

# MASTER THESIS

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Degree Program: Master in Biomedical Engineering

## DESIGN AND DEVELOPMENT OF AN INSTRUMENTED SOLE FOR GAIT ANALYSIS

By: Jorge Pascual Retuerta

Supervisor 1: Matthias Scherer, MSc (FH Wien)

Supervisor 2: João Pedro Santos da Costa, MSc (FH Wien).

Supervisor 3: Luis Serrano Arriezu (UPNA).

Vienna, 14<sup>th</sup> February 2020



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# Abstract

Gait analysis has become an important method to measure the pressure that a subject makes in each step, allowing the detection of several anomalies, which generate many pathology and problems in the subject.

The aim of this project is to design and develop an insole, which must be able to measure the pressure that a subject generates along his/her gait path.

On the theoretical side, an investigation about the most adequate positions to place the pressure sensors was carried out in order to detect the pressure during the gait and compare it between feet movements. It was also required to understand the foot anatomical distribution, mainly as bones are concerned.

On the other side, the practical one, a circuit was designed to do these measurements. Data recorded had been sent to a computer through Bluetooth connection. Then an algorithm for automated movement detection was developed, as well as an interface to make these measurements easier. Using a Bluetooth connection and a batterie it was possible to develop a wireless device, keeping the influence on the subject's gait behaviour at a minimum by providing the most comfort possible. The device was fixed at the gastrocnemius muscle height trying not to affect the subject's gait. For this purpose, a case was also developed to locate the prototype.

Finally, the results were analysed in order to know if the pressure registered had consistent values, and if the pressure detected in each point followed the logical order as it has been seen in other studies (**Vidya K. Nandikolla, 2017**). It was also tried to observe any relationship or change between the pressure in different foot points and a slope floor increasement.

**Keywords:** Insole, pressure, measurements, sensors, Arduino®, gait, steps, Bluetooth, pedobarography and Matlab®

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# **1. INTRODUCTION AND OBJECTIVES**

## **1.1 INTRODUCTION**

Nowadays, due to the booming of the sports (Ministerio de Cultura y Deporte, 2019), and mainly jogging, people has started to value their own comfort during sport activities (Phillip Bishop, 2013). This has generated an increase of the biomechanical studies, in order to fix wrong movements, avoid new ones and take advantage of the effort made. These studies can be based in the ergonomics, the way that one person moves or in the relationship between the joints. These kinds of analysis are carried out using sophisticated cameras, which record the exercises and allow to see them from several perspectives, angles and video speeds. However, recently new studies have been made with the help of several sensors, such as: pressure sensor, accelerometers or gyroscopes (Glen Cooper, 2009). This has created new methods like instrumented insoles or pressure plants in order to perform these measurements.

In this project, an instrumented insole has been developed. The insole can measure the pressure in various points of the foot during the gait, sending these recorded data to a computer. The obtained data are then analysed and processed, giving a result about the pedobarography of the subject.

Finally, to be able to understand this thesis it is important to define the meaning of a pedobarography. It is a tool that allows the measuring of the pressure that a subject makes during the gait. In other words, it analyses the pressure change not only in a dynamic position but also in a static position, providing information about the force that the different parts of foot are suffering (Allison Brashear, 2016).

## **1.2 OBJECTIVES**

The aim of this project is to develop a generic insole, which must be able to measure the pressure of specific points, which will be analysed further on, taking in account the size of the feet. Measurement of foot pressure distribution (FPD) is clinically useful because it can identify anatomical foot deformities, guide the diagnosis and treatment of gait disorders and falls, as well as lead to strategies for preventing pressure ulcers in diabetes (Skopljak, 2014). In addition, as this field has a lot of points to improve, different activities will be studied in order to get more information about their characteristics.

First a subject has done a march to find out the order in which different foot points hit the ground, then the same subject has performed some gaits with different slopes in order to establish a relationship between the foot pressure and the floor slope increasement.

With the purpose to progress with the project in an organized manner, all the steps were planned in a scheme as it shown Figure 1.

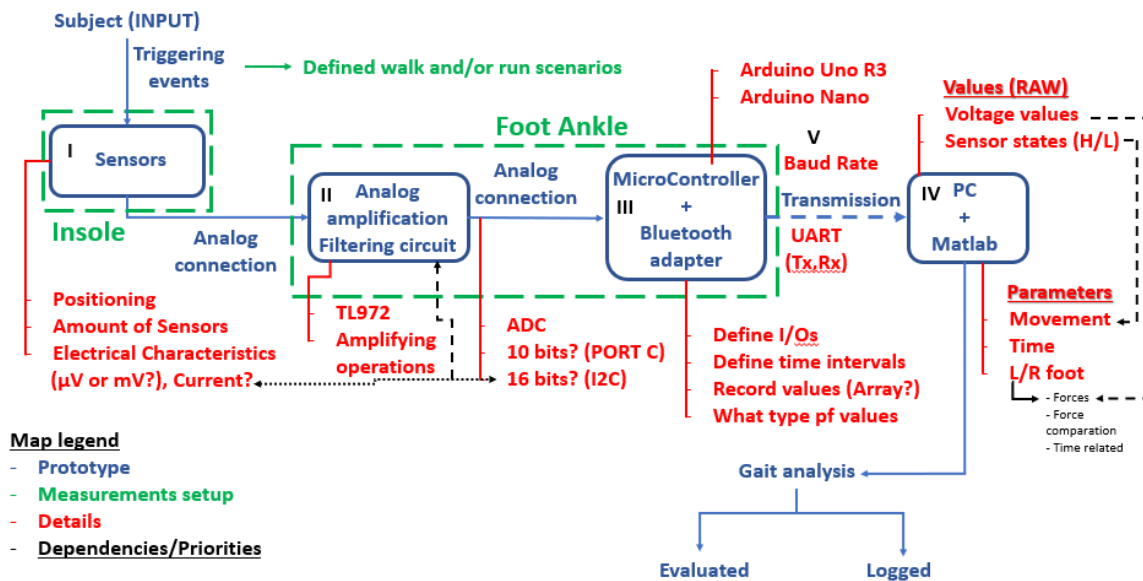


Figure 1. Steps followed to develop the project. Steps one, two and three represent the hardware part, meanwhile the last step encompasses the entire software design.

First, it was necessary to define and create a circuit that could measure the pressure in different points of the feet. Regarding that, an analysis about the pedobarography was carried out in order to know which the most adequate positions were to place the pressure sensors, as well as the amount of them. In this respect, a higher number of sensors would measure the pressure more precisely, the more sensors, the greater the measurement accuracy. However, the purpose was reaching similar results to (Mary Josephine Hessert, 2005) using the less sensors as possible. Moreover, it was necessary an analysis about the circuit characteristics considering the limits of the chosen sensors, considering the maximum currents and the voltage levels. As it is possible to see in the first green square in Figure 1, only this part of the project was included in the insole, trying to avoid different nuisances on the subject.

Secondly, it was necessary to adapt the signal received by the pressure sensor. Values recorded depended on the different passive elements of the circuit so different options to try to achieve a better signal were studied, in order to get a signal which could be easier to measure and interpret.

The third step of the project was to connect the circuit to the computer, in order to be able to interpret and manage the generated data. The circuit output is directly connected with a microcontroller, specifically, an Arduino MEGA2560 (Arduino s.r.l.), which has a Bluetooth device included, so it allows the analogical connection. In this point, it was essential to define the different requisites for the Bluetooth connection: time intervals, how to record the values and which type of values were going to be processed.

As previously mentioned (Figure 1), the second and third parts of the circuit were encapsulated in a case that was placed at gastrocnemius muscle height of the subjects, in order to allow a more natural gait.



Finally, the signal transmitted through Bluetooth was received by the computer, where through MATLAB® R2019b (Mathworks, Natick, US) the signal was processed. In order to understand and analyse the data received, an algorithm was also developed.

Considering the mentioned steps, there are two clearly separate parts. The first one is the definition of the project's hardware, which implies the design and development of a circuit composed by the first three points (sensors, filtering circuit and microcontroller with Bluetooth adapter). On the other hand, the last task involves the project's software. Despite their differences, both sides are two sides of the same coin.

To sum up, the electronic device must fulfil adequately the next specifications:

- To detect, interpret and calculate the pressure applied by a foot when it strikes the floor. Generating a pedobarography map with the help of the sensors located along the insole.
- Pedobarography map should work in real time, meaning once the foot has struck the floor completely and before it is in the floor again.
- To analyse a subject tread, being able to know the pressure measurements units throughout the gait, as well as the foot point which suffers the highest force.

### **1.3 HISTORICAL CONTEXT**

According to its definition Biomechanics is the study of the structure, function and motion of the mechanical aspects of biological systems, at any level from whole organisms to organs, using the mechanics' methods; it is considered as a branch of biophysics. (Knudson, 2003) (Hatze, 1974).

There are some registers about the first biomechanical studies from the Renaissance (15th and 16th centuries), when several scientists such as Leonardo da Vinci (Figure 2), Galileo Galilei or Bernoulli wrote about the corporal segments and movements of the animals as well as the mechanical application of these (Acero J, 2002).

During the following three centuries there is not a lot information about this topic. Mankind did not analyse again the movement of the body during the performance of different activities until the late nineteenth century. At that time, measuring several parameters was useful to reduce the effort and also the risk to suffer an injury, mainly in terms of war. Marey, a French physiologist, was probably one of the first man in this field, who in 1885 used a photographic gun to record the human gait, being able to describe the whole movement along a race. In addition, when the First World War finished, the ergonomic was studied stimulated by the transport industries (Winter D, 1990).

Nevertheless, in the last quarter of the 19th century, Beeley made the first recorded studies about the distribution of pressure in the foot. As far as the study concerns, the subjects had to step on a thin sack filled with plaster in Paris. He thought that those portions of the foot carrying the greatest weight would make the deepest impressions. Years later this technique

was copied by other scientists, but with this method they only obtained the size of the feet, not the pressure (Elftman, 1934).

