POLITECNICO DI TORINO

Master Degree Thesis

Rehabilitation devices in healtcare: a proposal

Supervisors:

prof. Mahmoud Tavakoli

prof. Marcello Chiaberge

Candidates

Gianvito Romito

231581

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Summary

The project that I developed in ISR (Institute of Systems and Robotics) of University of Coimbra wants to propose a balance game able to support patients who have suffered serious accidents that affect the motor faculties: for example, post-stroke patients often are affected by weakness on one side of the body, and therefore they can have big problems to balance. Moreover, the game is thought for patients who, after performing an invasive surgery, begin their rehabilitation path: Starting from a high resolution pressure mapping of a Smart InSole used in this project as test hardware, it has been possible to implement all the main features through three macro-steps:

- The Smart InSole made of soft-capacitive sensors was able to collect and send data through a Buetooth interface; thanks to this information it was possible to create a dynamic center of pressures (CoP) showing it on the graphical interface with the pressure map. At this point the patient is able to use the device acting on the weight distribution to move the center of pressure inside

the sole of the foot.

- The next step was to develop a training through which the user could make practice and started with his rehabilitative program. There are three levels of difficulty, each level composed by ten intermediate steps.
- In the lat section it is explained the carried out procedure in order to use the Smart-Insole as a keyboard: the final goal of this attempt was to use the sole as a controller able to command a simple computer-game.

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Chapter 1

Rehabilitation devices in healthcare

1.1 Overview

Already during the last decades of the 1800s, various medical conditions were studied using the measurement of pressure exerted by the foot. The first rudimentary technologies used for plantar pressure assessment provided investigators with semi-quantitative data coming from the application of simple but innovative methods [1]. One of the first studies in this regard is that of Beely in 1882 [2]. In this experiment, the subjects has to push the foot on a bag full of putty to produce an impression: Beely hypothesizes that the material would capture the shape of the foot by reproducing the areas in which the load is higher. However, this primitive technique was limited because it represented a rough measure of the total force of the foot that created the impression rather than the dynamic pressures underfoot during gait. Furthermore, this method was strictly qualitative and therefore susceptible to unreliability. In 1930, Morton [3] uses a device called *Kinetograph* consisting of a rubber mat with triangular corrugations on one side, a padded block and a sheet of paper soaked in ink. The subject moving on the mat, compresses the corrugations that are squeezed proportionally, producing an ink of corresponding density. The *Kinetograph* was the first deconstructed attempt to measure the pressures of the foot rather than the forces. In 1939 Elftman develops the *Barograph*

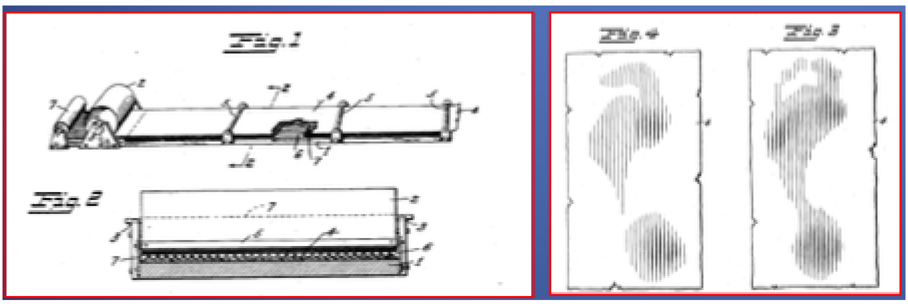


Figure 1.1. 1930 Morton's *Kinetograph*

that allows the observation of dynamic changes in the distribution of pressure as the subject advances. It consists of a smooth rubber mat on top and studded with pyramidal projections on the bottom [4]. The mat is placed on a glass plate which is the interface between the mat and the foot. As the subjects move on the plate, the contact area of the projections increases according to the changes in pressure under the foot. A video camera records the pattern of deformation of the carpet from below. Likewise, in 1947, Harris and Beath developed a similar system to

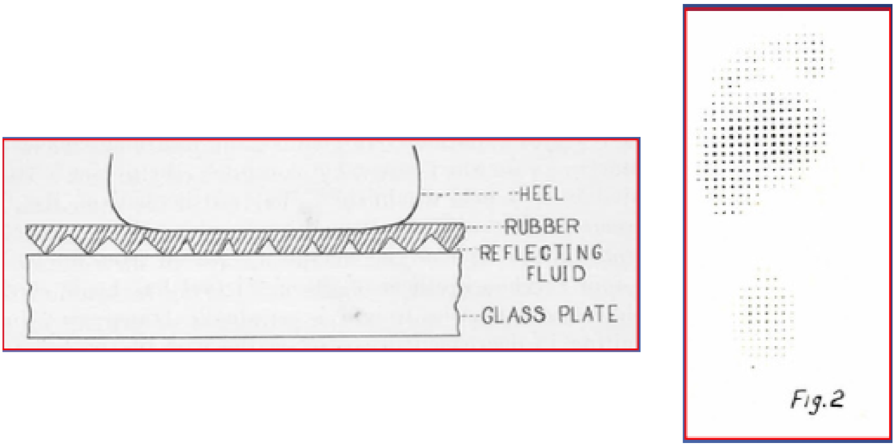


Figure 1.2. 1939 Elftman's *Barograph*

study foot problems and the resulting pressure distributions in a group of Canadian soldiers. Their device, called Harris-Beath Mat [5], uses a rubber mat with multi-layer inks in contact with a piece of paper underneath. When the subject exerts pressure on the rubber layer, the ink comes out of it, staining the paper. Therefore, the density of the impression depends on the applied pressure. The main problem with this device, however, is that it can not be calibrated depending on the applied pressure and also the ink on the piece of paper at the end of the test can not be quantified: this means that it is not possible to standardize the test. Silvino and Associates [2], however, have calibrated the Harris-Beath mat using a contact area

Figure 1.3. 1947 Harris&Beath mat

of known size and weight, creating a series of standard models that are used depending on the subject. A device similar to the Harris-Beath mat is the Podotrack system (Medical Gait Technology, the Netherlands)[6]. The system is based on the principles of the Harris-Beath carpet. However, the impression is produced by a chemical reaction with carbon paper instead of ink. Through this system, unlike the Harris-Beath mat, it is possible to highlight the different pressures acting on the sole of the foot through the shades of colors. During the second half of the 20th century, with the advent of the digital revolution, the field of heathcare as all the technological sectors had a very strong development: the measurements can now be carried out in a more precise way and it is possible to study both static and dynamic behavior; in 1972 for example Arcan and Brull designed a device had the ability to provide more detailed information on the distribution of foot pressure. The apparatus consists of a transparent rigid platform on which is laid a layer of optically sensitive elastic material and a reflective layer. Foot pressure measurements were performed both statically and dynamically and changes to the movement of the foot were recorded using a video camera[11]. The development of this instruments brought to today's *Podoscope*. It consists of a metal or plastic

Figure 1.4. Optical *Podoscope*

supporting structure with a transparent glass or plastic back-illuminated top[10]. The examined subject climbs barefoot on the platform and remains stationary in that position for a few minutes. The plane below the support surface is made up of a sloping mirror able to reflect the image of the soles of the feet, allowing them to be visualized and evaluated in static conditions. The platform also allows the visual assessment of the distribution of loads on both feet, highlighted by the different light intensity of the impression[12]. it is also possible to obtain a subsequent digital graphic processing of the image[13].

However, the importance of tactile sensor technology was recognized in the 1980s, along with a realization of the importance of computers and robotics. Despite this awareness, tactile sensors failed to be strongly adopted in industrial or consumer markets.

1.2 Need for Rehabilitation Tools and Game-Based strategy

As a consequence of the powerful push of technological development which began in the early nineties and still in progress, we have witnessed a progressive and unstoppable industrial automation, which encouraged the research in the robotic applications field and that has been referred to as ”Industry 4.0”. Nowadays the development of miniature, lightweight, and energy efficient circuit solutions for healthcare sensor applications is an increasingly important research focus, given the rapid technological advances in healthcare monitoring equipment, micro-fabrication processes and wireless communication. In parallel to this revolution, over the last few years, we are witnessing to a process of global aging. In particular an investigation brought forward by the English Government [7] says that:

- half those born after 2007 can expect to live over 100
- Between 2010 and 2030 the number of people aged over 65 will increase by 51%.
- The number of people aged over 85 will double during the same period.

With the increase in age of population and with the unstoppable technological advancement, investments in the field of health services and social assistance are also increasing: in particular with the new *ICT* solutions, considerable progress has been made in the field of *self-Rehabilitation*. The possibility of walking in the elderly is essential to maintain their independence, and the first symptoms of diseases can be measured from the age of 65 and in the majority of the 85-year-old population. Arthritis, stroke, Parkinson's disease and dementia are long-term conditions that can lead to significant problems with gait. The ability to adequately monitor walking ability is important for evaluating and guiding the rehabilitation process. The starting point is prevention: the feet are the interface of interaction during the locomotion, so it is important to diagnose their problems in advance to avoid injuries, for the management of risks and for the well-being of the person. To this end, it is important to develop systems that can predict this type of problem and correct them when they are present where possible. In this sense, rehabilitation devices can help:

- Post-stroke patients who often are affected by weakness on one side of the body, and therefore can have big problems to balance.
- Subjects who, after performing an invasive surgery, begin their rehabilitation path: in post-surgery rehabilitation in the case of a total knee or total hip surgery, is primary to train the patient to apply the same pressure on both feet.

Recently many innovative applications have been made for rehabilitation support. Based on this premise, techniques measuring foot pressure accurately and efficiently are critical to further development. Today it is possible to buy on the market different systems of plantar pressure that vary according to the type of sensors and the type of rehabilitation process [**?**]:

- *Distribution Platforms*: the subject walks on a designated path with built-in pressure sensors. This test can only be performed within a laboratory or clinical environment. Since it is difficult to reproduce the conditions of the real world by examining the different surfaces on which you are walking, the results of this test are often unreliable.

- *Imaging Technologies*: with sophisticated image processing software.

