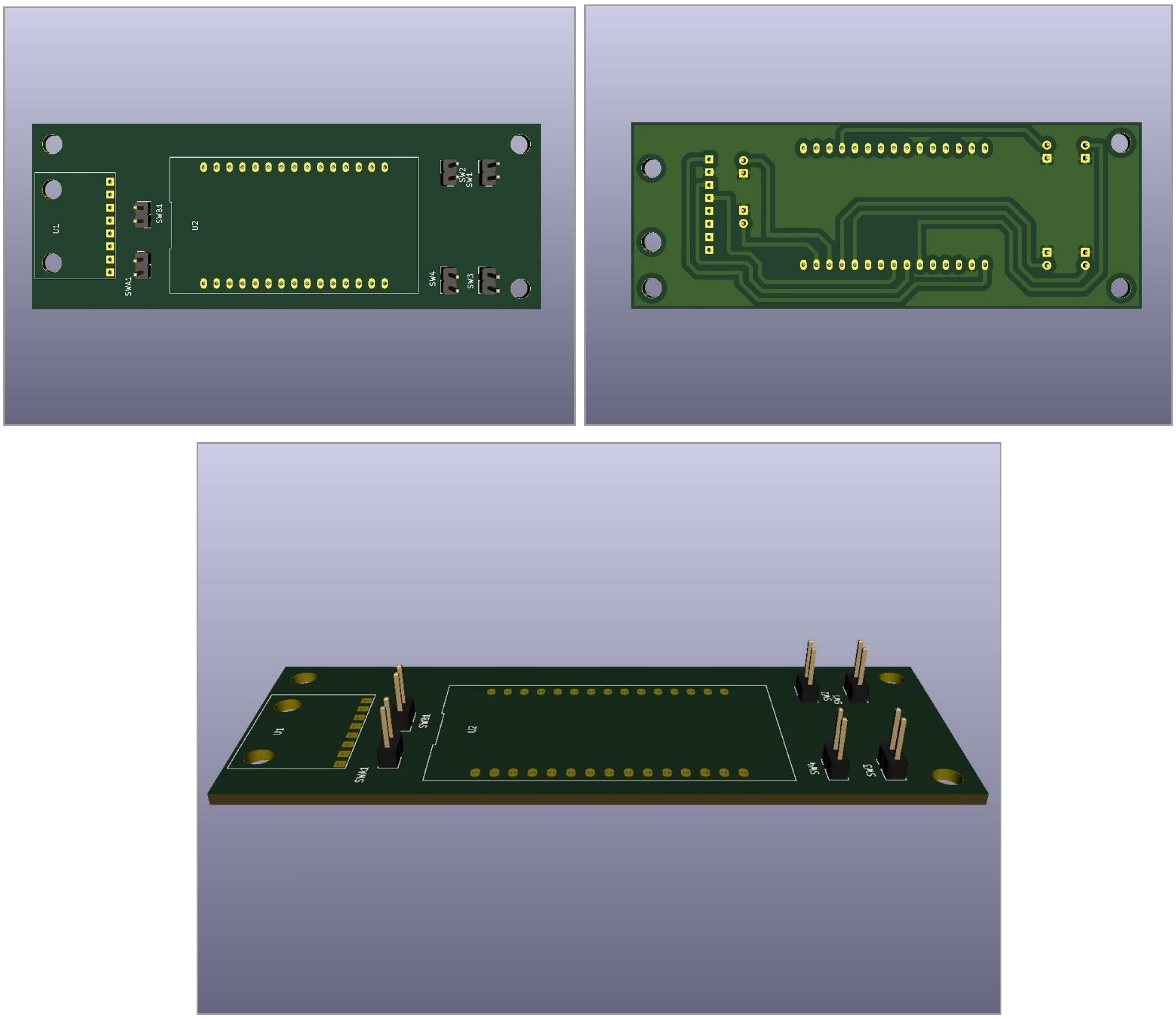


Figure 6.7. Front (a), Back (b) and lateral (c) view of the PCB 3D model.