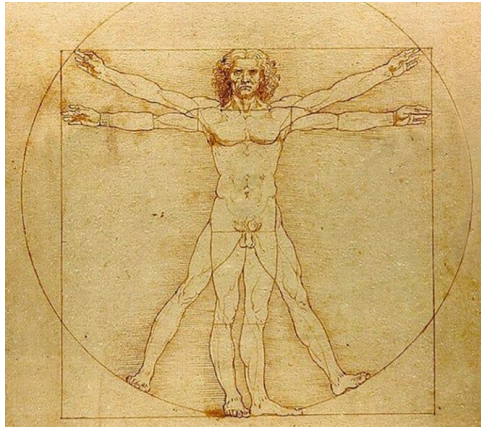


Figure 2. Da Vinci's biomechanical study (Vitruvian man) (Richman-Abdou, 2018)

However, it was not until the arrival of the personal computer when electronic insoles were developed. The most recent description of an instrumented shoe was in 1986 on a Ranu's report. He measured ground reaction forces by embedding cells in the subject's shoe sole. Multiple sequential steps could be studied, and centre of pressure excursion was documented. (Alexander, 1990). After the Second World War, like in other scientific fields, a big change was suffered due to the high-speed cinematography. Some years later, in 1984, Alley proposed the term Anthropometric instead of Kinesiology, which groups, Biodynamic, Biokinetic and Biomechanics (Acero, 2013).

## 1.4 STATE OF ART

Plantar pressure sensing systems have become indispensable in clinical and research settings.

The sole measurement systems on the market are usually of three different types: Pressure distribution platforms, pressure systems included in the footwear (in-shoe systems) and by means of image technology. All three methods depend directly on spatial resolution, sampling frequency, accuracy at the point of measurement, calibration, and sensitivity of the sensors. The first method consists on sensors arranged along a straight line. It offers a high spatial resolution of the plantar pressure, but is usually limited to analytical spaces or laboratories, since the measurement points are installed in the ground. The second type, the sensor method implemented in the footwear, can be used in any environment, however its disadvantage is the loss of sampling accuracy.

Most studies sub-sample the data by dividing the sole of the foot into several regions. This facilitates signal processing and data interpretation but can generate errors since it ignores most of the data. An adult could come into contact with 500 sensors on the ground during

the footprint analysis, but in many cases, these contact areas are reduced to 10 or 5 regions, thus reducing the sensing areas by 50 or 100 times.

If there is something in common between the two types of measurement mentioned (not the camera), it is that they generate an electrical signal proportional to the vertical force exerted on the implemented sensors. Most of these sensors are capacitive, piezoelectric, piezo resistive or resistive (Linah Wafai, 2015) (Abdul Hadi Abdul Razak, 2012) (Todd C. Pataky, 2008).

## 1.5 ANATOMICAL PRINCIPLES

An investigation was carried out, in order to gather as much information as possible not only about the gait and their parameters, but also the different ways that are used nowadays to measure the body parameters related with the movement. It was important to take into account some knowledge about the body in order to know the correct terminology better. First of all, it was necessary to know each body plane by its technical name, and the possible movements that they allow to do (Figure 3).

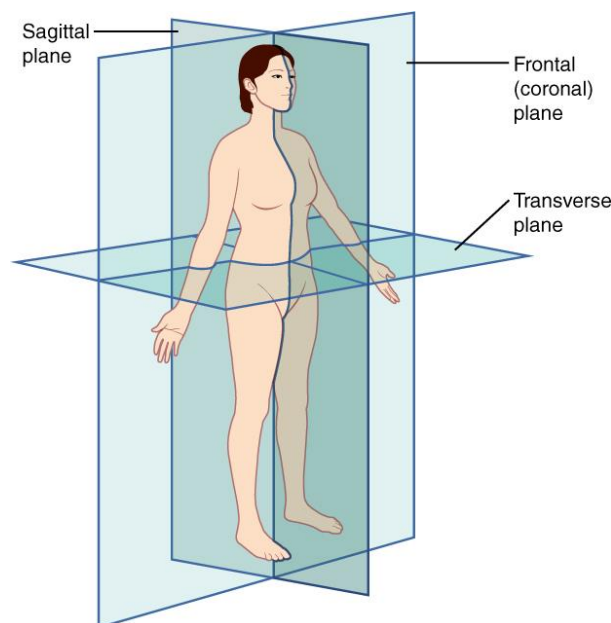


Figure 3. Body planes (Connexions, 2013)

Each plane has two different, and opposite, movements associated. In the sagittal plane it is possible to perform the extension and flexion movements, while in the transverse plane the abduction and adduction movements can be made. Finally, as regards the frontal plane, its movements are: eversion and inversion. In this project, special attention will be given to movements belonging to the sagittal plane, although movements that occur in the frontal plane will also be important. The latter will allow to know if the subject is a pronator or supinator, and in case this tendency is very marked, correct it, thus avoiding future injuries.

### 1.5.1 FOOT ANATOMICAL PRINCIPLES

It was primordial to know the feet muscles, bones and joints, so a study about which of them are more involved during the gait was made. The feet are one of the most complex parts of the body, being composed by 26 bones (Figure 4), 33 joints, 107 ligaments and 19 muscles. In addition, they must support the whole-body weight (Bonnell F., 1998).

The bones fall into three groups: tarsal bones, metatarsal bones and phalanges (Lillis, 2019).

1. Tarsal bones: they are a group of seven bones that make up the rear section of the foot, which are the grey ones in Figure 4.
2. Metatarsal bones: they are five tubular bones in the middle of the foot. They are in charge to connect the tarsal bones and the phalanges.
3. Phalanges: they are the bones that shape the toes. In the first toe, there are only two phalanges (proximal and distal phalanges) as it is possible to see in the Figure 4, meanwhile in the other four toes, there are three bones for each one, proximal, middle and distal phalanges.

The point where the second metatarsal and the proximal phalange are joined, it is the place where the foot suffers the most pressure, so it is usually a common area for foot pain.

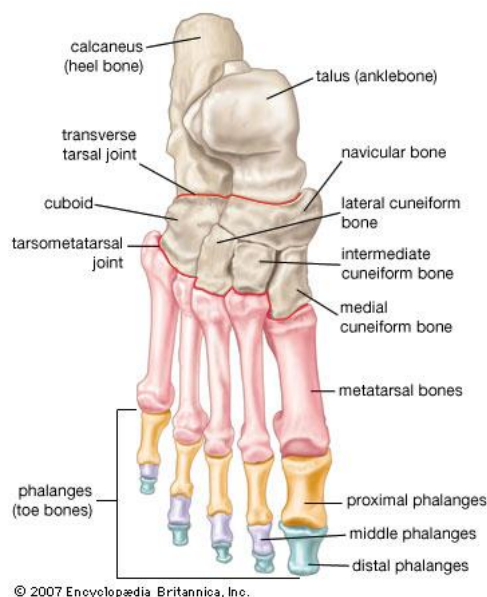


Figure 4. Foot bones (Britannica, n.d.)

### 1.5.2 GAIT ANATOMICAL PRINCIPLES

Human gait is defined as bipedal, biphasic forward propulsion of centre of gravity of the human body, in which there are alternate sinuous movements of different segments of the body with least expenditure of energy. Different gait patterns are characterized by differences in limb movement patterns, overall velocity, forces, kinetic and potential energy cycles, and changes in the contact with the surface (Sasidharan, 2012).

The gait cycle is divided into two phases: stance and swing. Firstly, it begins when the heel contact with the floor and ends with the contact of the same foot (Okunlodayk, 2018).

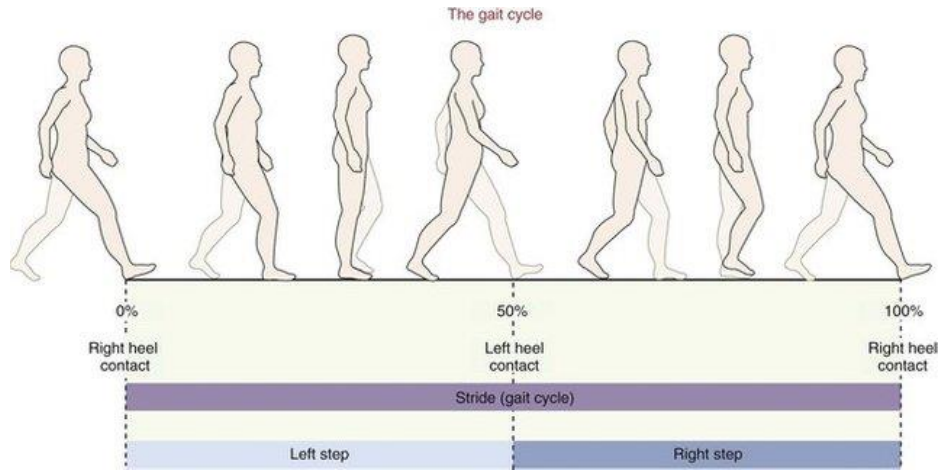


Figure 5. Human Gait. (Okunlodayk, 2018)

As it is shown in Figure 5 step and stride are not the same, in fact two steps are equal to only one stride. Step is the contact against the floor independently of the foot and gait cycle only takes into account the same foot.

Knowing the stride meaning, it is possible to explain better the walking speed term. It relates the stride length and the time that it takes (Equation 1). Each person has his own one, due to not only the anatomic aspects, but also the environmental ones.

$$Speed (m/s) = \frac{Distance (m)}{Time(s)}$$

Equation 1. Walking speed (Kirtley, 2006).

From walking speed equation, another parameter is defined, cadence. It represents the number of steps that a subject makes in a minute and in many studies it is represented by strides number per second (Equation 2).

$$Cadence = \frac{N^{\circ} Steps}{1 \text{ min}} = \frac{N^{\circ} Strides * 2}{60 \text{ secs}}$$

Equation 2. Cadence (Kirtley, 2006).

Finally, the stride length is calculated by means of equation 1 and the time between two strides, obtaining the next equation (Equation 3):

$$Stride \text{ length}(m) = Speed \left( \frac{m}{s} \right) * Stride \text{ time}(s)$$

Equation 3. Stride length (Kirtley, 2006).

## 2 MATERIAL AND METHODS

### 2.1 MATERIALS

Along this project several components have been used not only to measure the signal that the pressure sensors provide, but also to filter and process it. Some of them have been selected following different datasheets indications and others have been selected after many tests.

#### 2.1.1 FLEXIFORCE A301

In first tests 'Flexiforce A201' was used, but despite their characteristics (Tekscan, FlexiForce Standard Model A201, 2019) being the same as the 'FlexiForce A301' regarding the weight that both can bear, it was finally discarded due to having pins. Although in some applications its use could be interesting, it was considered that these long pins could be uncomfortable for the subjects (Figure 6), and in this study the subjects' comfort is primordial.