- *In-shoe Systems*: thanks to the presence of sensors in shoes or insoles, these measure the pressure between the foot and the shoe. This portable system allows you to conduct a greater variety of research that is not constrained by laboratory conditions. Moreover, it is a system with high energy efficiency and a reduced cost.

Platform systems are generally more accurate than in-shoe systems. However, due to the lack of portability of the former, the latter are increasingly its impact because they are cheap and in any case precise. Several commercially available in-shoe systems are designed with built-in sensors. The number of sensors inside the sole is limited by the size of the foot and the size of the sensors themselves. With sensor miniaturization, a higher sensor density can be achieved, and therefore greater measurement accuracy: the development in this field has an immense potential. In recent years, testing opportunities for clinical rehabilitation have also increased in the field of digital entertainment. The latest contemporary therapies integrate traditional rehabilitation activities with video games and virtual reality (VR), thanks to which it is possible to improve the tools of the real world by extending their use. Doctors and researchers have analyzed the use of consoles such as *Nintendo's Wii Fit*, *Sony's Play Station Eye Toy* and early research in VR systems suggests that VR-based gaming technology can be used effectively to improve the rehabilitation of motor activities of a series of functional deficits [17]-[28]. When using technological tools it is very important to develop a usability

Figure 1.5.

Figure 1.6. **a)** EyeToy Boxing, **b)** EyeToy Soccer, **c)** Wii Golf, **d)** Wii Bowling

study to define ease of use and to identify problems that need to be addressed in order to improve the design and functionality of the application. Usability criteria are classified as follows [28]:

1. Learnability: how easy it is for subjects to perform tasks the first time they use the device;
2. Efficiency: how fast users perform the activity once they have understood the operation of the device;
3. Memorability: after a period of non-use, how long does the user take to acquire new familiarity with the device;
4. Errors: the number of errors committed by users, the severity of such errors and the ease with which they can recover from errors
5. Satisfaction: how pleasant it is to use the device.

A wide range of products, devices and applications are tested for usability at different levels of development by providing information on how new users relate to the application / device during operation. By means of these analyzes, the researcher aims to involve the end user or the target audience: if it is for example a rehabilitation device for a youth target, more complex applications can be developed; if instead the end user is an elderly person, the simplicity of use and the clarity of the graphic interface will have to be the main objectives. In recent years, usability tests have been performed on VR devices developed specifically for telerehabilitation [29]-[31] Since these games were initially designed for entertainment, game mechanics are not fully applicable to those who use them for rehabilitation purposes and therefore changes are needed before they can be approved as rehabilitation tools for people with neurological disability. A very positive aspect of the use of video games in the rehabilitation process is certainly the psychological one: by a research done on a group of patients with SCI (Spinal Cord Ingury), the participants reported to not realize how long they were playing and feeling distracted by their disability. One participant suggested that playing these games could improve the "boring exercise regimes" [28]. But in this context, how should the therapist behave? From the same studies, it has emerged that therapists do not provide enough instructions to patients not only about using the game but also about how patients can play with the therapeutic goal in mind: some of them have observed more the progress of the game than the patient [28]. However, as with conventional treatment techniques, therapists must observe the patient to determine if the patient is behaving according to an appropriate and safe movement pattern. In any case, most studies agree that the use of VR and videogames for rehabilitation offers the potential to motivate patients to perform specific therapeutic tasks [32]-[35]. The popularity of this new generation of interactive devices such as EyeToy, Nintendo Wii and Nintendo WiiFit has offered an opportunity for interdisciplinary research and development that has led to improved clinical and home therapy for a range of impairments. From this point of view the Novint Falcon developed by Novit Technologies turns out to be the most complete and performing rehabilitation instrument [36][37][38]. The Novint Falcon is a game controller that provides realistic tactile feedback during the interaction between the user and the game. When using this device, the player perceives the weight, shape, consistency,

Figure 1.7. Novint Falcon device

size and strength of an object. For example, if you play a ball game, the player feels the impact of the ball coming into contact with his hand. Once the controller comes into contact with the virtual object, it applies a force to the handle that is perceived by the user. Feedback in the handle is updated 1000 times per second. This device can be used in place of a mouse with computer games and in addition, 19 mini-games from Novint have been specially developed[28]. This new field of application represented by the virtual technologies is in continuous progress and will be always more present in the healthcare solutions.

1.3 Aim of the project

In the first two sections we analyzed the state of the art about the plantar pressure technology making an historical excursus about the evolution of the pressure platforms. Moreover in the second section it is highlighted the need to improve the development in the field of rehabilitation for older people through a Game-Based strategy. Now that we have a sufficient background we can start to speak more in details about the developed project. During this treatment, data such as accuracy, real-time data analysis and the pressure range of a wireless-in-shoe device will be examined: the work will focus on the elaboration of a training modality to help the patient who decides to complete part of his rehabilitation process outside a clinical environment. The device used for the development of the thesis project is an in-shoe wireless system previously developed in the ISR (Institute of Systems and Robotics) of University of Coimbra. The system consists of a sensorized insole made up of 160 soft-capacitive sensors, a bluetooth device hooked to the sole able to acquire measurements of the sensors transferring them to a computer. These are processed in order to obtain a high-pressure pressure map through which the game has been implemented. The project is articulated in three phases:

- Starting from the data acquired by the Smart Insole, it was possible to define the dynamic center of the pressures that will be the patient's reference point for the execution of the training.

Figure 1.8. Insole made of soft-capacitive sensors and Bluetooth peripheral

- Development of the training modes through which the user can practice and start with his rehabilitation path.
- Through the implementation of a simple game (Pong-game), it was possible to use the sole as a controller exploiting the dynamic center of pressures. However, due to the high sampling frequency of the device it was not possible to obtain the desired results.

Chapter 2

Application's structure

In this chapter will be explained the core of the project: the system's tools will be illustrated explaining the way in which the program acquires data coming from the sole and what is really inside this data. Later on we will address more in detail the code specifications inside the application, how the application works, which are the main functions implemented in, which were the problems founded during the development and the solutions adopted.

2.1 Implementation

All the specifications related to the project has been developed in Visual Studio 2015. Microsoft Visual Studio is an integrated development environment (IDE) from Microsoft. It is used to develop computer programs for Microsoft Windows, as well as web-sites, web apps, web services and mobile apps. It supports different types of languages including C, C++, C#, VisualBasic.NET, F#. The programming language adopted in this project is C#. Going to analyze the application structure, we have two main files:

- The first one is SceneP.xaml (3.6). It contains all the elements that are going to populate the user graphical interface; when the application starts, the user will see on the screen the shape of the foot with its pressure arrangement, the button to start the training, some commands that define the sensor's sensitivity and other features that will be explained later on. Thanks to this file it is possible to define the design of the graphical interface. One of the main goals is to have a device easy to use: since the patient utilizes the device far from the hospital and the doctor, maybe in the house, he must be enabled to use all the main functions without any help.

- Inside SceneP.xaml.cs instead, all the elements in the first file are characterized from the code point of view; for example, in this sheet there is the function that defines the colour associated to the pressure-map. Else, there is a function allowing to create what we will call "Dynamic Center of Pressure", that acquiring pressure values and using the coordinates of each sensor, will create in SceneP.xaml file a point able to follow the pressure distribution acting on the sole.

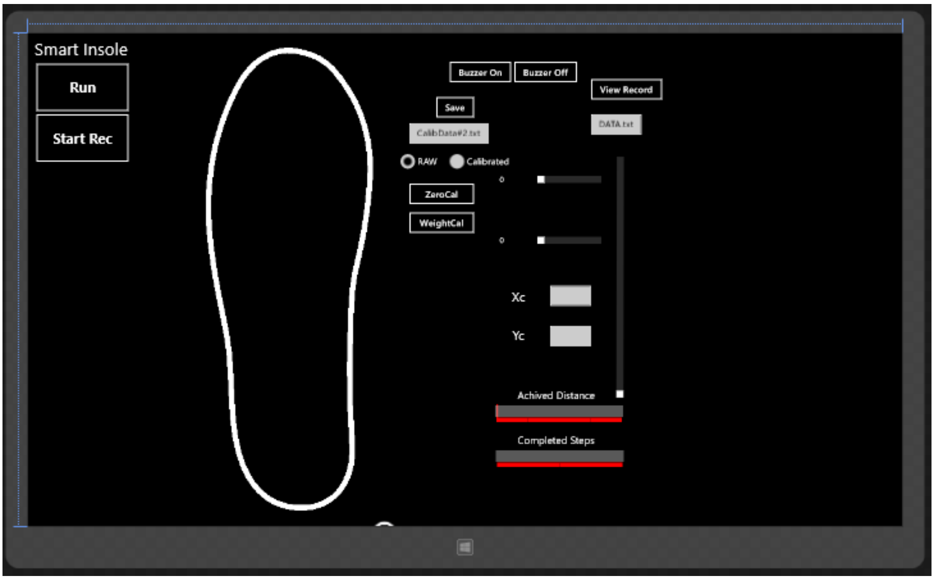


Figure 2.1. Graphical interface for the user

To clarify the procedures adopted to define the main functions developed in the code we have to analyze the way in which the system acquires data from the Bluetooth peripheral and exactly what is inside this data and how this data have to be analyzed in order to create a dynamic Centre of Pressure. The first important consideration is that the information inside this data are not directly related to the pressure values acting on the sole, but rather those are integer values coming from the measurement of the capacitance inside the sensors. For instance this numbers are sent to the application within a Matrix[26][8]; the element Matrix[0][0] shows the capacitance value for the sensor in the bottom right corner. The system continues to acquire data from right to left. For each element of this Matrix[26][8] an instance in the pressure map is generated: the measurements are than compared to a fixed range of values to assign them a specific colour.The functions allowing this procedure are:

- HSV (Hue, Saturation, Value) It is a colour model in which red, green and blue light are added together in various ways to reproduce an array of colours. The main purpose of this method is for the sensing, representation and display of images in electronic systems, such as televisions and computers, though it has also been used in conventional photography and principally it is based on the human colour perception. Implementing the HSV function is now possible to draw the pressure map.