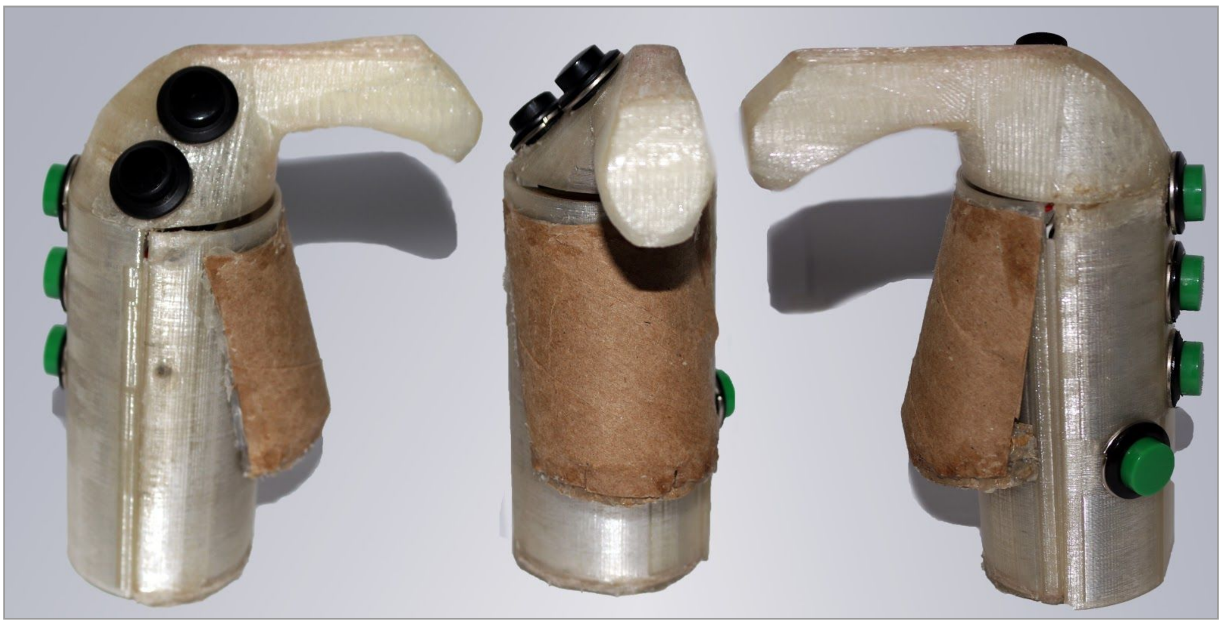
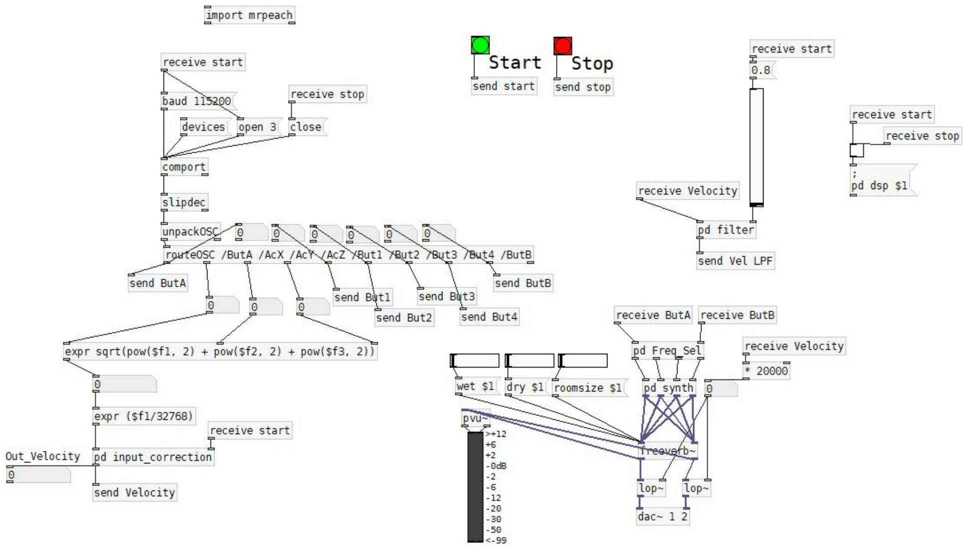


Figure 6.8. Side and back view of the hump of the real device, shaped in cardboard.