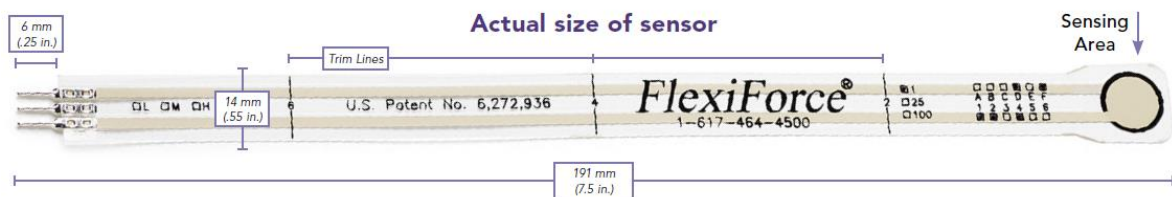


Figure 6. Flexiforce A201 (Tekscan, FlexiForce Standard Model A201, 2019)

'Flexiforce A301' (Figure 7) has a sensing area of 9.53mm diameter, which means 71.33mm<sup>2</sup>, and a thickness of 0.203mm. It works on a principle of piezo resistivity, meaning that its resistance changes when the semiconductors materials are submitted to different stress. As they have different resistances the output voltage also changes, allowing to measure weight or pressure changes (Romero, 1993). In each case, it is important to know the relationship between the weight and the output voltage which will depend on two factors: the input voltage and the values of the active low pass filter that Tekscan recommends implementing. Both will be explained further on.

In particular, this sensor was selected due to its brief time of response (5μs), which makes possible to measure instantly the pressure in each sensor. In addition, it can measure up to 445N, which means that its response will be lineal until approximately 45kg where it would be saturated. It is important to consider that the maximum recommended current is 2.5mA, so some modifications in the circuit were needed (Tekscan, FlexiForce Standard Model A301, 2019).

## Actual size of sensor

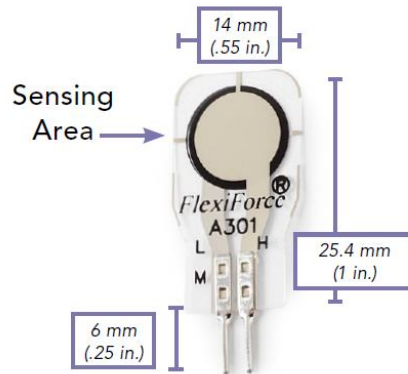


Figure 7. Flexiforce A301 (Tekscan, FlexiForce Standard Model A301, 2019). Pressure sensor used in the project

### 2.1.2 ARDUINO MEGA 2560

At the beginning 'Arduino Bq Zum' (Arduino Uno) was used to design the first parts of the circuit, but in the end, it was changed because the Bluetooth device could not connect with this board. Finally, Arduino Mega 2560 was implemented (Figure 8).

Arduino Mega was selected because apart from Bluetooth connection, it presents different characteristics. On one hand 'Arduino Uno' is a microcontroller based on ATmega328, having fourteen digital input/output pins and only six analogue input. In this case as five sensors have been used it was not so significative, but in the future, it could be useful to add more sensors and that would require more analogue inputs. On the other hand, 'Arduino Mega 2560' is a microcontroller board based on ATmega2560, which is more robust. It has fifty-four digital input/output pins and sixteen analogue pins.

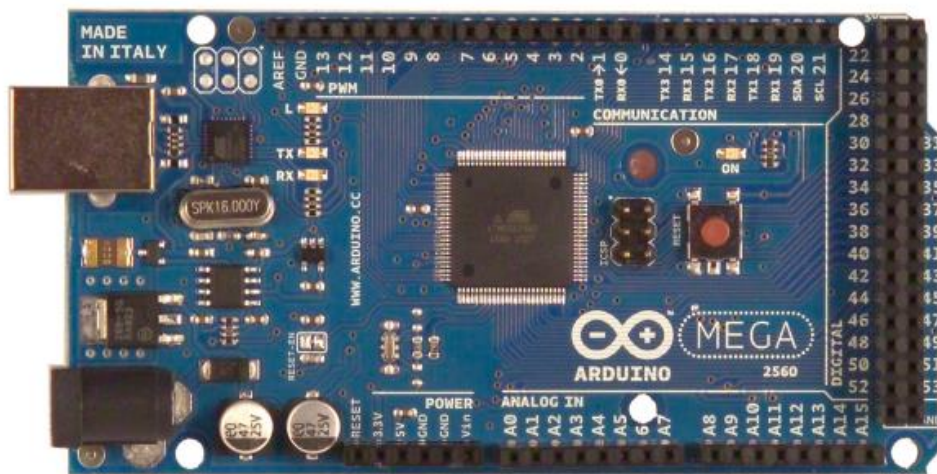


Figure 8. Arduino Mega 2560 (ecrobotics, n.d.). Arduino board used in the project.

Regarding the rest of particularities, they are quite similar, as both of them have a power jack, an ICSP header, USB connection, a 16MHz resonator (clock speed) and a reset button. About electronic characteristics, they define the ones of the circuit. Arduino Mega works with an operating voltage of 5V, meanwhile it needs an input voltage between seven and twelve voltage to work, being in this case supplied by a battery of nine voltage which ensures the wireless condition. Moreover, their analogue pins generate a current of 40mA, so it was necessary to add a buffer to reduce the current in the circuit. Serial pins zero and one have been used as RX and TX, in order to control the data sent by the Bluetooth device.

### 2.1.3 TLC272

This component is an operational amplifier which combines a wide range of input offset voltages with low offset voltage and it also offers a high input impedance generating insignificant noise in most applications (Instrument, 2002). This last point is the main reason why it has been selected.

This operational amplifier has been used as a buffer or 'Op-Amp Follower', which means that it does not make any change in the voltage, but it decreases the circuit current, because the one generated by the 5V Arduino pin is extremely high to supply the pressure sensor. It has been connected as non-inverting amplifier, where non gain is required, in order to avoid changing the circuit voltage. This fact is shown in the next scheme (Figure 9).

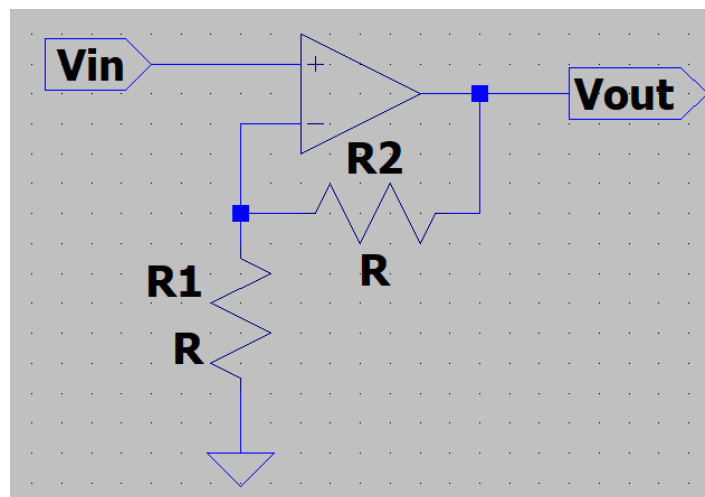


Figure 9. Buffer follower schema with gain

$$Gain = 1 + (R2/R1)$$

Equation 4. Buffer follower gain

With the purpose of avoiding the change in the voltage and following 'Equation 4', R1 and R2 have been deleted, changing R2 by a plain wire, which has effectively zero resistance. Furthermore, as R1 it is not connected to ground at all, it has infinite resistor (Figure 10). In



accordance with TLC272 datasheet, it has a huge input impedance (ideally it could be supposed as infinite) and a very low output impedance, avoiding introducing high currents into the circuit (Terrell, 1996).

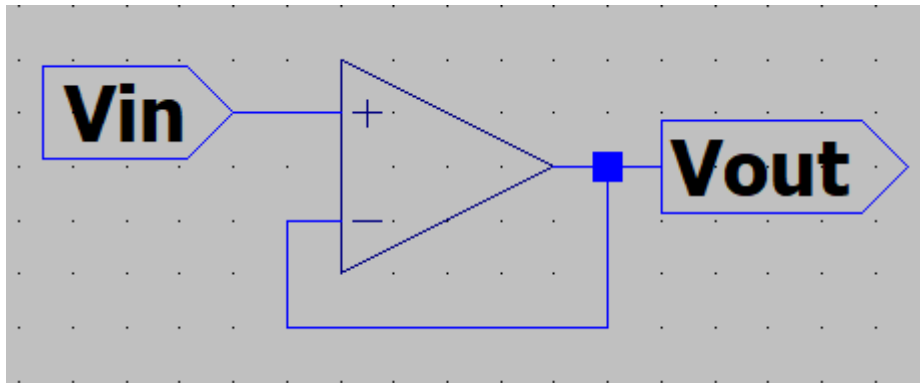


Figure 10. Buffer scheme used in the designed circuit. It has not resistances, because no gain is desired.

Regarding their characteristics it has eight pins, therefore two operational amplifiers can be used, and it has to be fed with 5V and the last pin is linked directly to ground. Summarising, at the end of this component, there are almost about 5V and a practically negligible current.

### 2.1.4 TC7660

According to 'Flexiforce A301' datasheet (Tekscan, FlexiForce Standard Model A301, 2019), it has to be supplied with a negative voltage in order to get a positive output voltage. That is the reason why TC7660 (Figure 11) has been added (Technology, 2012).

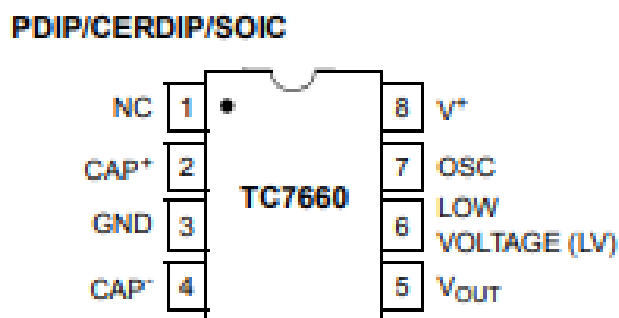


Figure 11. TC7660 pins connection (Technology, 2012)

TC7660 is a charge pump DC to DC voltage converter, it means that it receives an input voltage and it supplies the same voltage (it is not the same voltage because there are some losses as in every electronic component) but with the opposite sign. It has an input voltage range between 1.5 and 10V so it can be connected to 5V Arduino pin without any problem.

Furthermore, it eliminates inductors and their associated cost, size and electromagnetic interference.