- DrowInsole (data) In this piece of code the pressure map is initialized. Now we have to think that this pressure map will not be an immutable object because it will change its status each time new data will be acquired from the application depending on the frequency of the system. To create this type of object the WtriteAbleBitmap method has been implemented; in this way it is possible to access to each pixel of the pressure map and manipulate them depending on the pressure data. At each cycle a new instance of Bitmap will be generated and populated from new values.

As mentioned before, we can act on the sensitivity of the sensors directly in the file SceneP.xaml also after starting the application: there are some features providing this functionality. MinPressure slidebar: it imposes the minimum offset pressure that the sensors can detect. If it is close to 0 the sensor works also as proximity sensors but we want to avoid this condition because during the test mode the foot is always in contact with the sole and the proximity effect disturbs the normal data acquisition. MaxPressure slidebar: it imposes the maximum pressure that the sensors can detect.

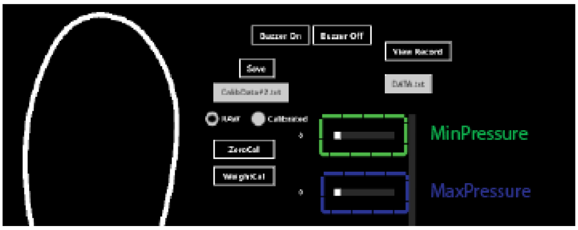


Figure 2.2. Slide-bars in the graphical interface

Until now the matrix of values and the pressure map are defined but this is not sufficient to draw a uniform image of the foot because the number of sensors is too low: in this initial situation the pressure map will be covered by only 160 instances. Originally the system was composed by two grids of conductive material overlapped, forming a rectangle. The total number of available sensors was 208 arranged in 8 columns and 26 rows (as we can understand form the matrix) and each of them was originated by the intersection of two layers of conductive material. The basics of the code refers to this numbers. Later on, this grid has been cut in order to have the shape of the foot reaching the final number of 160 sensors. The final shape can be personalized depending on the size of the foot. Since, starting from the initial conductive layers, we can have different final configurations, and before cutting we don't know which will be this configuration, the system in implemented to acquire 208 measurements and if a sensor misses, the system generates random values. In this case, since the application is set to read 208 inputs but those real are 160, the pressure map becomes misrepresented. For this reason, after the values acquisition, the HideDarkSensor() function has been developed: with the implementation of a counter, it is possible to set to 0 the pressure values coming from the sensors that effectively does not exist anymore. In the following image it is possible to see the modifications realized from the initial shape. In grey we can see the final shape of the sheet of sensors, instead that one originated cutting the sensors is highlighted in brown.

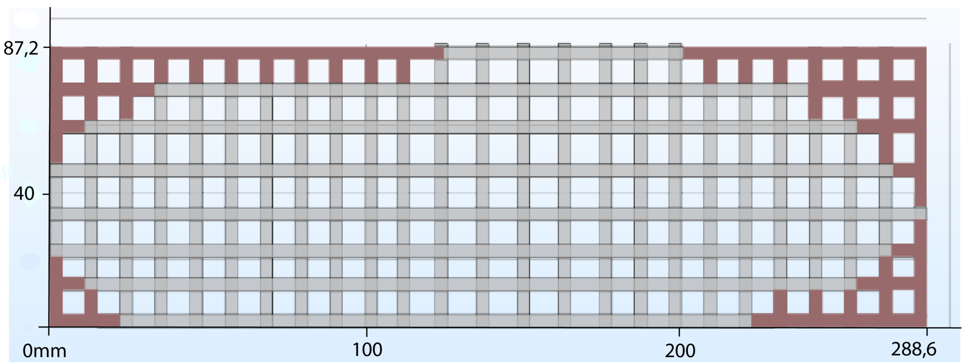


Figure 2.3. Sensor's grid

As said before to draw a more uniform pressure map we need more data. Since we can 't increase the number of sensors, the solution adopted to overcame this problem was to create a particular method allowing to interpolate pressure values.

Interpolation is a method of constructing new data points within the range of a discrete set of known data points. The known data points are those coming from the sensors, obtained by sampling the pressure values. Starting from this values the method InterpolateData() populates the pressure map with other instances.

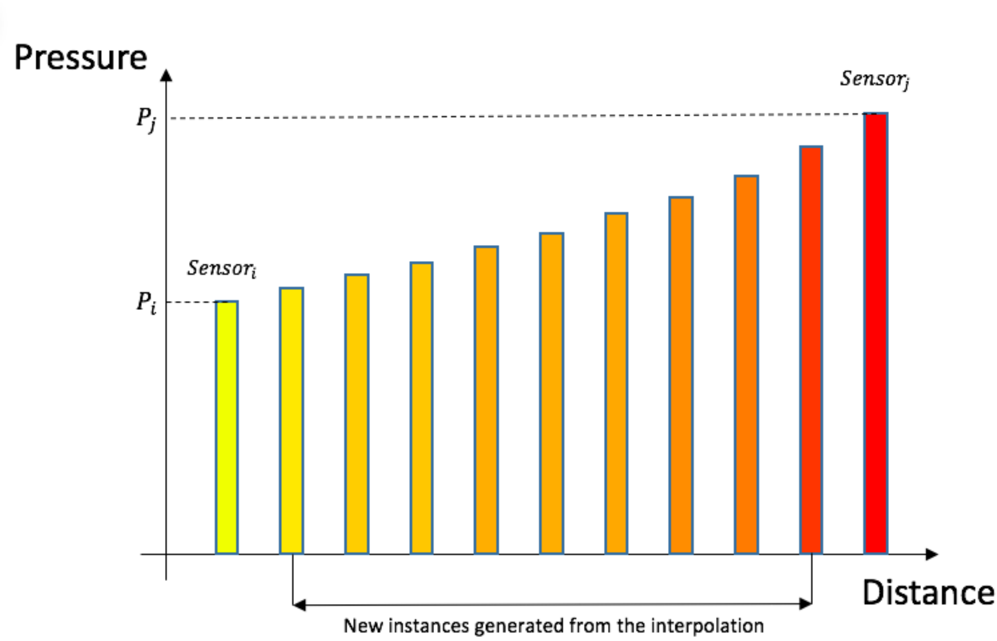


Figure 2.4. Interpolation

The possibility of examining the trajectory of the center of pressures (CoP) is fundamental to study some foot pathologies and also to plan the patient' recovery and rehabilitation processes. The CoP is defined as the center of all external forces acting on the surface of the foot and since the system to which it refers is dynamic, its position will change in every instant of time depending on the pressures acting on the sole [40]. To get an overview of the patient's pathology, it will be necessary to understand the spatial relationship between the CoP and the position of primary joints that make movement possible. [39]. A better understanding of the pressure distribution during the gait will facilitate the evaluation of the doctors and will improve the treatment in patients who have suffered serious accidents involving the motor faculties: the post-stroke patients, subjects who have suffered accidents or operations to the knees or to the hip. The first step of this project was to acquire the CoP to develop a training able to help the patient during his rehabilitation process. We must understand that this type of application must be developed in such a way that everyone can use it without the support of the doctor, outside the hospital, perhaps at home: its use must be direct and simple. Thus, the CoP within the graphical interface was simply localized by a white circle. This point is a dynamic reference of the weight distribution acting on the sole and the user can change his position by shifting the weight forward and backward. Now that we know what the center of pressure is, we focus on implementing the algorithm to create it. Which is the procedure identifying the CoP's position? To understand this, we have to take into account vectors simulating the spatial distribution of the sensors along X axis and Y axis.

- The distance along X axis between each sensor is 11.1 mm and it will be represented by an array of 26 elements.

$$X = 0, 11.1, 22.2, ...288.6;$$

- The distance along Y axis between each sensor is 10.9 mm and will be represented by an array of 8 elements.

$$Y = 0, 10.9, 21.8, ...87.2;$$

Each sensor represents a centre of pressure and, as we can see from the image, all components originated by the binding reaction between the foot and the ground, can be summed to yield a single ground reaction pressure vector.

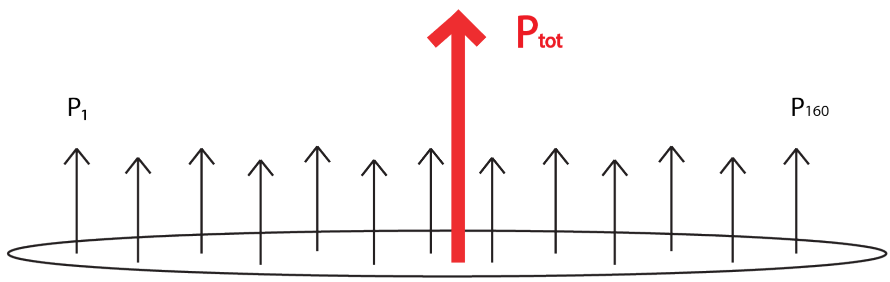


Figure 2.5. Interpolation

Using the coordinates in vector X and Y and the pressure matrix, it is possible to calculate the exact CoP's position using the following formulas:

$$X_{cp} = \sum_{k=1}^{160} \frac{P_k X_k}{P_k}$$

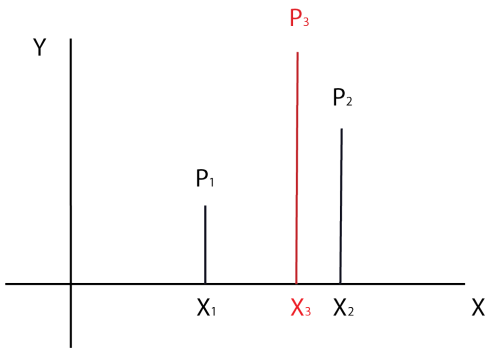
$$Y_{cp} = \sum_{j=1}^{160} \frac{P_j Y_j}{P_j}$$

where:

- X_{cp} and Y_{cp} are the coordinates of the center of pressure.