6.2.1. Synthesis and Mapping System

The audio synthesis engine and the mapping strategy used for this project has been programmed in Pure Data[5].

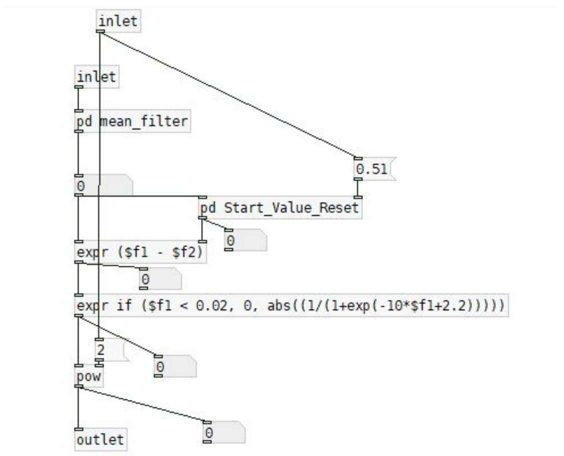


Figures 6.9. The Main project program of the mapping between the electronics and the sound synthesis.

In the figure 6.9, it is possible to see the entire main program that manages the instrument. The program is made up of three stages, the first one is responsible for receiving raw data from the DMI, a second level for filtering data and calculating synthesis parameters and a third one is responsible for sound synthesis.

The first level provides the opening of the serial port where the instrument is inserted, from which it receives OSC messages that it unpacks and sends to the respective units through the functions *"unpackOSC"* and *"routeOSC"*. The data received are related to the triaxial acceleration and the status of the six buttons. From the three accelerations the normal vector is calculated to know the acceleration module and then it is normalized to the full scale.

[5] Pure Data (abbreviated as Pd) is a visual programming language created by Miller Puckette. Developed from Patcher in the 1990s, it is an open source project released under a BSD license.



Figures 6.10. Input correction function. Used to stabilize the input, as a noise gate and has a non-linear mapping function.

The second state consists of two low-pass filters. The first is the "Input_correction" function, which stabilizes the values by a weighted average based on five previous values. This operation is handled by the sub-function *"mean_filter"*, while the real time correction of the input offset is handled by the sub-function *"Start_Value_reset"*, la which receives shifted values of an almost continuous offset and background noise component as input and returns the value to 0 if below the threshold set as *"non-movement"*. When instrument movements are detected, the function subtracts the static offset threshold value from the input, which can be set by the user. This threshold value affects the sensitivity of the instrument.

The *"Input_correction"* function maps the received and processed input value to an output value according to a nonlinear function in this way:

$$f(x) = \left(\frac{1}{1+e^{-10x+2.2}}\right)^2 \qquad (6.1)$$

Where the two constants of the exponential control the sensitivity of the instrument. The amount that multiplies the variable is used to set the slope of the curve and the added value shifts the curve along the axis of the variable.

This function deals with reacting with higher sensitivity in the range of input values between 0.2 and 0.6, empirically evaluated as the two extremes in that most of the movements are represented. Figure 6.11 shows the behavior of the function used.

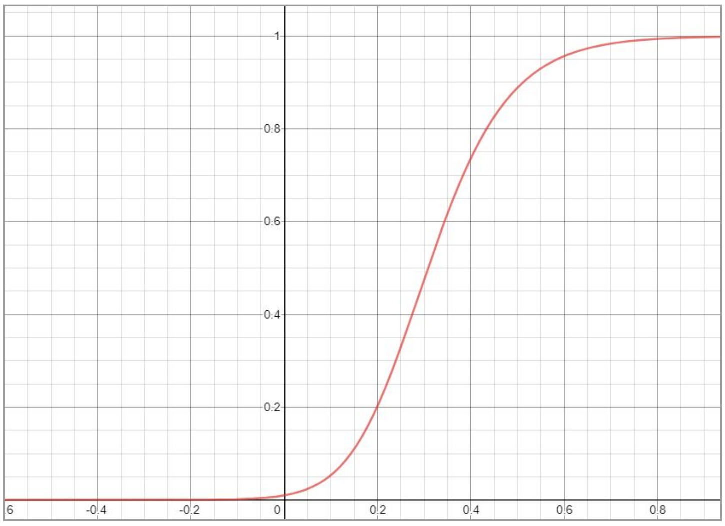


Figure 6.11. Function graph, shows the type of sensitivity returned in output.