As the component datasheet indicates, it has been necessary to introduce two capacitors of  $10\mu\text{F}$  each one. The first one is placed between  $\text{CAP}^+$  and  $\text{CAP}^-$  (pins two and four) and the other is located between the voltage output and the ground, acting both as a decoupling capacitor to reduce voltage fluctuations and maintain power and signal integrity (Fang, 2001). In addition, pin six has not been associated because the voltage supply is bigger than  $3.5\text{V}$ . So, the final connection is the next one:

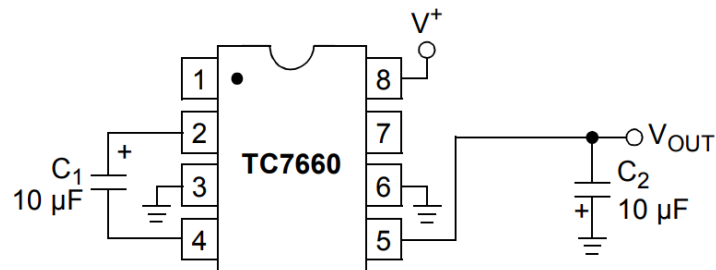


Figure 12. TC7660 connection implemented in the circuit (Technology, 2012)

Pin one is not connected, meanwhile pin eight represents the power supply positive voltage input, which is linked with TLC272 pin 1 (voltage output). Finally, pin seven is an oscillator control input whose value could be changed to optimize the system performance, but it has been considered that this change was not worth it, as it already works properly. To sum up, ideally, at the end of this component the voltage has a value of  $-5\text{V}$ .

### 2.1.5 MCP6004

This component was selected because it is the one recommended to implement the pressure sensor by Tekscan. The microchip belongs to family MCP600 and being more specific it has fourteen pins (Figure 13). It is integrated by four operational amplifiers, allowing the connection of four sensors at the same time, which was considered as a notable benefit of this component against other operational amplifiers.

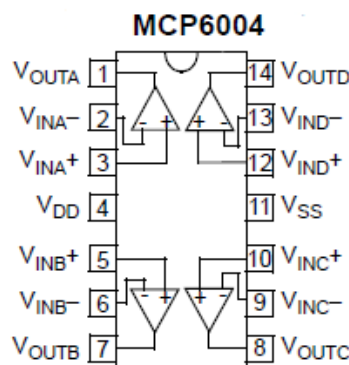


Figure 13. MCP6004

Other important advantage that it presents is its supply, being able to be fed at 5V, the same as all the components on the circuit, making easier its implementation. Its connection is not complicated, following the scheme provided by Tekscan (Figure 12).

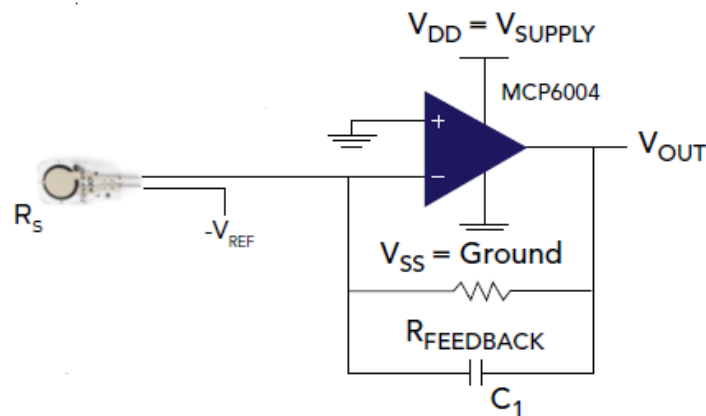


Figure 14. MCP connection (Tekscan, FlexiForce Standard Model A301, 2019)

Each  $V_{IN^-}$  is connected to pin H of 'FlexiForce A301', meanwhile each  $V_{IN^+}$  is linked directly to ground,  $V_{OUT}$  represents the Voltage output that every operational amplifier generates. Regarding to  $R_{FEEDBACK}$  and  $C_1$  they will be explained further on. At last, pin four is connected to 5V supplying the operational amplifiers and pin eleven is connected to ground.

Every  $V_{OUT}$  is linked directly with one Arduino analogue input, including from A0 to A4 (5 sensors), hence two MCP6004 have been required, however only one operational amplifier of MCP6004 has been used, so more sensors (three more) could be included if necessary.

## 2.2 VOLTAGE DIVIDER

This part of the circuit is not considered a component as such, because it is formed by only two resistances, being able to decrease the voltage of a circuit. In this specific case, the voltage divider (Figure 15) is located between the TC7600 and the sensor.

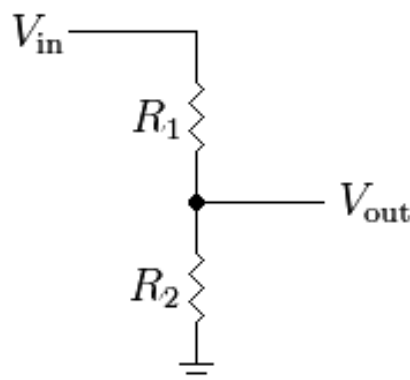


Figure 15. Voltage divider scheme

As previously mentioned (2.1.4), at the end of TC7600 the obtained voltage must be around -5V. Nevertheless, being more specific, after two electrical components and their losses the measured voltage is around -3.4V. According to the sensor specifications, it must be supplied with a voltage between 0.25 and 1.25V, so an extra voltage decrease was required. After many tests it was decided to obtain a  $V_{out}$  of approximately -1V, making the calculations easier and achieving results like the ones in Mary Josephine Hessert's study. At this point and knowing the voltage input and output the values of  $R_1$  and  $R_2$  were calculated by means of Equation 5.

$$V_{out} = \frac{R_2}{R_1 + R_2} * V_{in}$$

$$-1V = \frac{R_2}{R_1 + R_2} * -3.4V$$

Equation 5. Voltage divider

There are two variables but only one equation, so it was necessary to give a fix value to one of them, calculating the other.  $R_2$  was introduced as  $1K\Omega$ , having in this way a value of  $2.4K\Omega$  for  $R_1$ .

## 2.3 ACTIVE LOW PASS FILTER

The filter is also not a component of the circuit because it only includes one resistance and one capacitor in each case (one per sensor), although it is true that the sensor and the operational amplifiers that are inside of the MCP6004 could be considered as a part of the filter.

An active low pass filter is used to mitigate the high frequencies of the signal components, allowing to pass only the low frequencies. It is usually compounded by four to five components as Figure 16 indicates. In some cases, other resistances could be added between  $V^+$  and ground, but not in this case (Niewiandowski, 1989).

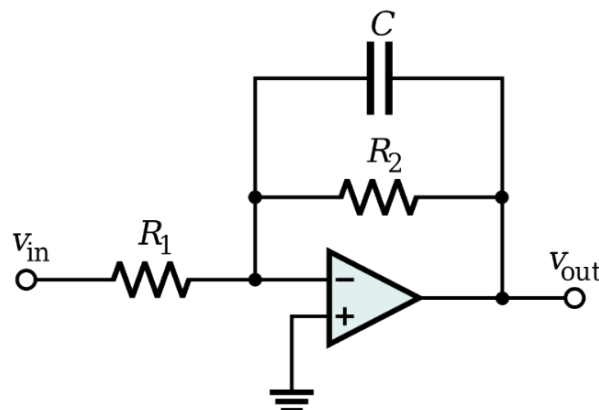


Figure 16. Active low pass filter (Inductiveload, 2008).  $R_1$  is the pressure sensor.

Comparing Figure 14 and Figure 16 it is possible to observe that the pressure sensor has been installed instead of R1. They both have the same purpose, but the sensor, is able to change its impedance. The value of the capacitor is the one recommended by Tekscan (47pF). Despite it is suggested to install a potentiometer to change the resistance value of R2 (Tekscan, FlexiForce Standard Model A301, 2019), it was decided to connect a fix value so that the filter answer remains the same.

Different resistances values of R2 were assayed in order to calibrate the sensor and to know the relationship between the force applied and its response. At the beginning of the test there were three variables:  $V_{in}$ , R2 and the pressure. The first one was fixed to -1V, so some tests were made with the last two variables, obtaining the next results:

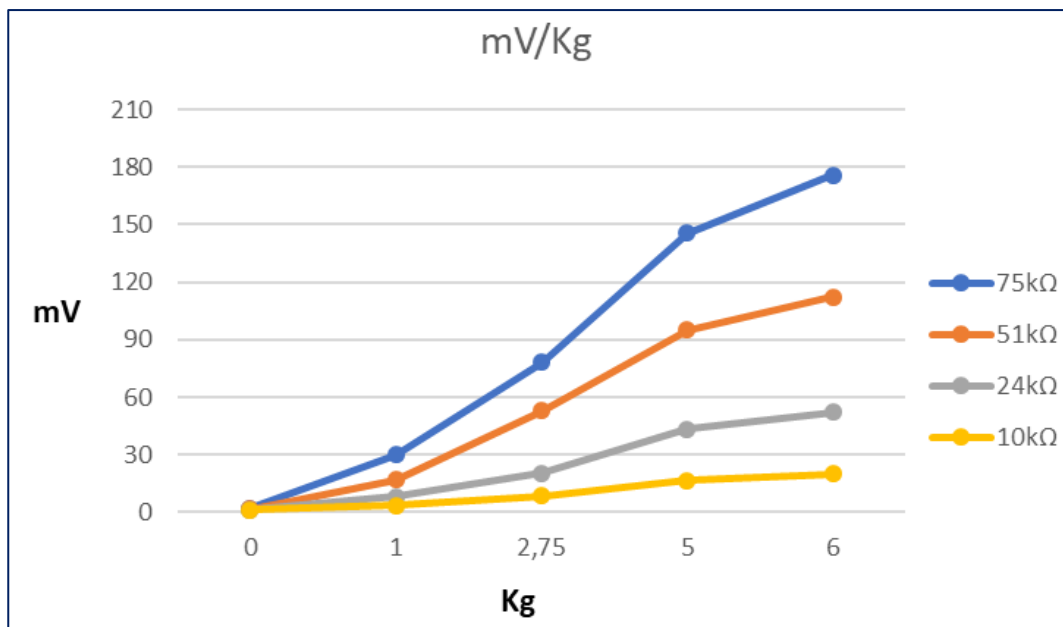


Figure 17. Relationship between mV and kg. 'x' axis makes references to weight [kg], meanwhile 'y' axis refers to V output measured [mV] Each line represents a study with a different resistance value.