- P is the local pressure that is applied to a specific sensor. This values will change depending on the acquisition frequency that is $100Hz$;
- X and Y identify the position of a specific sensor that are the equation's constants;

In the following model is shown the procedure just described for two instances.



$$X_3 = \frac{p_1 x_1 + p_2 x_2}{p_1 + p_2}$$

with $p_2 = 2p_1$ and $x_2 = 2x_1$. Therefore,

$$X_3 = \frac{p_1 x_1 + 4p_1 x_1}{3p_1} = \frac{5}{3} x_1$$

The algorithm is implemented in the file SceneP.xaml.cs and the results are collected in SceneP.xaml to make visible to the user the CoP. The displacement in centimeters of CoP with respect to the bottom right corner is indicated in two boxes inserted under the slide bars.

2.2 Test Phase

After the implementation of the algorithm, the test phase starts in order to check the behaviour of the center of pressure in operation mode. For instance, we can analyze the CoP placement when only the atmospheric pressure acts on the sole: since the initial position is the center of the sole ($X_c = 137mm$, $Y_c = 34mm$), if the sole is unloaded, we expect that the white circle has to be stationary in that point. However, during the first tests it was clear that it doesn't respect the parameters imposed by the algorithm, in fact the CoP seemed to move randomly inside the pressure map. One way to better understand this behaviour was to verify the values coming from the sensors checking if these were uniform or not. This was done increasing the sensors' sensitivity in such a way that it was possible to check if some sensors sent data different from the average: imposing a threshold, it was easy to exclude the contribute of sensors respecting the specifications highlighting the wrong behaviour of the others. Actually, the graphical interface showed a strange range of pressure, with some areas blue and green coloured, influencing a lot the CoP position. Moreover, since this values were not constant but they swung over time, the CoP was strongly influenced by them. In this way it has been possible to verify that some sensors showed values different from what we expected. Once this problem has been identified, it was fundamental to understand which and how many were the sensors affecting by this behaviour. To do that a vacuum prove has been necessary. The tools for this procedure were:

- A rotary vane pump (type GeneVac) with two-stage pumps able to reach pressures below 10^{-6} bar

Figure 2.6. GeneVac Vacuum Pump

- A vacuum bag that due to constructive constraints could bear only a pressure close to 0 Atm.

The aim of this test was to apply to the sole a high uniform pressure distribution able to show through the pressure map analysis if there was any sensor or group of sensors recording a different value with respect to the average. Taking into account that the vacuum pressure applied to the sole was around $10 \cdot 10^{-}5Pa$ and knowing that the total surface of the sole is $164cm^2$, it has been possible to calculate the total applied force

$$F = P \cdot A = 100000[Pa] \cdot 0{,}0164[m^2] = 1640[N]$$

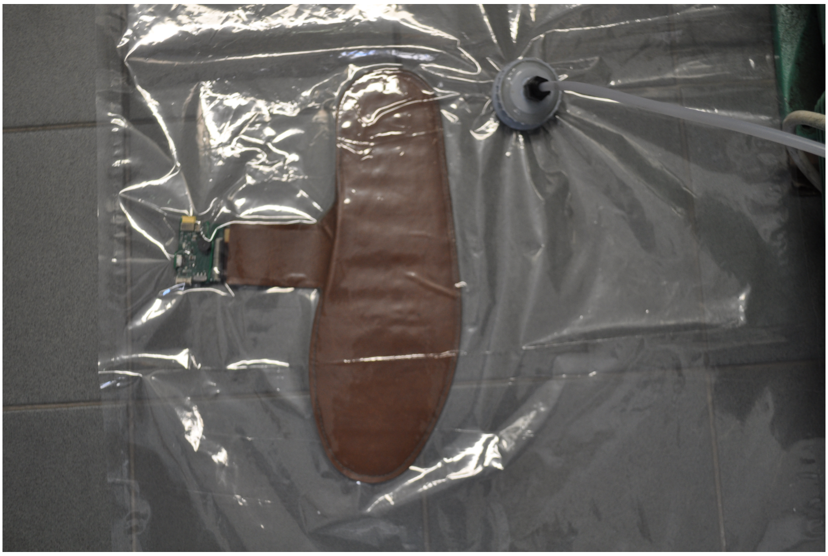


Figure 2.7. Vacuum-Bag

, that is equal to apply a weight of

$$m = \frac{F}{g} \frac{[N]}{[\frac{m}{s^2}]} \simeq 167[kg]$$

As we can see from the following picture, the result coming from the prove highlighted some areas in which the sensors recorded pressure much higher with respect to the average. Therefore, it was clear that the sensors transferred to the application fake data and for this reason the CoP couldn't be in the right position. The areas interested by this behaviour were in proximity of the heel and the tiptoe: this witnesses that this problem was due to an high usage of the sole that probably caused an irreversible deformation of the sensors.

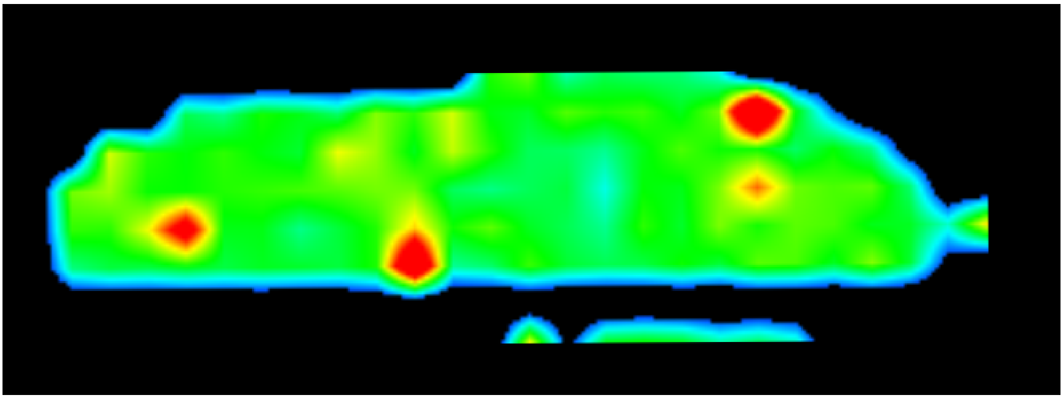


Figure 2.8. Pressure distribution in Vacuum condition

2.2.1 Offset function

Once this offset problem has been identified, there was the need to implement a new algorithm in order to eliminate or at least to minimize the contribute of those sensors that negatively influenced the behaviour of the CoP. Furthermore, analyzing the values coming from the sensors on other problem has been highlighted; to understand it, it is necessary to come back to analyze what is inside the matrix of integer values identifying the pressure acting on the sensors: we spoke a little about it saying that it doesn't give information directly related to the pressure, but rather it transmits the capacitance of each sensor that changes when a pressure is applied on it. The starting values associated to each sensor are very high, but the variation of these are much lower also when the pressure applied to the sole is big. The consequence is that the acquired values does not respect the effective pressure variation.

To better understand this point, we can imagine that a sensor in a position different from the centre of the sole, has a capacitance value of $2000nF$; if I apply a pressure on this sensor increasing it up to $2200nF$, the position of the CoP will not have big changes because the starting value was already big.
To avoid this problem it was necessary to impose an offset able put to zero all the starting data coming from the sole. With the implementation of this filter, on one side we can manage values that are compatibles with the capacitance variation and on the other we can decrease the impact of the out-of-scale sensors. The solution adopted for this purpose was to create a method called ZeroCall-function that uses a new vector of dimension 208 initialized to 0 (that we will call offset_data), comparing it position by position to the vector containing the capacitance data:

$$If(offset\_data[i] < capacitance\_data)$$

$$offset\_data[i] = capacitance\_data$$

So, each time we invoke the method (this is done pressing the button ZeroCall showed in the user graphical interface before starting the training), if the value of the capacitance acting on a sensor is major than 0, that value of capacitance is overwritten in the vector of all 0s. This is done for each sensor. Finally, we get a new variable born by the difference between this two vectors.
When the application starts, before pressing the ZeroCall button, the user must wait some seconds in order to allow the device to stabilize the connection with the

sole. Moreover the ZeroCall must implement its function when the sole is in the rest position otherwise the offset will distort the test. Let's try to analyse the logic of the code; for the first cycle we have:

1. The user presses the ZeroCall button;
2. The if-cycle can run (it can run only if the ZeroCall button is pressed and it will be enabled only one time);
3. For each sensor, the other part of the code performs the operation

   $pressure\_data[i] = offset\_data[i] - capacitance\_data[i] \simeq 0$

   This means that for the first cycle the system is in the rest condition;

With point (1.), the initial values of the capacitance are uploaded in the $offset\_data$ vector. The values stored in this vector will remain the same up to when the ZeroCall button will be pressed an other time: in that case the condition for the if-cycle is respected and the $pressure\_data$ vector is overwritten with new thresholds.

At each sampling time, the system performs the operation in point (2.), so if we move on from the rest condition applying a pressure to the sole, the capacitance values will increase and so as a consequence also $pressure\_data$ will increase. The values that we will take into account to calculate the position of the center of pressure will be stored in $pressure\_data$ and these finally are compatible to the real pressure acting on the sensors. Now it is possible to check the behaviour of the system in two different conditions, the static and the moving one. This analysis will be very important in order to perform the algorithm for the training.