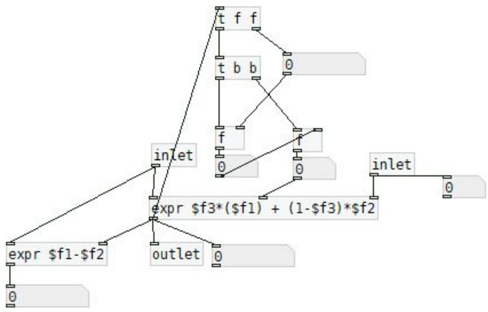
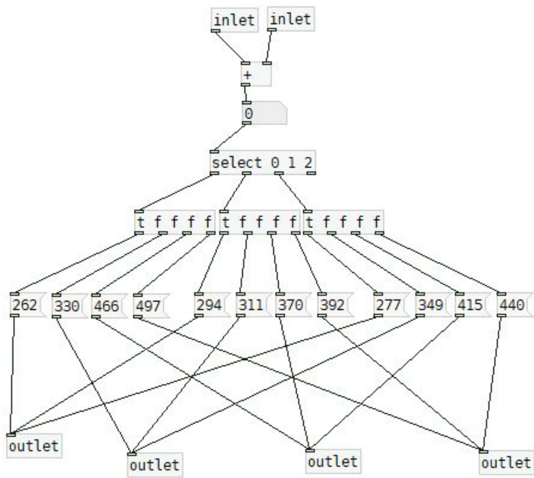


Figure 6.12. Input Filtering Function. Using a prediction filter.

Following the first stage of input correction and filtering a second stage of predictive filtering is used to return a velocity value as stable as possible. This is done by the *"filter"* function whose patch is present in figures. The Velocity calculated from this stage is sent to the final stage to control two synthesis system parameters, the amplitude of the wave produced by the oscillators and the upper margin, expressed in Hz, of a low pass filter, which controls the brightness of the output sound.

The final stage consists of four objects, the "Freq_sel" function, the "synth" function, a reverb and a low pass filter.

- **Freq_sel**: Calculates which of the three possible combinations to send out, each of the three combinations has a set of four notes to send out (the four notes correspond to the values assigned to the Note Buttons), figures 6.13. This frequency combination is currently arranged in such a way as to allow the major and minor chords and the corresponding sevenths of all the unaltered tones (sharp and bemolli) to be played easily in a two-instrument configuration. A better optimization of this arrangement of notes, considering the high number of possible combinations, is not possible to carry out on paper, it would need the help of a computer.



Figures 6.13. Output note selection function. Depending on the status selected by the Status Buttons (SWA1 e SWB1), this function assigns to each Note Button the pitch to be played.

- synth: Assigns to the four synthesis engines the frequencies of the note to be played, figures 6.14. The output of this function is the sum of the audio signals generated by the synthesis engines, which in this case are the sub-functions "But_Osc", figures 6.15.

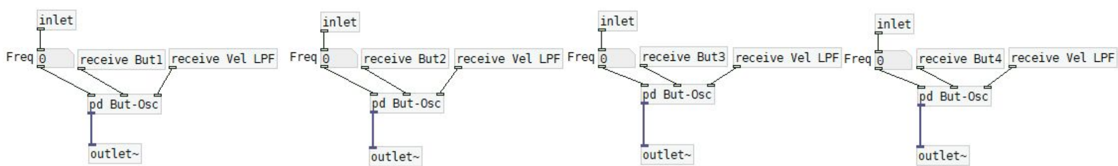


Figure 6.14. Output note assignment function. Assigns to the four oscillators the frequency they will play at.

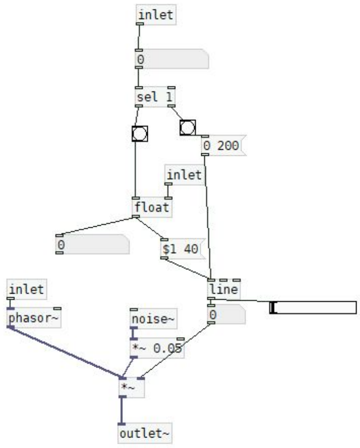


Figure 6.15. Sound synthesis engine.