As it is shown in Figure 17, four R2 different values were tested, and as it was expected the bigger the value of the resistance, the higher  $V_{OUT}$ . For this reason,  $R2=75k\Omega$  was selected. Although it is not perfectly linear, it is possible to see an increase about 30mV per kg.

## 2.4 CIRCUIT

Once all the parts of the circuit and their order inside the circuit have been described, it is possible to draw a schema (Figure 18).

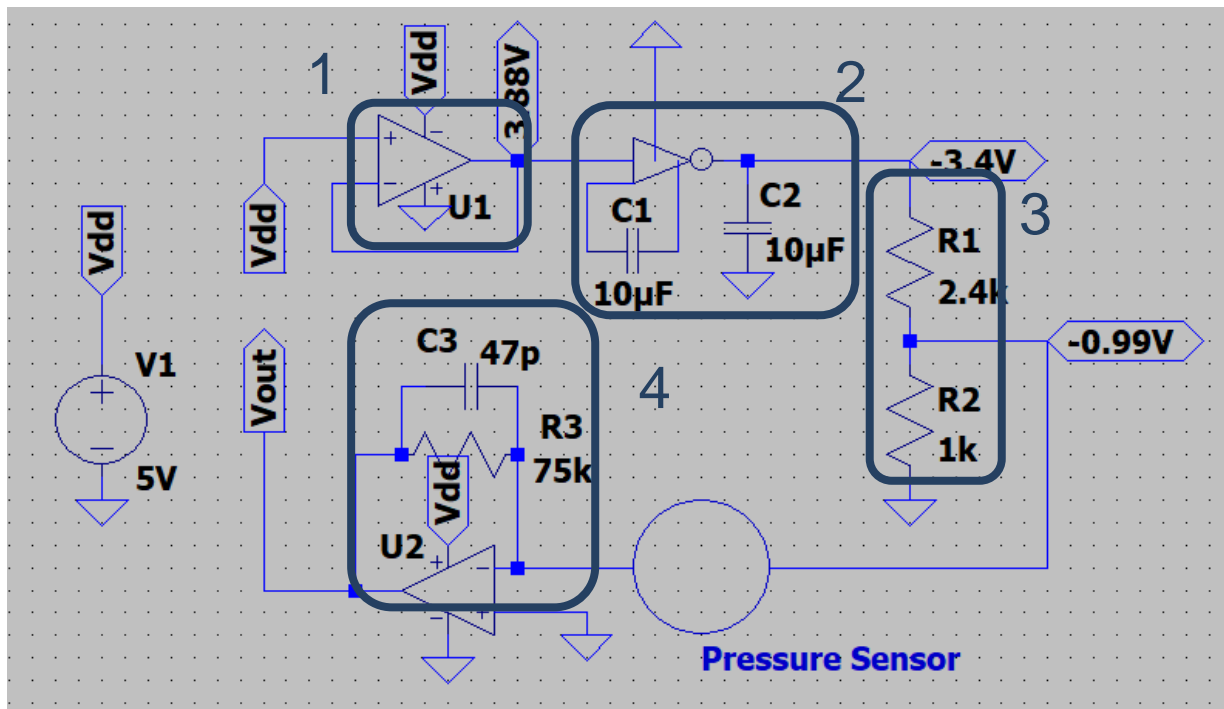


Figure 18. Circuit schema developed. Only one sensor is drawn. Vdd is directly connected to 5V, and the ground is common in the whole circuit. Point one, refers to buffer follower (2.1.3), square two refers to TC7660, point three is the voltage divider. Finally, point four shown the connection between MCP6004 and the pressure sensor.

As it is noticed, this is a simplified schema. where only one sensor is connected (Figure 18). Can be seen also the measured voltages in each point, being significant the voltage drops after the first component (approximately a 25% of the original voltage). After that, the values are as expected, a little voltage drops after TC7660 (0.48V), which means a loss of 12,37% and -0.99V after the voltage divider, since it was designed to obtain this value. It should be mentioned that every sensor is implemented to the same point (-0.99V), therefore the designed circuit until the voltage divider is common to all the sensors, making its design easy.

The circuit was designed with the help of 'BlackBoard' application, adapting it at the board provided, which has a size of 25x18 holes. Then the different components have been placed, as it is shown in Figure 19. Numbers and boxes in this figure are referred to the ones in Figure 18. In addition, in this figure there is a socket, which makes reference to the position where the Bluetooth device (analysed in 2.6) is located.

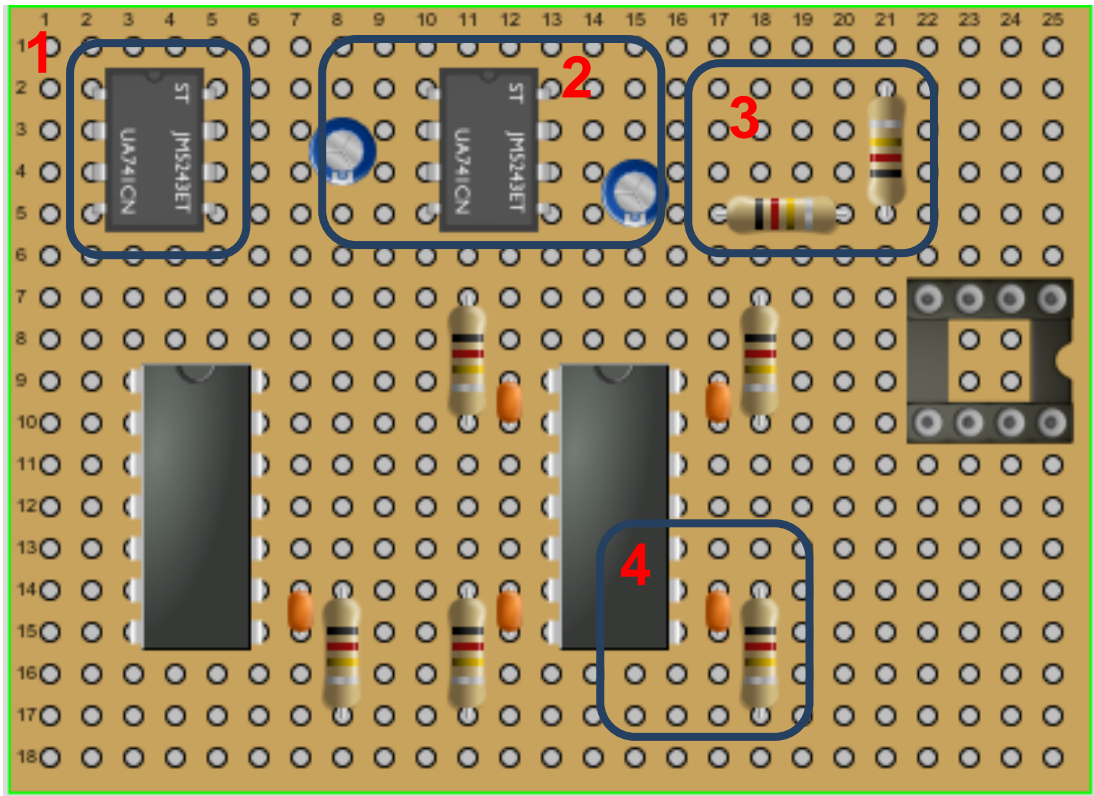


Figure 19. Designed circuit distribution in the board provided. Resistances have different values, which are in square three have: 2.4kΩ and 1kΩ (the vertical one). The rest of resistances have a value about 75kΩ. Component located in square 1 is TLC272 and component next to two is TC7660.

## 2.5 SENSOR CALIBRATION

In concordance with Tekscan datasheet (Tekscan, FlexiForce Standard Model A301, 2019), there are three variables generated by each sensor that are influencing  $V_{OUT}$ , in particular:  $V_{IN}$ , pressure made and R3 value (Figure 18). The purpose was to receive the highest value of  $V_{OUT}$  with the intention to measure it properly and efficiently, thus two alternatives are proposed by Tekscan, increase  $V_{IN}$  (its absolute value) and increase also R3. Initially R3 was a potentiometer but it was decided to introduce a fix value.

$V_{IN}$  was adjusted to -1V, as it must be between 0.25 and 1.25, and it was considered an appropriate value which would make easier the calculation and selection of the components. Further on, the same schema as in Figure 18 was designed to test and calibrate the sensors. Different weights about 0.5, 1, 1.25 and 5kg were provided allowing this process. It is considered that the calibration and measurements had not been made ideal, because of the different sizes between the pressure sensor and the weight, as it is shown in Figure 20.

Different tests were made obtaining the data represented in Figure 17, which are the ones shown in Table 1. To carry out these tests the circuit explain in Figure 18 was implemented, allowing to measure the voltage output that different weight generated. It was supposed that every sensor has the same behaviour against the same weight.

Table 1. Sensor calibration values obtained in the circuit with different weights

<b>R3 (kΩ)</b>	<b>10</b>					<b>24</b>				
<b>kg</b>	0	1	2.75	5	6	0	1	2.75	5	6
<b>Vout (mV)</b>	1.3	3.4	8.5	16.7	20	1.4	8.2	20.3	43.3	52.2
<b>Relationship (mV/kg)</b>		<b>3.40</b>	<b>3.09</b>	<b>3.34</b>	<b>3.33</b>		<b>8.20</b>	<b>7.38</b>	<b>8.66</b>	<b>8.70</b>
<b>R3 (kΩ)</b>	<b>51</b>					<b>75</b>				
<b>kg</b>	0	1	2.75	5	6	0	1	2.75	5	6
<b>Vout (mV)</b>	1.8	16.8	52.8	95.2	112.1	2.1	29.9	78	145.7	175.9
<b>Relationship (mV/kg)</b>		<b>16.80</b>	<b>19.20</b>	<b>19.04</b>	<b>18.68</b>		<b>29.90</b>	<b>28.36</b>	<b>29.14</b>	<b>29.32</b>

Table 2. Descriptive statistics about relationship between mV/kg measured in the experiment. Standard deviation indicates the data dispersion, the higher, the more dispersion

Variable	Mean	StDev	Minimum	Median	Maximum
10k	3.2911	0.1368	3.0909	3.3367	3.4
24k	8.235	0.613	7.382	8.43	8.7
51k	18.431	1.108	16.8	18.862	19.2
75k	29.18	0.634	28.364	29.228	29.9

Considering results of Table 2, where the values were bigger as the resistance was increasing, it was decided to select the higher one. As it is possible to observe, the mean is pretty close to 30mV/kg and notwithstanding their high results in comparison with the other resistances, the standard deviation and variance have small values (Figure 21), where the box diagram is the best distributed. Due to this last fact it is believed that the answer will be more linear and stable (Atanasio, 2015).