2.2.2 Static Behaviour

Testing the static behaviour is done in order to understand the real accuracy of the CoP and the behaviour of the InSole when it is inserted in the shoe. It was immediately clear that the CoP was able to follow the the pressure-inputs of the foot but it was diffcult to move the CoP along the Y axis because the foot doesn't comply with the surface of the sole. Even stretching the sole of the foot it was difficult to direct the CoP towards the external part. The solution that I tried to

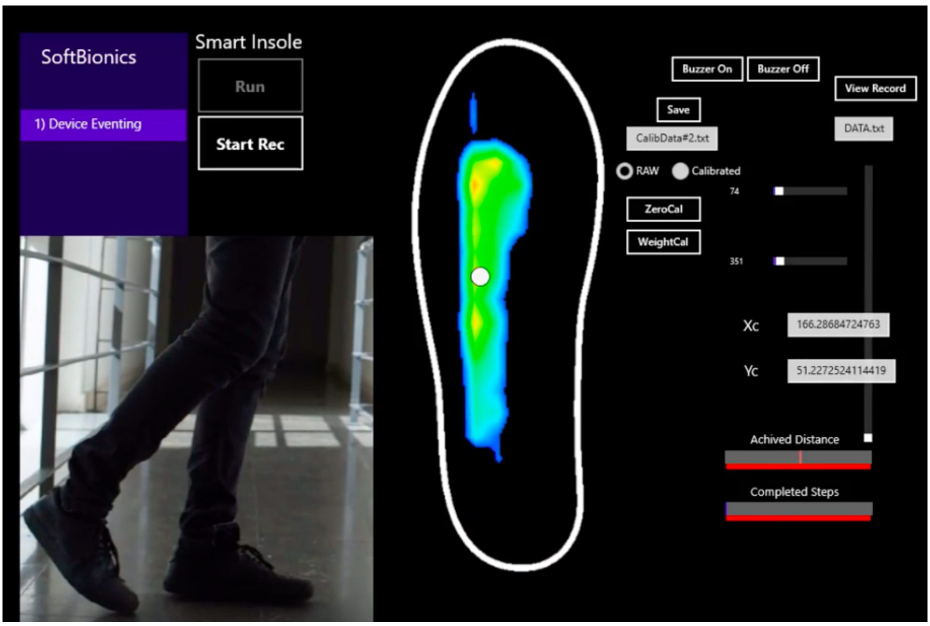


Figure 2.9. Static behaviour: CoP doesn't reach the board of the sole

perform was to create a kind of supports for the lateral sides in order to bend it slightly trying to make it adhere to the shape of the foot. In this way the sole should always be in contact with the foot being more responsive to pressure variations. This type of strategy has proved to be unworkable because the modification of the spatial configuration of the sensor grid has influenced the pressure values recorded by the sensors that were affected by the curvature.

2.2.3 Moving Behaviour

Even if this work focuses on developing a smart application in which feet have to be stationary, it is important to verify the behaviour of the device when the user moves. During the next experimentation there will be the possibility to integrate this game with a rehabilitation path that will include a dynamic training. The subject performing this test walked along a straight path of 10 meters. The total number for steps to complete the path ranged from 12 to 15. In order to perform a good test the user must rest the heel completely, gently. The impact with the ground is therefore more amortized and distributed over a larger area. Only after the foot is completely in contact with the ground the user can push energetically with the fingers. Both the user and the pressure map have been recorded in order to verify if the system was able to reproduce the movement of the foot during walking. The results coming from several attempts reveal that the CoP was able to follow the pressure distribution in a satisfied way if the velocity didn't overcome

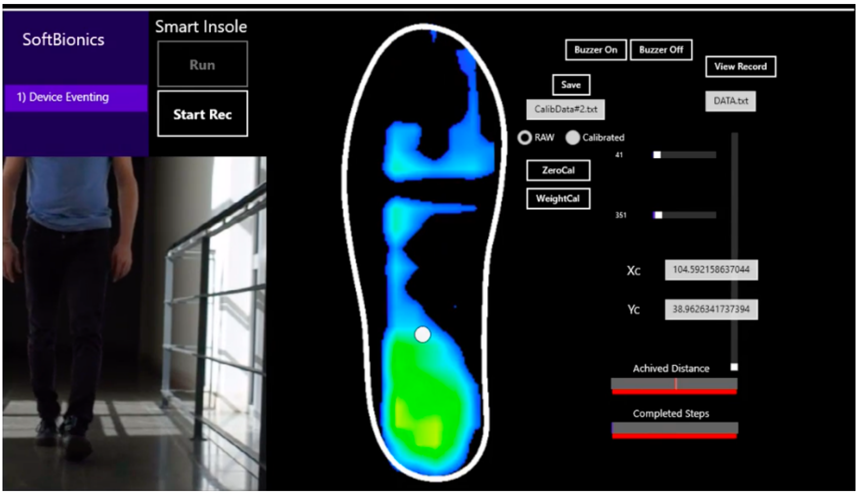


Figure 2.10. Moving behaviour: load on the heel

1.2, 1.5 m/s.

Chapter 3

Training modes

Through the implementation of a filter, it has been possible to avoid the condition in which some sensors sent data different from the real ones. That it has been possible to test the system in different condition highlighting some problems due to constructive constraits. Until now the application is able to show the Center of Pressure position following the pressure distribution. In the third chapter will be explained the solution adopted in order to perform the real training. We will examine the different levels of difficulty analyzing the way in which the user is enabled to reach the final goals.

3.1 Implementation

Since the project wants to respect the specification according to which the training has to be as simple as possible, the best idea to reach this objective was to create an other point that appears in the graphical interface. This second point is always stationary and its position doesn't depend on data coming from the sensors but it will be imposed randomly during the training. Obviously, it has to appear always inside the pressure map and in a position that is attainable by the CoP. The goal is precisely to allow the user to move the center of pressure up to this target in order to improve confidence with his equilibrium. Depending on the ability of the patient, the system offers three different levels of difficulties. The distance between the center of the sole and the target point increases switching the level. Inside each level we have several steps that have to be completed. To complete one step the patient must bring the center of pressure nearby the target. In this way the user realizes which parts of the foot he must use and he or she obtains a visual confirmation of the pressure that has to be impose during the exercise. This targeted training is very important in order to force the patient to concentrate on the correct weight distribution. Now that we know which is the basic idea we can continue explaining how the training works. For instance, the patient's goal is to bring the center of pressures closer to the target and remaining nearby for a few seconds. It is not necessary that the center of pressures lies perfectly overlapped to the target, but to complete the goal is sufficient to overcome a distance threshold imposed in the application. The procedure adopted to define the threshold was to fix the distance along the X axis that the CoP must achieve in order to complete the training. Since I wanted to define the threshold as a circle around the target, if I impose a minimum distance between the target and the threshold this means that I'm imposing the radius of the circle. Therefore, fixing the radius imposing the achieved distance along the X axis, the achieved distance along the Y axis will depend only on the specifications referring to the X axis:

- *X Axis*; Along the horizontal axis the system imposes that the distance that the CoP must complete in order to achieve the goal is equal to 75% of the difference between the target and the center of the sole position. This means that if the target is in position $X_t = 215mm$, knowing that $X_{center} = 137mm$,

  $$X_{ac\_min} = 0.75 \cdot |X_{center} - X_t| = 0.75 \cdot |137 - 215| = 58.5mm,$$

  where X_{ac} is the minimum achieved distance along X axis. This means that the system recognizes the good result when the CoP will be in position

  $$X_{CoP} = X_{center} + X_{ac}, with$$

  $$X_{ac} > 58.8mm$$

  The results of this calculations says that the X coordinate of the CoP must be greater than

  $$X_{CoP} > 137 + 58.8 \simeq 196mm$$

In this way it is possible also to impose the radius r_t of the threshold in the following way,

$$r_t = X_t - X_{CoP\_min} = 215 - 196 = 19mm$$

However, since we have that the CoP can also overcome the threshold from the other side, we have to take into account also the last position that the CoP can hold. This will be equal to

$$X_{CoP\_max} = X_t + r_t = 215 + 19 = 234mm$$

In conclusion, for this specific example we have that the range of the X_{CoP} in order to come in the target area is,

$$X_{CoP} \in [196; 234].$$

- *Y Axis*; As explained before, the coordinates along the vertical axis are imposed depending on the previous calculations. Knowing that the radius of the threshold is r_t, we can calculate Y_{CoP_min} as the sum of r_t and the target coordinate Y_t. The better clarify this point we can start from the last result for the X axis in which we calculated the radius of the circle $r_t = 19mm$. We can imagine that the target is in position $Y_t = 10mm$. Therefore,

$$Y_{CoP\_min} = r_t + Y_t = 19 + 10 = 29mm$$

This means that, knowing $Y_{center} = 34$ it is possible to calculate the minimum

Y_{ac} as,

$$Y_{ac\_min} = |Y_{center} - YCoP\_min| = |34 - 29| = 5mm$$

As for the X axis also for the Y axis it has to be calculated the Y_{CoP_max},

$$Y_{CoP\_max} = Y_t - r_t = 10 - 19 = -9 \simeq 0$$

In this case the result is negative and this means that the threshold is no more a circle but instead it is cut in the part below because in that section there are not available sensors.

In the following figure the procedure just explained is shown graphically. As we

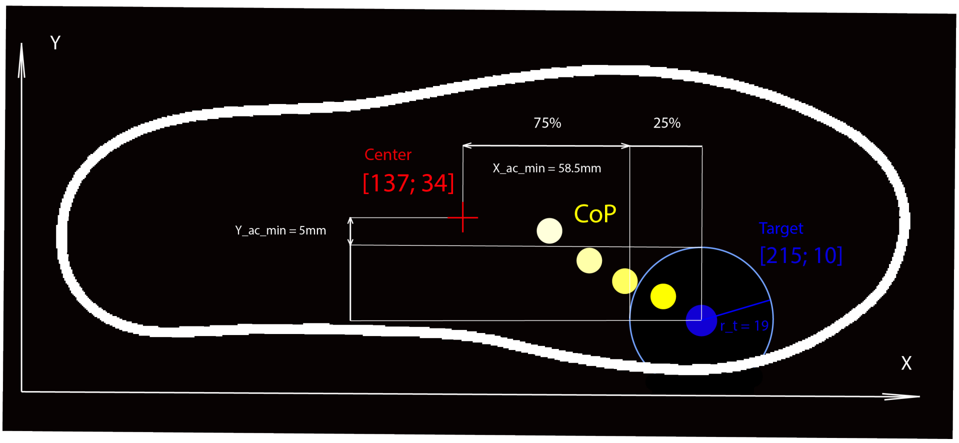


Figure 3.1. Achieved Distance

can see, we have two fixed points that are the Target and the Center, instead the CoP moves in the Target direction in order to overcome the threshold that is represented by the blue circle around the Target. When the center of pressures comes inside the target area, a timer is activated. Depending on this timer the user can complete the exercise. Each time the CoP overcomes the threshold, it must remain around that position for at least 5 seconds in order to achieve the goal. Each time the CoP goes out from that portion, the timer is set another time to 0. Both the distance threshold and the counter can be easily modified in the file SceneP.xaml. Moreover, in the SceneP.xaml.cs a *progress-bar* is implemented in order to show to the user the percentage of the achieved distance, highlighting when it overcomes the threshold. This is the basic idea for what concerns the training. Now we are interested in understand how to impose the Target position. The first approach was to impose its coordinates randomly in the pressure map but after the first tests it was clear that this solution was not satisfactory because the new position was always nearby the previous. In this way the user wasn't enabled to train different parts of the foot. The second attempt has been done creating a rectangular path around the center of the sole imposing that the Target had to appear only across this trajectory (fig.3.2). In this way it was possible to create different levels of difficulty implementing routes more and more far from the center. However, even with this implementation the random-function didn't work as it should have, in fact the target continued to move close to the first position imposed by the algorithm. To overcome this problem, the solution finally adopted was to impose that the Target positions were only 6 for each rectangular path (fig.3.3):