In this work, the sound design has not been completed, so the synthesis engines generate a sum between a sawtooth signal and a white noise, whose frequency depends on the value passed by the "Freq_sel" function, the amplitude depends on the value of Velocity and its attack is 40ms and the sustain is 200 ms.

- Reverb: This is a reverb effect controlled by three parameters (Wet, Dry and Room).
- LPF: This is a low-pass filter whose higher cut-off frequency is calculated from Velocity, which is a value between 0 and 1, multiplied by 20000. This means that at low velocity values, the resulting sound will be darker (richer in low frequencies), while at high values, it will be a brighter sound.

6.3. Future Proposals

The DMI described in this work is anything but a finished product. The work carried out has led to a slightly more advanced phase of a concept design, which implements the minimum functionalities conceived. It is far from reaching the ambitious goals proposed. There are several things to consider and things to improve, as well as numerous implementations that could be added in the future.

6.3.1. Sound synthesis system

One of the first things to improve and complete is definitely the sound design. The use of a sound that better reflects and matches the movements of the performer would surely lead to an improvement in interaction with the DMI. This could be achieved through a physical sound synthesis model, which guarantees a huge flexibility and leads to a more natural sound emission. Moreover, for the way the sound synthesis system is currently structured, the use of a compressor in the final stage is fundamental. The cause is the four audio engine that always exceed the audio master dynamic range, since the master output is the sum of their outputs.

6.3.2. Player Experience

Currently, the full capacity of the MPU 6050 is not being used. The mapping system only recognizes and uses the acceleration variations. This is just one of the many potential features of the MPU 6050, which also has the function of a triaxial gyroscope and detects temperature variations. All these functions can be used to increase the number of user gestures recognized. On the subject of gestures, the use of a Wifi module for wireless data transmission would help the performer's mobility by improving his experience of use.

Moreover, some hardware changes can be made to the system to increase the realism. The addition of an embedded audio synthesis engine, an amplification state and an integrated speaker becomes necessary.

A further improvement for the player experience can be obtained by acting on the physicality, adding a tactile feedback engine. This, for example, can be added to each individual Note Button, in order to give a tactile feel when pressed.

From a software point of view a "plug and play" network environment could be created. Controllers and synthesizers should be able to announce their presence and make their input and output parameters available for arbitrary connections, using a graphical mapping tool. This may also allow the configuration of the Note Buttons to be varied to suit better the genre of music played by the performer.

6.3.3. Playability

To ensure a good learning curve, the instrument need two different setups, one for the beginners and another for expert performers. In addition, a fretless keyboard for advanced performers could be considered.

7. Conclusions

In this work a new digital instrument designed on the concept of physical and cognitive ergonomics was presented. This concept is important because it represents a breaking point in the history of musical instruments.

History has often shown the evolution of musical instruments as a function of the paradigm of sound response. This has led to an improvement from the musical point of view of acoustic instruments, neglecting the needs of the musician. In recent decades, a growing interest has been shown in this area, since several studies have shown that musicians are a high-risk category of workers for muscle-skeletal injuries. The cause of these injuries is linked to several factors including extremely repetitive movements, unhealthy musician posture and lack of ergonomics in traditional instruments. Because a musical instrument luthier cannot intervene on aspects such as the number of repetitions of a movement or the musician's posture, the ergonomics of the instrument is the only parameter that can be controlled. Since all the physical characteristics of an acoustic instrument affect its sound traits, changing its shape to make them more ergonomic would be a difficult and risky process. On the other hand, the digital instruments do not present this connection between physical and sound characteristics. Therefore, it is interesting to consider that these ergonomic arrangements can be applied to digital instruments, which is what has been explained in this work.

The design of this new ergonomic digital instrument involved four controllers of different shapes, whose mockups had previously been made of cardboard. The four controllers all had the same interaction with the user, therefore only the pros and cons of physical ergonomics were evaluated. The one with the best usability was implemented, even if there were not the best physical ergonomics of the four controllers evaluated.