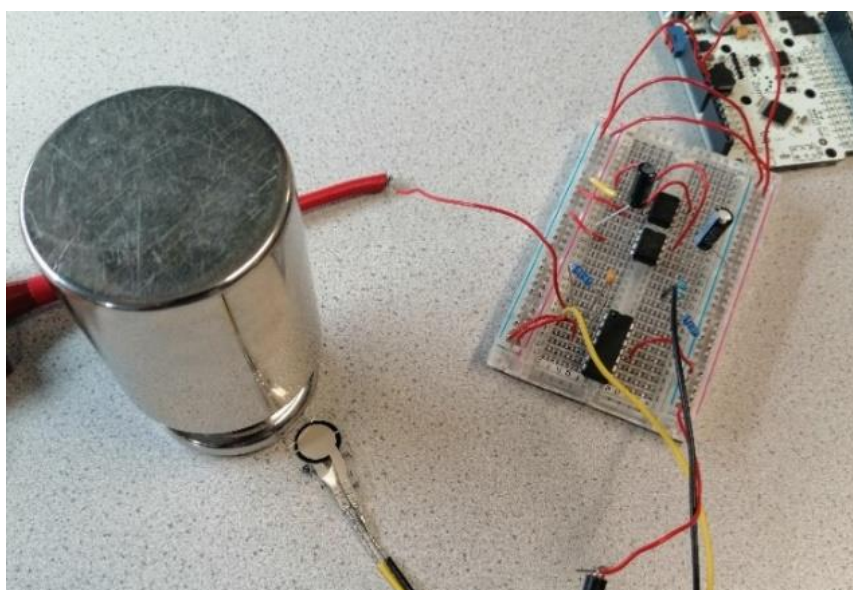


Figure 20. Calibration circuit (it is the same that is shown in Figure 18) and weight (1kg). To carry out this test, it was used an Arduino Uno as shown in the figure. The circuit was implemented in a protoboard.



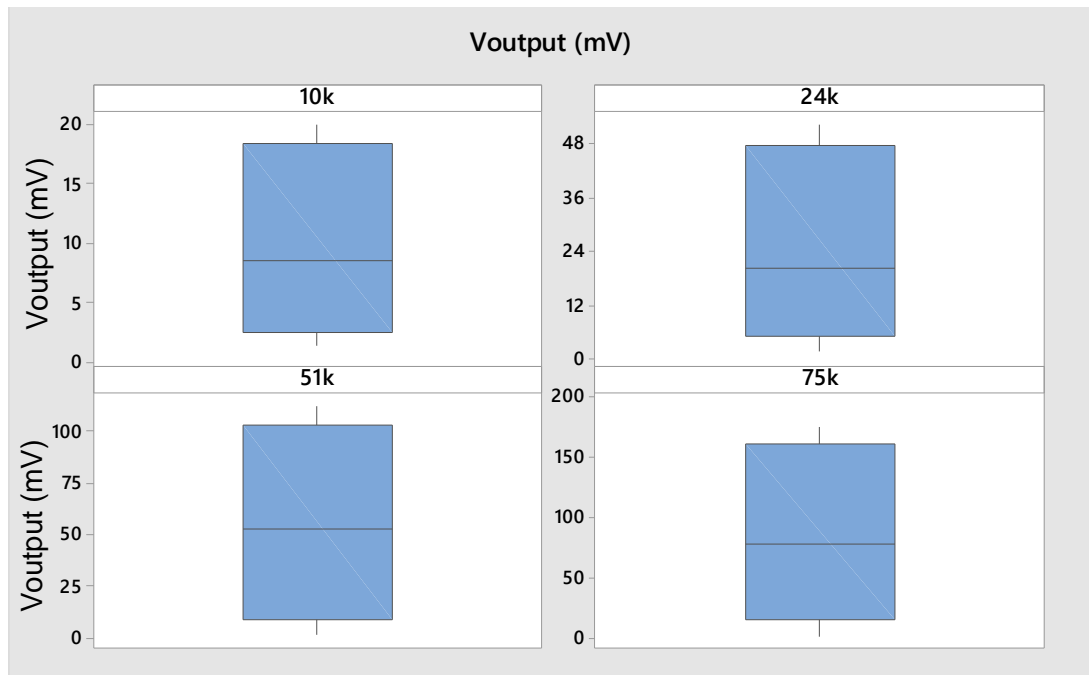


Figure 21. Comparison between mV/kg relationships. Each boxplot represents data recorded distribution in the experiment, where the 'y' axis is referred to voltage output in mV.

## 2.6 BLUETOOTH DEVICE

'HC-05' Bluetooth device has been selected due to the amount of information and libraries that it has on internet, making its programming and setting easy.

This component has six pins as it is shown in Figure 22, although only the four pins in the middle have been used.  $V_{cc}$  has been directly connected to 5V Arduino pin, because as HC-05 datasheet indicates it must be supplied with a power between 3.3 and 6V to make it work. GND is linked to the common ground of the circuit. Regarding TXD and RXD, which allow the Bluetooth communication, they have been wired with RXD and TXD Arduino pins respectively. TXD is the pin where the data are sent so it must be linked with the Arduino pin in charge to receive the data, which is RXD. The union between RXD Bluetooth device and TXD Arduino follows the same explanation.

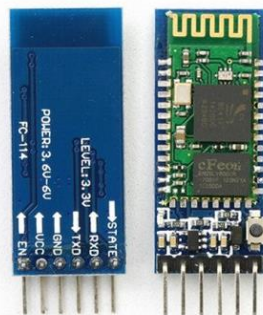


Figure 22. Bluetooth device 'HC-05' (MyTechTools, n.d.) used to connect 'Arduino 2560' and the computer

## 2.7 CASE

The necessity to develop a device which allows to measure the pressure along the gait and minimises the external factors that could suppose a modification in the subject's usual tread was primordial. Not only was the best sensor and wire distribution sought, as it is shown in Figure 26, but also a case where the designed circuit and the 'Arduino' board could be hosted during the steps was needed. It was thought that the best place to locate it would be the gastrocnemius muscle, as other similar applications have already done, such as the one of 'Tekscan'.

The case was designed with 'Autodesk Inventor' program and then printed in a 3D printer. It is composed by three different parts (Figure 23) and the measures have been adapted to the Arduino board as it is the biggest component. In addition, it was decided to include an extra space in order to introduce the battery there, so that the device could be 100% wireless. Two auxiliary parts were included as it is shown in the middle of the figure, in order to fix it to the leg via a 'Velcro' strip.

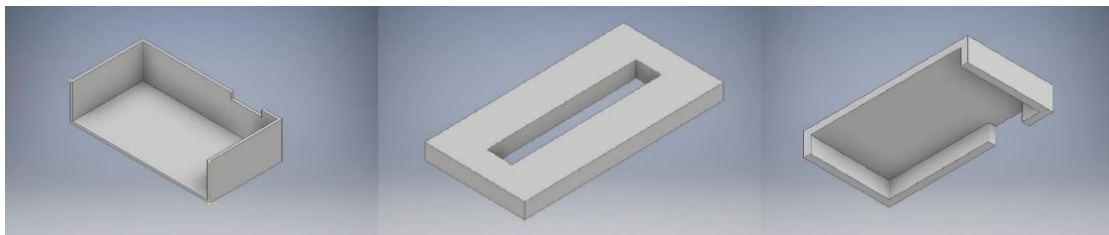


Figure 23. Case parts designed to hold the circuit developed

In Figure 23 can be seen the upper and lower part have a hollow which is used for the passage of wires from the device to the insole. Its final shape is shown in Figure 24.

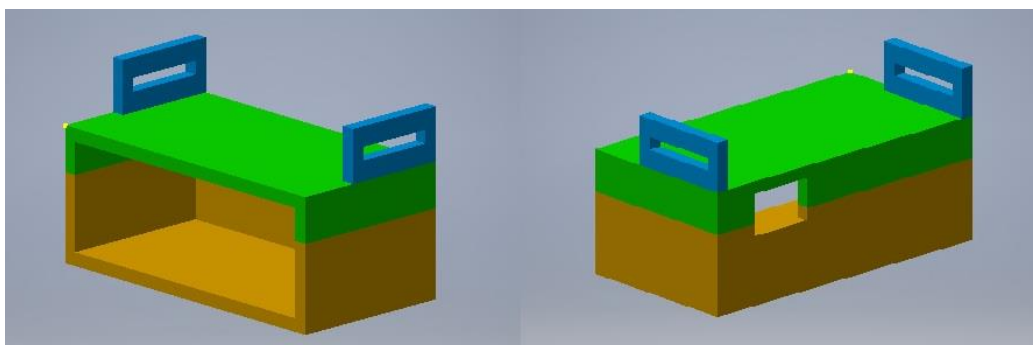


Figure 24. Case final shape

## 2.8 SOFTWARE

The signal introduced in the circuit by the Arduino board is processed and introduced again on it by its analogue pins, where the  $V_{OUT}$  generated by the pressure sensors are sent.

## 2.8.1 BLUETOOTH DEVICE CONFIGURATION

The first program was developed due to the requirement to configure the Bluetooth device before establishing the communication between it and the computer. It was selected due to the libraries and information found on internet.

In this way, it was important to know that it has four possible states such as: disconnected, connected, state AT1 and state AT2. Throughout the project, the second state (connected) has been used most of the time allow to the data transmission between the device (slave) and the computer (master), meanwhile AT states have been used only to configure it (Naylampmechatronics, 2016).

The program includes the 'Softwareserial' library at the beginning, and then it defines the pins that are going to work as RX (received data) and TX (sent data). Secondly, the loop is continuously reading the information received by the RX pin and in case a value is detected, it is saved.

After that, it was possible to check and change the values of different parameters like the name of the device, its password, the role that it is going to have (slave or master) and its communication speed, among others. Finally, the connection with the computer Bluetooth was done, allowing the data exchange.

## 2.8.2 SENSOR LOCATIONS

Initially the intention was to find some research with an extent library about different pedobarographies recorded on different subjects, in order to analyse the common points where the pressure is usually stronger from the colors differences. As the research did not give back any result, it was decided to process some pedobarography images and then compare the results with different studies (Mary Josephine Hessert, 2005) (Vidya K. Nandikolla, 2017).



Figure 25. Analysed pedobarography picture (Medicapteurs, n.d.). First image is the original, second image represents the first dimension of the first one (R, G, B), the third is the negative of the second but softened and the last is the filtered where edges can be seen.