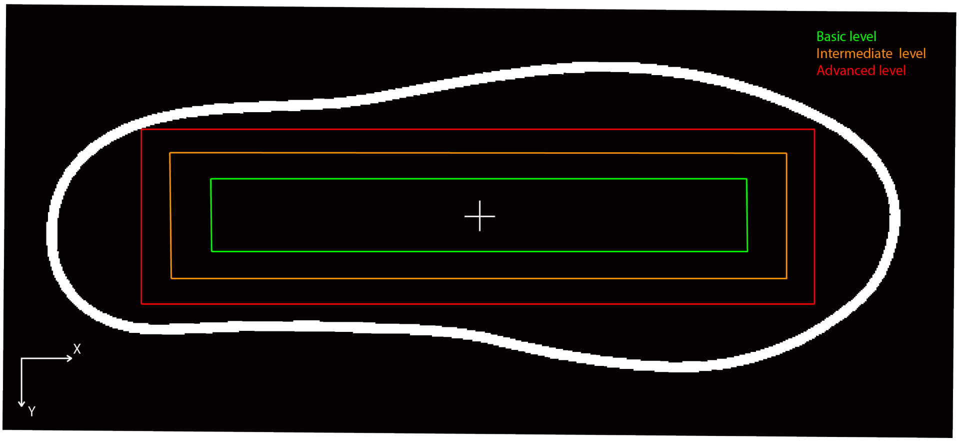


Figure 3.2. Rectangular trajectories for the training modes

- Two vertices of the rectangle in the tiptoe area;
- Two for the lateral side of the foot in the middle of the path;
- Two for the heel that are the other two vertices.

Through this procedure it has been possible to limit the possible sites of the Target allowing the random-function to work in the right way. This solution is also acceptable for the training performance because it includes in the exercises all areas subjected to the greatest load during the static phase. This allows to create a complete rehabilitation path. Basically, as we can see from the pictures the application implements three different levels (Basic, Intermediate, Advanced). The training starts from the basic one and it develops as follows:

- The Target appears in a random position within the six available ones;

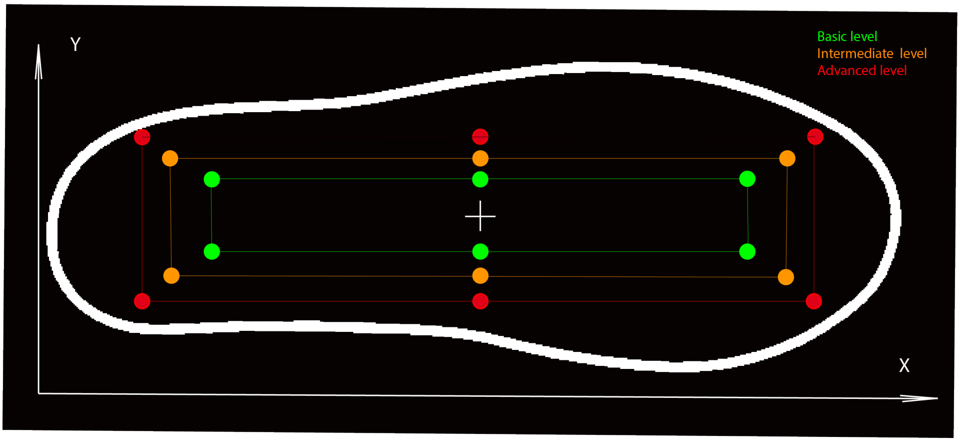


Figure 3.3. Six possible Target positions

- The user moves the CoP nearby the target for five seconds in order to complete the first step of the exercise;
- The first two points are repeated ten times in order to complete the Basic level;
- The first three points are repeated for the two remaining levels.

3.2 Game-based approach

This is the last section of the project. During the course of the experimentation it was not possible to complete this last goal. It was decided to report in this section the partial results and in the fourth chapter "Conclusions and Future Works" the problems encountered and the available solutions.

The objective of this experiment was to couple the developed system to a game. The basic idea was to utilize the Smart Insole as a controller able to command a simple computer-game. In fact, as a traditional controller implements the basic inputs like direction, velocity and acceleration through buttons or keys, the In-Sole had to be able to perform the same tasks collecting data coming from the sensors. According to this approach, the center of pressures that incorporates the pressure distribution instance by instance, has to be able to send correct inputs in order to control the game depending on its position in the pressure map. For instance we can imagine that the CoP can control the direction of a ball in a labyrinth avoiding that the ball goes inside holes along the path. This simple game is implemented in the computer version and takes as input only four keys giving the direction to the ball. So we can think that when the user shifts the weight forward, the ball in some way has to go forward as well and the same happens for the other three directions. The labyrinth-ball was simple but not enough. I was conscious that the most reactive areas in the pressure map were those around the heel and the tiptoe and so I stated to look for a game implementing only the up and down command.

3.2.1 Pong-Game

Pong is one of the first computer game ever created. It is a simple "tennis-like" game with two paddles and a ball. The goal is to defeat the opponent by being the first one to gain 10 point. A player gets a point once the opponent misses a ball.

The game can be played with two human players, or one player against a computer controlled paddle. The game was originally developed by Allan Alcorn and released in 1972 by Atari corporations [41]. Soon, Pong became a huge success, and became the first commercially successful game, On 1975, Atari release a home edition of Pong (the first version was played on Arcade machines) which sold 150,000 units. Today, the Pong Game is considered to be the game which started the video games industry, as it proved that the video games market can produce significant revenues[42]. In the computer version the only keys that are used are two for each

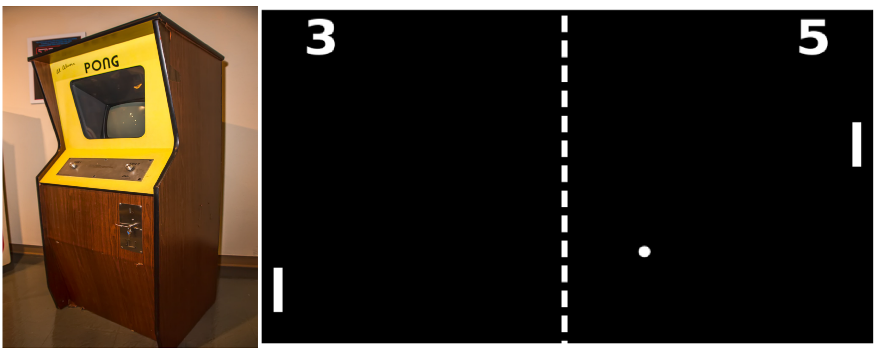


Figure 3.4. Pong

player, one to move up the paddle and the other to move it down. In open-source version the key "w" and "up-arrow" are the up-inputs and "s" and "down-arrow" are the down-inputs. The point is to understand the way in which the system is able to send signals different from the position of the CoP or better how the information about the position of the center of pressures is able to give to the game inputs in order to move the paddle. For example we can imagine that if the CoP overcomes a certain position in the pressure map, the system is able to generate a letter allowing the movement of the paddle. So, the solution to achieve this goal is to insert in the system a new interface that is able to interpret data coming from the sole transforming those in keyboard inputs that are sent directly to the computer in order to command the game.

3.2.2 BLE HID Keyboard implementation

In order to understand the way in which data are transformed we have to speak about the Bluetooth module. It is produced by *Cypress*. As we know, this chip is inserted in the PCB that takes data from the sensors. It can perform different operations and in this case it has to be configured as a HID (Human Interface Device). But, how is it possible to change the configuration? During this project a new board has been used in order to upload the keyboard configuration on the Microcontroller inside the BLE (Bluetooth Low Energy) module. The *CY8CKIT-042-BLE Bluetooth Low Energy (BLE) Pioneer Kit* is intended for use as a development platform for hardware or software in a laboratory environment. To develop and debug the BLE project the software tool *PSoC Creator 4.1* has been used. It is a standard integrated design environment (IDE). The BLE protocol has been abstracted into an easy-and-drop BLE Component in PSoC Creator [43]. Here a new project has been implemented and it performs the connection between the new board and Micro-controller inside the Bluetooth.There are many ways to interface a micro-controller to an other. The easiest way is to use *UART* i.e. *Universal Asynchronous Receiver Transmitter*. It is a way of communication between the micro-controller and the computer system or another micro-controller. Data exchange can be done using serial or parallel techniques.

- In the first one, the complete byte of data is sent at one time with each bit having a separated dedicated data line. It is very fast but more expansive.
- The second one is slower as every bit of data is sent serially one by one but since only two data lines (transmitter and receiver one) are required it is not so expansive. Serial data communication can be further divided into two categories:
  - With a synchronous communication, transmitter and receiver are synchronized by a clock
  - With an asynchronous system, no clock pulse is shared between receiver and transmitter.