The implementation was done through modern 3D modeling and molding technologies and PCB molding. Corrective factors, such as anthropometric measurements, were taken into account in the 3D modeling phase to make it comfortable to play for the musician.

The resulting instrument has a pleasant comfort in the hand and the nature of the interactions, although currently very basic, avoids uncomfortable positions.
The implementation process required skills such as 3D design, embedded electronics, computer programming, networking and sound design.

The problems identified are mainly technological issues of the materials used to make the prototype:

- The plastic used to print the model is not really resistant and durable, and it does not always maximize hand friction.
- The presence of a microcontroller cable that connects the instrument to the computer, excessively limits the movements of the performer.
- The buttons do not react quickly when pressed and often block or create a false contact due to the miniaturization of the space inside the DMI.

This work is not meant to compare acoustic instruments with digital ones, neither to evaluate which one is the best or healthiest to play. Each one has its own limitations that are not comparable. Instead, a pioneering approach that combines new DMI technologies with new HCD-based design models is exploited. In other words: after decades of studies proving problems with the ergonomics of acoustic instruments, why this disadvantage should be brought into the new digital instruments as well?

Last, the expectation of the writer is to have placed a new milestone into the digital lutherie field.

Acknowledgment

I would like to thank Prof. Tavares and Prof. Servetti without whom this work would not have been born and also for the opportunity given to me to do this work in the best way possible.

I would like to dedicate this work:

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To Connie, who endured and supported me against all expectations and despite the infinite distance. I love her so much. To the one who took a 24-hour trip just to see me there in Brazil.
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Summary

RSI and Musicians

Numerous researches show that musicians are a vulnerable population for RSI. These studies reveal a general prevalence of musculoskeletal complaints between 55% and 86% in professional musicians of orchestras and between 26% and 87% of the general population of musicians. This percentage is high compared to other professions, such as office workers, where studies indicate 37% prevalence of work-related complaints in the system.

DMI Concept

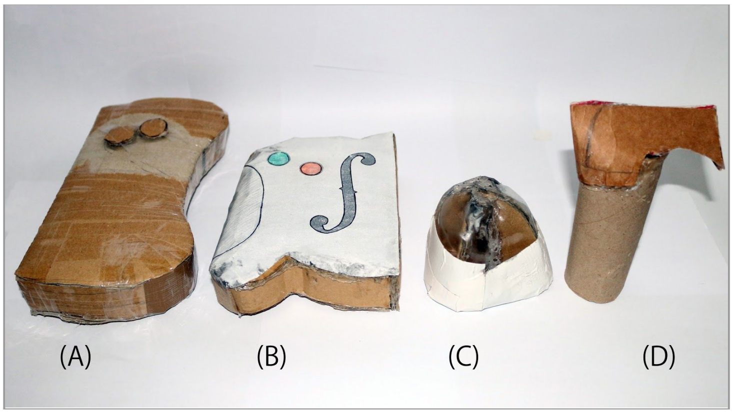
The main goal is to prototype an ergonomic and portable DMI. A set of constructive guidelines has been created to achieve this goal. The instrument has to be shaped according to human-centred design and has to be light to avoid musculoskeletal disorders after hours of practicing. It has to fit perfectly in one hand: for this reason, anthropometric measurement standards to design its shape have been used. This new instrument has to guarantee the maximum musical expressiveness, meaning being comfortable to play for most music genres: the DMI will play in all chromatic scale, solo notes, and chords. One-handed use allows the performer to play with two different controllers, one in each hand, granting polyphonic and homophonic music textures. Moreover, one-handed use permits the beginner to start practicing on each hand separately. To ensure a good learning curve, the instrument has two different setups, one for beginners and another for expert performers.