To develop this program a pedobarography picture was selected (Medicaptureurs, n.d.) and it was processed, obtaining the results shown in Figure 25. The first image used represents the pressure distribution, where the red color indicates highest pressure and blue the lowest pressure, being yellow and green middle values. The real value of the pressure in this case is unknown since it is only interested in knowing the color contrast between different points. In Figure 25, it is possible to differentiate four illustrations. The one on the left is the original picture, which has been modified deleting its colours and transforming into an image where the pixels are only expressed in values between 0 and 1, where 0 is white and 1 is black. Then a gaussian filter has been applied to soft the image and finally using 'edge' MATLAB command the edges have been found. The method followed is 'Canny', which allows to locate sharp intensity changes and to find object boundaries in an image. Canny method classifies a pixel as an edge if the gradient magnitude of the pixel is larger than those of pixels at both its sides in the direction of maximum intensity change (Goshtasby, 2001). Matching with the results in the studies before mentioned (Mary Josephine Hessert, 2005) (Vidya K. Nandikolla, 2017), as it is possible to see in the last picture of Figure 25, there are four remarkable points where the pressure is supposed to be greater. These points are: first distal phalanx, the joint between second distal phalanx and second proximal phalanx, the joint between first distal phalanx and first proximal phalanx and the calcaneus. In accordance with the data obtained, the sensors were placed in the insole as it is possible to observe in Figure 26. The picture was scaled and the distances between the points were measured in order to set them properly. Finally, the coordinates were introduced in MATLAB to develop future codes.



Figure 26. Sensor distribution along the insole

### 2.8.3 VOLTAGE OUTPUT READING

Before processing the data generated by the sensor in MATLAB, it was required to introduce a program in the 'Arduino' board to get these values.

At first, five variables were defined one per each  $V_{OUT}$  which have been considered as 'int' variables. In contrast, other variable was defined referring to the time, but in this case, it was declared as 'float'. These differences were made because voltage values are going to be always between 0 and 1023 (10 bits) as Figure 27 indicates, meanwhile time variable could be longer than 32767 seconds (the maximum value of an int variable).

BOARD	OPERATING VOLTAGE	USABLE PINS	MAX RESOLUTION
Uno	5 Volts	A0 to A5	10 bits
Mini, Nano	5 Volts	A0 to A7	10 bits
Mega, Mega2560, MegaADK	5 Volts	A0 to A14	10 bits

Figure 27. Arduino resolution differences

After that, the values were read with the 'Arduino' command 'analogRead', which allows to read the analogue values that the analogue pin is receiving. At this point it is important to take into account that the values need to be processed to get their real voltage values, so an equation is required (Equation 6).

$$V_{OUT} = AnalogRead \text{ (bits)} * \frac{5 \text{ (V)}}{1023 \text{ (bits)}} * 1000 \text{ (V} \rightarrow \text{mV)}$$

Equation 6. Bits to mV

These new values are also defined as float variables, because their values could be bigger. It was decided to introduce a wait time of 0.6 seconds, in order not to saturate the communication between 'Arduino' and MATLAB.

### 2.8.4 ARDUINO TO MATLAB

To communicate and receive the data generated after the code explained before (2.8.3), it was necessary to understand how MATLAB creates and works with the Bluetooth channels and to install 'Arduino Hardware MATLAB Support Package'.

The first step was to create the 'Bluetooth object' through the command 'Bluetooth'. It allows to associate the object with the name of the device, in this case 'HC-05', and to select the channel where the data are going to be transferred. In this respect, it has been decided to use channel 1.

Once the object was created, it was required to find other MATLAB commands to control it.

- 'fopen' and 'fclose' control the aperture of the object allowing to share information with the Bluetooth device.
- 'instrfind' is used to know the open channels, which is very useful in case the communication cannot be made.
- 'instrreset' deletes every channel.
- 'fscanf'. This last command is in charge of reading the data received once the channel is opened. As the data sent, are float variables it is necessary to specify its format introducing a '%f'.

It has been considered to add an 'instrreset' at the end of every code, to avoid the saturation of the port where it sends the information.

## 2.8.5 VOLTAGE READING

As the voltage reading is a process that it is going to be continuously repeated, it has been decided to create a function to call in every loop of the main program.

This function is only executed when the Bluetooth object status is opened, and it reads the information sent by the Bluetooth device using 'fscanf'. This information is sent in an array of six values: time, Sensor 1 (calcaneus), Sensor 2 (the joint between second distal phalanx and second proximal phalanx), Sensor 3 (distal phalanx), Sensor 4 (5th metatarsal) and Sensor 5 (the joint between first distal phalanx and first proximal phalanx). The time is divided between 1000, to have the value in seconds and then each voltage value is processed to know the real pressure value, following the next process:

$$\tau = \frac{F \text{ (N)}}{S \text{ (m}^2\text{)}} = \frac{m \text{ (kg)} * a \text{ (m/s}^2\text{)}}{S \text{ (m}^2\text{)}}$$

Equation 7. Pressure.

$$a = g = 9.80665 \text{ m/s}^2$$

Equation 8. Standard value of gravity on Earth. Defined by the International Bureau of Weights and Measures, under the International System of Units. (List, 1968).

If the value of the gravity acceleration is introduced in Equation 7 and knowing that the pressure surface is 71.33mm<sup>2</sup>, the result is a new equation (Equation 9).

$$\tau = \frac{m \text{ (kg)} * 9.80665 \text{ (m/s}^2\text{)}}{71.33 * 10^{-6} \text{ (m}^2\text{)}} = m \text{ (kg)} * 137482.82 \text{ Pa}$$

Equation 9. Pressure depending on kg.

At last, as it has been demonstrated in Equation 10, 1kg generates a voltage about 30mV approximately and if 1Kg generates a pressure of 137482.82Pa, it is possible to know the relationship between the received mV and the pressure that it implies.

$$\tau(1\text{kg}) = 137482,82 \text{ Pa}$$

$$30\text{mV} = 137482.82\text{Pa} \quad \longrightarrow \quad 1\text{mV} = 4852.7\text{Pa}$$

Equation 10. Relationship between mV and Pa

Accordingly, these values obtained in Equation 10 are multiplied for each voltage value read in the array received from the Bluetooth device, obtaining the final value that is going to be represented in the pedobarography map (Figure 28).

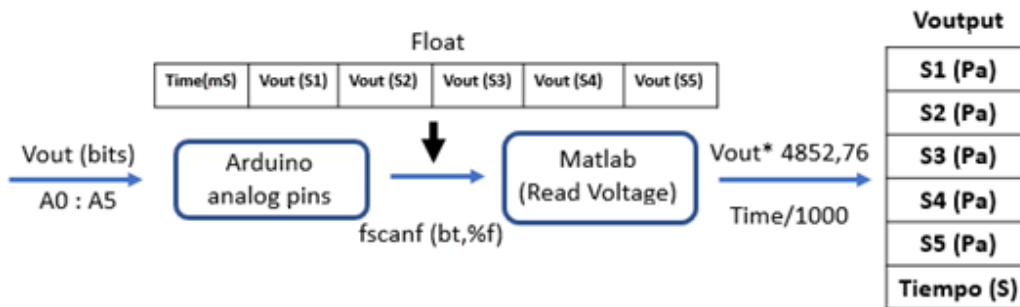


Figure 28. Voutput summary

## 2.8.6 PRESSURE POINTS SIMULATION

To generate the pedobarography map it was necessary to simulate the pressure obtained in the previous code giving a value to the coordinates previously fixed in 2.8.2. These coordinates are represented by a pixel in the image, which is not enough to draw a pedobarography map, since the pressure is not only applied in a pixel, it covers a larger area instead. At this point a supposition had been made. It does not affect the real results of the measurement, it was only made to improve the visualization and making it more real, trying to cover the whole foot area.

It has been supposed that each sensor measures an area about 6cm of diameter, taking into account that the maximum values registered along some tests are about 150mV or, in other units, 727914Pa, so it should be decreased 24236Pa/mm to get a null value in a 3cm radius. By means of the scale that have been used before to calculate each sensor coordinate, it is known that every pixel represents 0.317mm, so the next value is reached:

$$\frac{24236\text{Pa}}{\text{mm}} * \frac{0.317\text{mm}}{\text{pixel}} = 7691.62\text{Pa/pixel}$$

Equation 11. Relationship Pa/pixel

The function 'pressure points' has four input values; the image, to know its size; the length of the radius in pixels in case that it would be desired to change its area; the coordinates where the sensors are located and the pressure values. It starts providing to the sensors coordinates their respective values and then a loop of 95 iterations (95 pixels \* 0.0317cm = 3cm) is initiated. In every loop a circle of an increasing radius is calculated, and each pixel of its perimeter takes the pressure value, being -7691Pa (Equation 11), in each iteration. This process is repeated for every sensor, until the 95<sup>th</sup> iteration or until the null value is reached. Finally, these round matrices are located in the output image that this program generates, in Figure 29 an example it is shown.

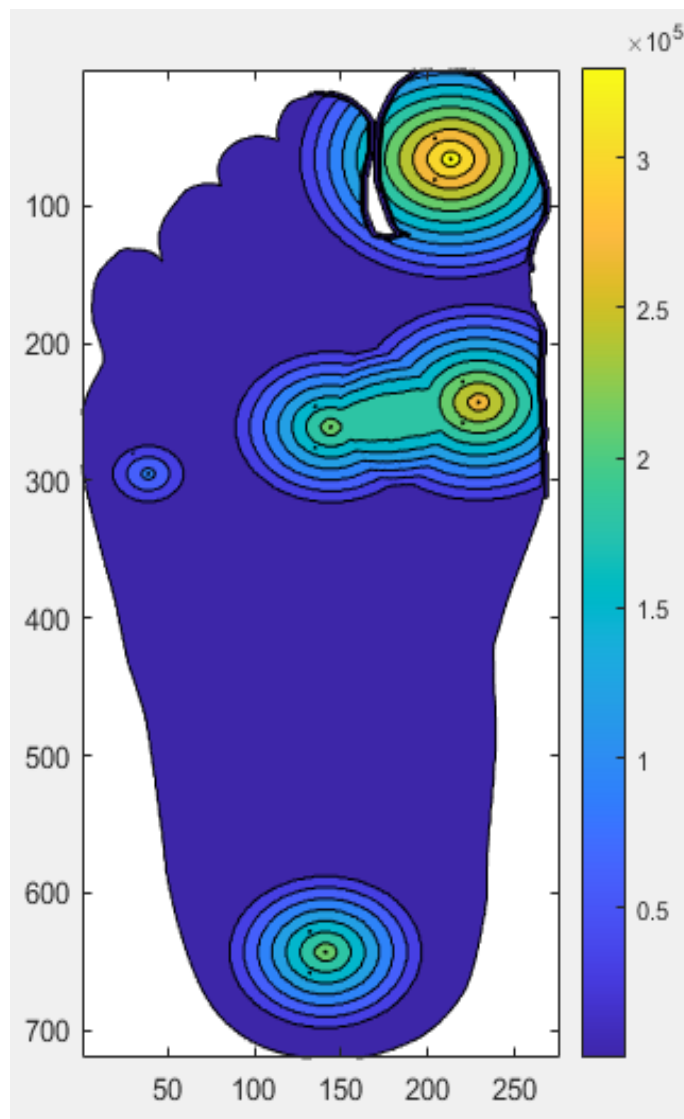


Figure 29. Pedobarography obtained (example). Scale is represented in Pa\*10<sup>5</sup>



## 2.8.7 MAIN PROGRAM

'AppDesigner' tool of MATLAB has been used in order to develop a graphic interface that facilitates the data reading, being more intuitive and easier to use. Its design is shown in Figure 30.