As the name suggests UART is an example of asynchronous communication. Since no common clock is shared, a known data transfer rate called *baud rate* must be choosen in order to perform the transmission. The receiving UART needs to know the transmitting UART's baud rate (and conversely the transmitter needs to know the receiverâs baud rate). Our system is composed by a Serial Peripheral Interface (SPI) module, a standard UART with baud rate of 115200 bps and a

USBUART component that uses a USB interface to emulate a COM port. In the UART protocol, the transmitter and the receiver do not share a clock signal. Due to this reason the protocol is said to be asynchronous. That is, the receiving UART needs to know the transmitting UART's baud rate (and conversely the transmitter needs to know the receiver's baud rate, if any) in order to allow data acquisition. The transmitter shifts out the data starting with the LSB first. Once we fix the baud rate, both the transmitter and the receiver's internal clock is set to the same frequency. The receiver "synchronizes" its internal clock to that of the transmitter at the beginning of every data packet received [44]. To summarize, connecting this board to the Bluetooth through a UART protocol, the computer is able to recognize the BLE Device as a keyboard. Therefore, from now on the information that the Bluetooth are sending to the computer will be characters instead of the CoP coordinate. When the application runs it performs all the traditional operations that we explained until now, but in the code developed in PSoC Creator 4.1 there is an other section that analyzes time by time the CoP position comparing it with two thresholds. Each time the CoP overcomes one of this thresholds the Bluetooth sends a character to the computer. To test the system's response, the series of operations that the user preformed is the following:

- The keyboard program is uploaded to the PCB's BLE through the Cypress development board. Each time the code undergoes some changes, it has to be uploaded an other time to the BLE connecting the board as shown in the following picture.

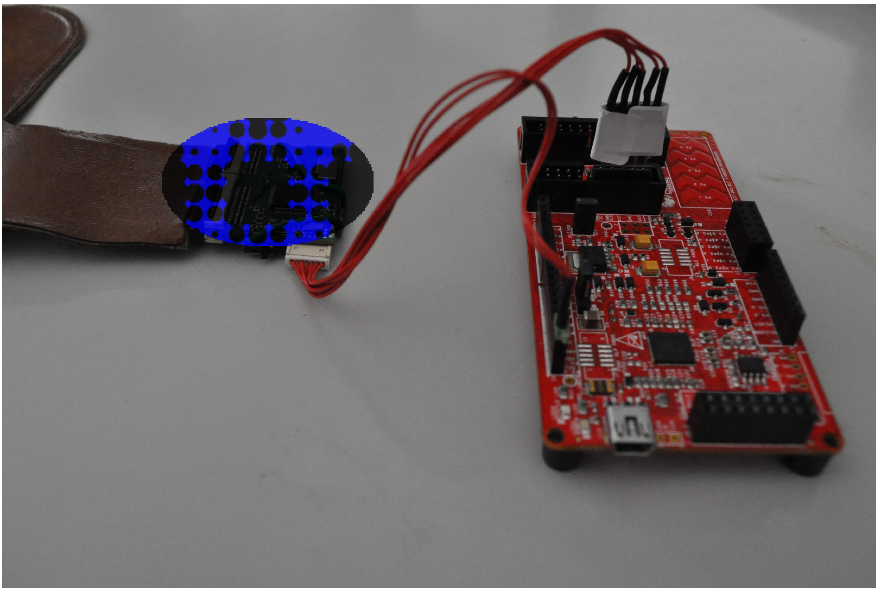


Figure 3.5. Connection between the Cypress development board and the BLE peripheral

- Before starting the test it is necessary to open in the computer a writing program like for example Microsoft Word or Notes-Block in such a way that it will be possible to check if the Bluetooth are sending letters to the computer.

- The application starts and the user enables the ZeroCall button in order to activate the offset function.

- Now, the condition to enter in the code's section enabling the keyboard is verified and the CoP's position is compared to an upper and a down threshold enabling the *PutChar()* operation in this way:

- If $X_{CoP} > 180mm$ UART_UartPutChar('w')
- If $X_{CoP} < 110mm$–> UART_UartPutChar('s')

Implementing this code, the system is able to write the letters w and s like a keyboard.

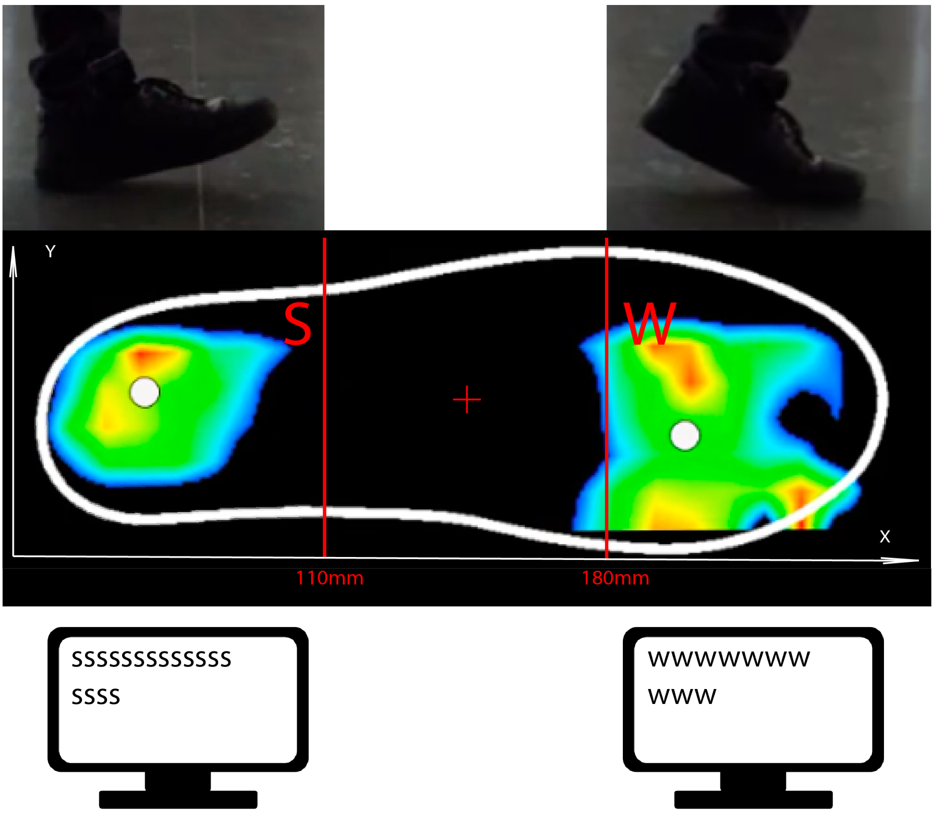


Figure 3.6. Smart-Keyboard-InSole

- Then the Smart Insole sends the character to the receiver (computer) depending on the sampling data period (100ms). The character will be printed on the screen in the opened writing program. Notice that the Smart Insole behaves like a "little" keyboard.

It is possible to increase the number of characters that the system sends for each instance of pressure modifying some indices in the acquisition-algorithm. The good behaviour of the system has been checked with different acquisition velocities but it didn't work in the right way when it was coupled with Pong. In the last chapter the possible reason of this problem will be cited.

Chapter 4

Conclusions and Future Works

The research project carried out at Institute of Systems and Robotics of Coimbra University allowed me to investigate important aspects related to the rehabilitation process of post-stroke patients and subjects that have suffered an invasive surgery like total hip or total knee surgery. Retracing the evolution of plantar pressure platform, we investigated the obtained results through the use of rudimentary methods such as the bags full of putty that produced an impression capturing the shape of the foot reproducing the areas in which the load was higher. Later on, with technological evolution we came to design complex devices tracing the distribution of pressure with the help of optical sensors capable of examining both static and dynamic behavior.

Nowadays, the importance of these devices grows more and more since the average life expectancy continues to increase and therefore there is a progressive aging of the population. As we verified, the fields of application of plantar rehabilitation devices are also expanding in the video-game field in order to make the rehabilitation process more engaging. Game-consoles such as the Nintendo Wii Fit, the Sony Play Station Eye Toy and the VR technology allowed to design games created specifically to help patients during the rehabilitation process and the obtaining results are more than satisfactory. With technological advancement especially in the VR field, these innovative rehabilitation methods will be gradually improved and used in parallel with traditional methods, reducing costs and making the patient more independent from the hospital and from the physiotherapist.

During the course of the dissertation, an attempt was made in order to provide a low-cost device implementing a rehabilitation training. The first step was to collect data creating the foot's dynamic center of pressures that was able to move in different areas according to the weight arrangement on the sole of the foot. The problems encountered during the implementation of the CoP's algorithm were highlighted by the incorrect information that some sensors sent to the computer despite the sole was discharged. The subsequent vacuum test showed that, with the same pressure applied, sensors normally subjected to greater load during the working phase recorded higher values. This behavior was probably caused by a previous plastic deformation affecting a group of sensors nearby the tiptoe and the heel. It was probably due to the excessive sole usage.

After a first phase of testing aimed at verifying the effective operation of the CoP's algorithm, the code for the rehabilitation training has been implemented. Since the application was developed in the Windows environment, and therefore the user interface was a computer, it was decided to implement only a static training that would allow the user to stay standing in front of the screen. In the future the code will be reproduced in mobile and this will allow the development of the dynamic rehabilitation phase. For now, the latest results allow the patient to complete the rehabilitation process independently. The user is able to bring the center of pressures in correspondence with target points appearing in the graphical interface during the operating mode.

In the last part of the project we tried to use the Smart-Insole as a controller to command the game Pong. After the first check about the correct functioning of the smart-insole as a keyboard, I tried to use an open-source version of the game.

However, problems were highlighted during the paddle movement. The vertical movement of the paddle was very slow and intermittent even if the *"buttons" w and s* were pressed. It seamed as if the game only read part of the instances w and s coming from the sole and therefore its behavior was distorted. It is possible that this phenomenon was caused by a problem in the signal acquisition process made by the game. The solution could be to redesign the game from scratch by matching its frequency of acquisition to the sampling frequency of the Smart-Insole.

The field of rehabilitation using electronic devices and in particular exploiting the Game-based approach belong to a recent research area. However, in my opinion there are all the prerequisites both from a technological and from a social point of view to place resources in order to offer to the final user more and more smart solutions.