Hardware Design

During the designing phase of the appearance of the DMI, four different shapes were considered. For each one, the guidelines set in the previous paragraph and hardware needs were taken into account. The device size has to be large enough to accommodate a microcontroller, a three-dimensional motion sensor, and buttons. The crucial part of this design space for the hardware is the amount, the type and position of the buttons used to play. To perform all the notes in the chromatic scale, twelve keys, that correspond to the twelve notes of the chromatic scale, are needed. However, this approach is not applicable due to a lack of ergonomics and usability. The best setting for the DMI is one button for each finger. Since five buttons don't allow the musician to play all the notes in the chromatic scale, a finite state structure has been introduced, allowing to play all the notes with only six buttons:

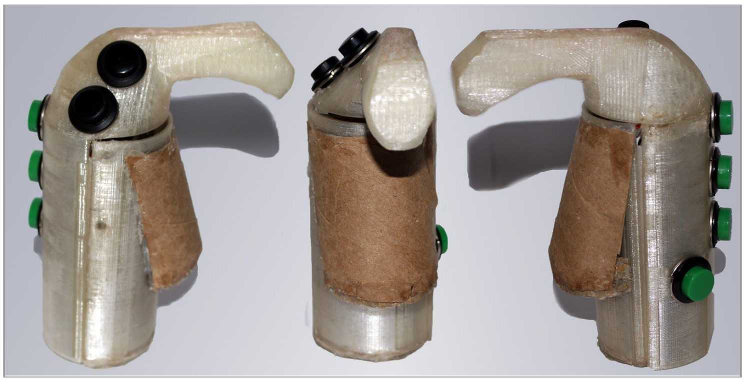
$$N_1 = B_1,\ N_2 = B_2,\ N_3 = B_3,\ N_4 = B_4,\ N_5 = B_1 + B_A,\ N_6 = B_2 + B_A,\ N_7 = B_3 + B_A,$$
$$N_8 = B_4 + B_A,\ N_9 = B_1 + B_B,\ N_{10} = B_2 + B_B,\ N_{11} = B_3 + B_B,\ N_{12} = B_4 + B_B\ .$$

Where B_A and B_B are the State Buttons, while B_1, B_2, B_3 and B_4 are the Note Buttons. Hence, the thumb has to be able to press two distinct buttons. This is possible since the thumb is opposable, reaching two separate buttons more comfortable than the other fingers without the loss of comfort for the musician. Once the number of buttons is chosen, the positioning and the shaping of the instrument are exploited. All prototypes were useful to understand what kind of shape the DMI should have. All of them were produced on cardboard Mock-up without standard measures, such as anthropometric measurements. This approach helped to understand how to shape the instrument on which the standard hand measurements corrections will be applied. The "D" prototype design, is extremely minimal, did not present any factor of adaptation to the hand, except for the hook holder, which drew the back curvature of the hand. Since it allowed more efficient mobility of the fingers without limiting the performer by external supports, this one was chosen for the realization, even if it did not present the best physical ergonomics out of the four proposed.



Implementation

The 3D model of the DMI was designed using *Blender*. Anthropometric measurement such as Palm length, Hand length and Grip diameter was used to correct the DMI model dimension. The Blender model was then printed out in 3D. The DMI circuit, designed in KiCAD, is made of three components: an accelerometer (MPU6050) used to modulate the Velocity of our DMI, the microcontroller (Arduino Nano) and the six buttons. The audio synthesis engine and the mapping strategy used for this project has been programmed Pure Data[6].



Conclusion

The resulting instrument has a pleasant comfort in the hand and the nature of the interactions, although currently very basic, avoids uncomfortable positions. The implementation process required skills such as 3D design, embedded electronics, computer programming, networking, and sound design. The problems identified are mainly technological issues of the materials used to make the prototype.

[6] Pure Data (abbreviated as Pd) is a visual programming language created by Miller Puckette. Developed from Patcher in the 1990s, it is an open source project released under a BSD license.

- The plastic used to print the model is not very resistant and durable, and does not always maximize hand friction.
- The presence of a microcontroller cable that connects the instrument to the computer, excessively limits the movements of the performer.
- The buttons do not react quickly when pressed and often block or create a false contact due to the miniaturization of the space inside the DMI.

This work is not meant to compare acoustic instruments with digital ones, neither to evaluate which one is the best or healthiest to play. Each one has its own limitations that are not comparable. Instead, a pioneering approach that combines new DMI technologies with new HCD-based design models is exploited. In other words: after decades of studies proving problems with the ergonomics of acoustic instruments, why this disadvantage should be brought into the new digital instruments as well?

Last, the expectation of the writer is to have placed a new milestone into the digital lutherie field.