Bibliography

[1] Boulton AJM, Hatdisty CA, Betts RP, Franks CI, Worth RC, Ward 1D et al.*Dynamic foot pressure and other studies as diagnostic and management aids in diabetic neuropathy.*, Diabetes Care 1983; 6: 26- 33

[2] Aristidis Veves, John M. Giurini, Frank W. LoGerfo, *The diabetic foot - Medical and Surgical Management*, Springer 2002.

[3] R.M. Kenedi, J.P. Paul, John Hughes, *Disability: Proceedings of a Seminar on Rehabilitation of the Disabled*, Springer 1979.

[4] Herbert Elftman, *Dynamic structure of the human foot*

[5] E. Ann Welton, *The Harris and Beath Footprint: Interpretation and Clinical Value*, First published October 1, 1992; American orthopedic Foot&Ankle society, Research Article.

[6] C.H.M. van Schie, C.A.Abbott, L.Vileikyte, J.E.Shaw, S. Hollist and A. J. M. Boulton, *A comparative study of the Podotrack, a simple semiquantitative*

plantar pressure measuring device, and the optical pedobarograph in the assessment of pressures under the diabetic foot , 1999 British Diabetic Association. Diabetic Medicine (pages 154-159).

[7] Juliette Jowit, *Ageing population will have huge impact on social services, Lords told*, February, 24th 2013; The Guardian

[8] Abdul Hadi Abdul Razak, Aladin Zayegh, Rezaul K. Begg, Yufridin Wahab, *Foot Plantar Pressure Measurement System: A Review*, Sensors 2012, 12.

[9] Alessandro Santuz, Antonis Ekizos, Adamantios Arampatzis,*A Pressure Plate-Based Method for the Automatic Assessment of Foot Strike Patterns During Running.*, Annals of Biomedical Engineering, 2016, 44, 5, 1646

[10] Navaporn Laowattanatham, Kittipol Chitsakul, Suradej Tretriluxana, Cherdpong Hansasuta,*Smart digital podoscope for foot deformity assessment*,The 7th 2014 Biomedical Engineering International Conference

[11] Peter R.CavanaghMichiyoshiAe ,*A technique for the display of pressure distributions beneath the foot* , Biomechanics Laboratory, The Pennsylvania State University, University Park, PA 16802, U.S.A.

[12] Alejandra Alicia Silva Moreno, Francisco ChÃ¡vez GutiÃ©rrez ,*Digital podoscope for remote diagnosis* , Proceedings Volume 8287, Eighth Symposium Optics in Industry; 82870K (2011); doi: 10.1117/12.912135. Event: Eighth Symposium Optics in Industry, 2011, Toluca de Lerdo, Mexico

[13] Navaporn Laowattanatham, Kittipol Chitsakul, Suradej Tretriluxana, Cherdpong Hansasuta,*Smart digital podoscope for foot deformity assessment*, January 2015, Reasearchgate.

ARTICOLI SU RIABILITAZIONE CON I GIOCHI

[14] Giovanni Morone, Marco Tramontano, Marco Iosa, Jacob Shofany, Antonella Iemma, Massimo Musicco, Stefano Paolucci, and Carlo Caltagirone, *The Efficacy of Balance Training with Video Game-Based Therapy in Subacute Stroke Patients: A Randomized Controlled Trial*, BioMed Reasearch International.

[15] Lange B, Flynn S, Proffitt R, Chang CY, Rizzo AS., *Development of an interactive game-based rehabilitation tool for dynamic balance training.*, Research Support, U.S. Gov't, Non-P.H.S.

INIZIO CITAZIONE [13-24]

[16] Boian R, Sharma A, Han C, et al., *Virtual reality-based post-stroke hand rehabilitation.*, Stud Health Technol Inform 2002;85:64-70.

[17] Chuang TY, Huang WS, Chiang SC, Tsai YA, Doong JL, Cheng H., *A virtual reality-based system for hand function analysis.*, Comput Methods Programs Biomed 2002;69(3):189-96.

[18] Adamovich SV, Merians AS, Bojan R, et al., *A virtual reality based exercise system for hand rehabilitation post-stroke: transfer to function.*, Conf Proc IEEE Eng Med Biol Soc 2004;7:4936-9.

[19] Dvorkin AY, Shahar M, Weiss PL., *Reaching within video-capture virtual reality: using virtual reality as a motor control paradigm.*, Cyberpsychol Behav 2006;9(2):133-6.

[20] Fung J, Malouin F, McFadyen BJ, et al., *Locomotor rehabilitation in a complex virtual environment.*, Conf Proc IEEE Eng Med Biol Soc 2004;7:4859-61.

[21] Fulk GD., *Locomotor training and virtual reality-based balance training for an individual with multiple sclerosis: a case report.*, J Neurol Phys Ther 2005;29(1):34-42.

[22] Baram Y, Miller A., *Virtual reality cues for improvement of gait in patients with multiple sclerosis.*, Neurology 2006;66(2):178-81.

[23] Fung J, Richards CL, Malouin F, McFadyen BJ, Lamontagne A., *A treadmill and motion coupled virtual reality system for gait training post-stroke.*, Cyberpsychol Behav 2006;9(2):157-62.

[24] Mirelman A, Bonato P, Deutsch JE., *Effects of training with a robot-virtual reality system compared with a robot alone on the gait of individuals after stroke.*, Stroke 2009;40:169-74.

[25] Yang Y, Tsai M, Chuang T, Sung W, Wang R., *Virtual reality-based training improves community ambulation in individuals with stroke: a randomized controlled trial.*, Gait Posture 2008;28(2):201-6.

[26] Subramanian S, Knaut LA, Beaudoin C, McFadyen, Feldman AG, Levin MF., *Virtual reality environments for post-stroke arm rehabilitation.*, J Neuroeng

Rehabil 2007;4:20-5.

[27] Oddsson LI, Karlsson R, Konrad J, Ince S, Williams SR, Zemkova E., *A rehabilitation tool for functional balance using altered gravity and virtual reality.*, J Neuroeng Rehabil 2007;4:25-32.

FINE CITAZIONE [13-24]

[28] B. Lange, S. Flynn and A. Rizzo, *Initial usability assessment of off-the-shelf video game consoles for clinical game-based motor rehabilitation*, Institute for Creative Technologies, University of Southern California, Marina Del Rey, CA 90292, USA

INIZIO CITAZIONE [39-41]

[29] Deutsch JE, Lewis JA, Burdea G., *Technical and patient performance using a virtual reality-integrated telerehabilitation system: preliminary findings.*, IEEE Trans Neur Syst Rehabil Eng 2007;15(1):305.

[30] Lewis JA, Deutsch JE, Burdea G., *Usability of the remote console (ReCon) for virtual reality telerehabilitation: formative evaluation.*, CyberTherapy and Behavior, Special Issue on IWVR 2006;9(2):142 7.

[31] Deutsch JE, Lewis JA, Whitworth E, Boian R, Burdea G, Tremaine M. *Formative evaluation and preliminary findings of a virtual reality telerehabilitation system for the lower extremity.*, Presence, Special Issue on Virtual Rehabilitation 2005;14(2):98 213.

FINE CITAZIONE [39-41]

[32] L. Oddsson, C. W. III, P. F. Meyer, and J. Konrad,*A virtual environment with simulated gravity for balance rehabilitation of bedridden patients and frail individuals* , presented at XV-th Congress of the International Society of Electrophysiology and Kinesiology, Boston, 2004.

[33] H. Barbeau, K. Norman, J. Fung, M. Visintin, and M. Ladouceur,*Does neurorehabilitation play a role in the recovery of walking in neurological populations?*, Ann N Y Acad Sci, vol. 860, pp. 377-92, 1998.

[34] You SH, Jang SH, Kim YH, Hallett M, Ahn SH, Kwon YH, et al.,*Virtual reality-induced cortical reorganization and associated locomotor recovery in chronic stroke: an experimenter-blind randomized study.*, Stroke 2005;36:1166â71.

[35] Lam YS, Man DWK, Tam SF, Weiss PL. ,*Virtual reality training for stroke rehabilitation.*, NeuroRehabilitation 2006;21:245â53.

[36] Aman V. Shah, Scott Teuscher, Eric W. McClain, and Jake J. Abbott *How to Build an Inexpensive 5-DOF Haptic Device Using Two Novint Falcons*, Department of Mechanical Engineering, University of Utah Salt Lake City, UT, 84112, USA

[37] Pierre Renon, Chenguang Yang, Hongbin Ma *Haptic interaction between human and virtual iCub robot using Novint Falcon with CHAI3D and MATLAB*, Proceedings of the 32nd Chinese Control Conference, 26-28 July 2013

[38] Steven Martin, Nick Hillier,*Characterisation of the Novint Falcon Haptic Device for Application as a Robot Manipulator* , Australasian Conference on Robotics and Automation (ACRA), December 2-4, 2009, Sydney, Australia Chapter 3

[39] Vipul Lugade, Kenton Kaufman ,*Center of Pressure Trajectory during Gait: A Comparison of Four Foot Positions*, Motion Analysis Laboratory Division of Orthopedic Research Mayo Clinic Rochester, MN 55905 USA

[40] Nima Jamshidi, Mostafa Rostamib, Siamak Najarianc, Mohammad Bagher Menhajd, Mohammad Saadatniae, Firooz Salamia,*Differences in center of pressure trajectory between normal and steppage gait*, November 2009, https://www.researchgate.net/publication/200453850

[41] Sellers, John,*"Pong". Arcade Fever: The Fan's Guide to The Golden Age of Video Games.*, August 2001, Running Press. pp. 16â17. ISBN 0-7624-0937-1.

[42] Kent, Steven,*"And Then There Was Pong". Ultimate History of Video Games.*, 2001, Three Rivers Press. pp. 40â43. ISBN 0-7615-3643-4.

[43] Cypress Semiconductor 198 Champion Court San Jose, CA 95134-1709,*CY8CKIT-042-BLE BluetoothÂ® Low Energy (BLE) Pioneer Kit Guide*, Doc. 001-93731 Rev. *G

[44] Electronics Engineering Society IT-BHU,*Interfacing Micro-controller with PC*