The designed application starts when the 'BT connection' button is pushed. At this moment, if there is an object occupying the data sending port, it is deleted. Then it creates a new Bluetooth object as it has been seen in Figure 31 and once this process has been finished a green lamp is switched on.

In continuity, 'left\_foot' image is uploaded pushing 'Load Image' button. After that, the program's main part is ready to start. 'START' button is clicked and the Bluetooth channel is opened, allowing the data reading by means of 'Voutput' function as it has been explained before (2.8.5). An array is created composed by the obtained pressure values, which are going to be introduced in 'Pressure\_Points' function, returning the image that is possible to see on the left of Figure 30. Finally, the pressure values are saved in individual arrays (one for each sensor) in order to show their progression along the time in the graphic once the 'Show results' button is pushed. This process is repeated continuously until 'STOP' option is selected, which causes the Bluetooth channel closure.

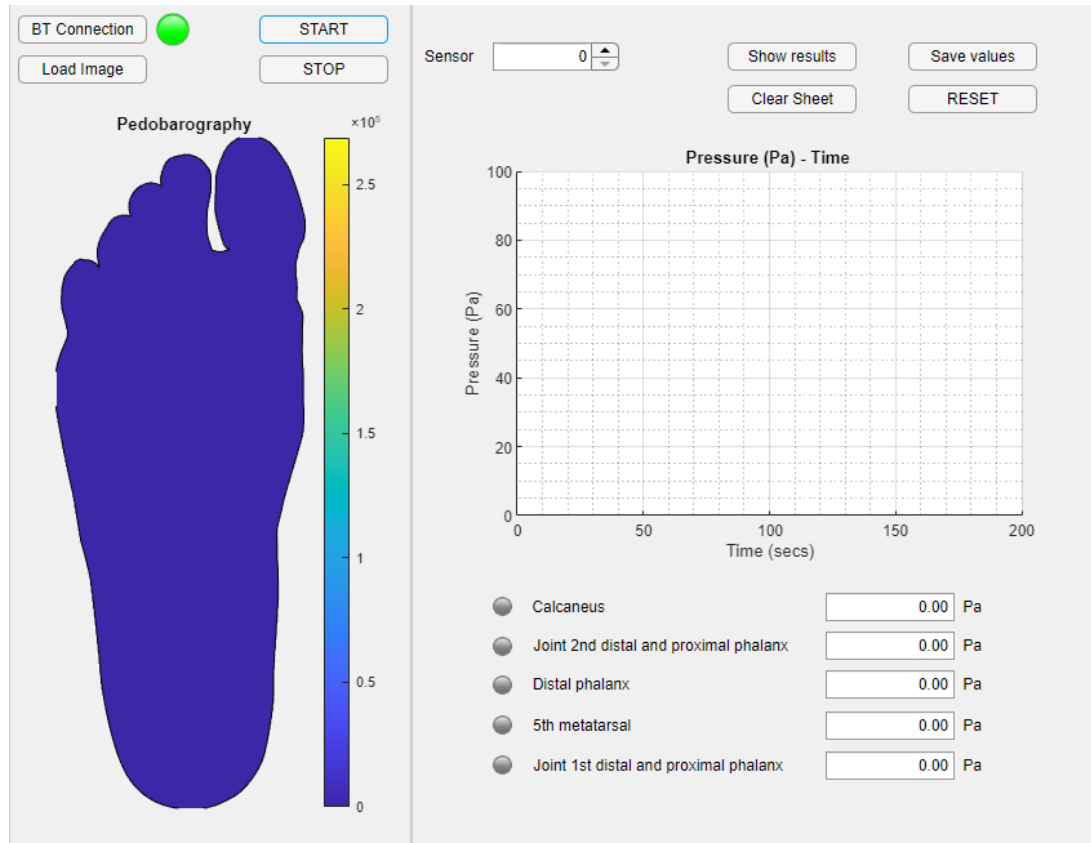


Figure 30. Pedobarography app designed in MATLAB AppDesigner. The foot image shown is the first image that the program shows before recording any pressure value

In addition, some details to make more useful the application have been added. For example, it is possible to save the values in a '.xlsx' document, clicking in 'Save values' button which allows to select the folder where they are going to be saved. Furthermore 5 numeric boxes have been included to see in real time the values that the pressure is taking and finally a 'RESET' button has been inserted to delete every variable, the foot image and the graphic.

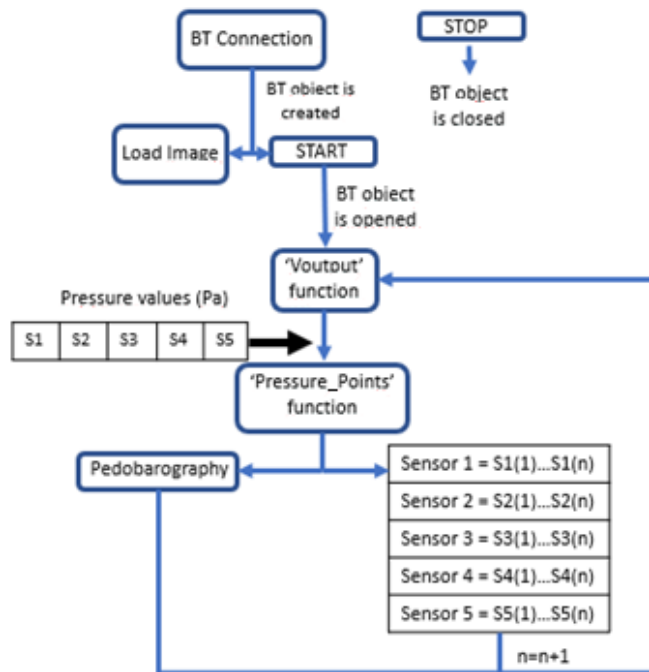


Figure 31. Main program summary developed in MATLAB. 'Voutput' and 'Pressure\_Points' are functions that are repeated every time in the loop. The values of Sensors 1 to 5, are saved in Pa.

### 3 RESULTS

Once the application has been designed and the insole and the circuit are ready to make measurements, different studies have been carried out (Figure 32). The same conditions in cases were the tests must be reproduced many times, in order to compare only the that the external factors had the lowest influences as possible. Furthermore, due to the project fragility (it is only a prototype), a non-compressive footwear has been chosen to avoid wires breakage or sensor movements; although it is true that some tests have been made with trainers (that are more compressive) and the pressure values were obviously greater.

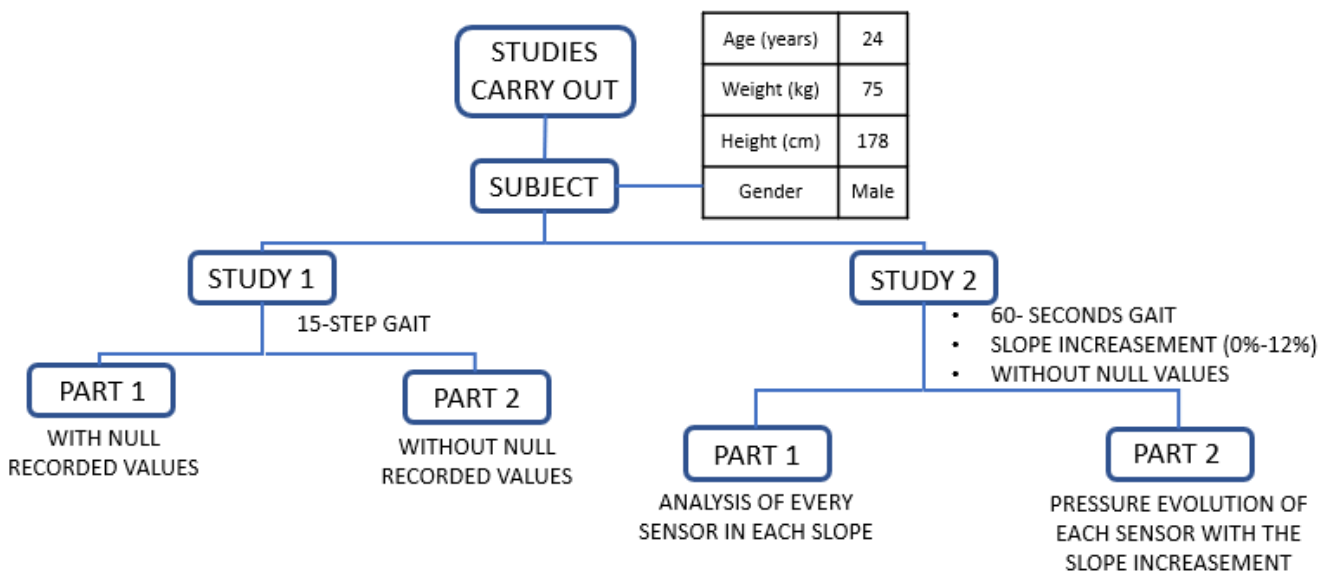


Figure 32. Two studies have been carried out and both have been analysed from two different points but with the same subject.

#### 3.1 STUDY N°1

For the first study a subject with the characteristics exposed in Table 3 has been selected. A 15 steps gait has been recorded in order to view the different pressures that he makes along them.

Table 3. Study 1. Subject characteristics, who has carried out the study.

Age (years)	Weight (kg)	Height (cm)	Gender
24	75	178	M

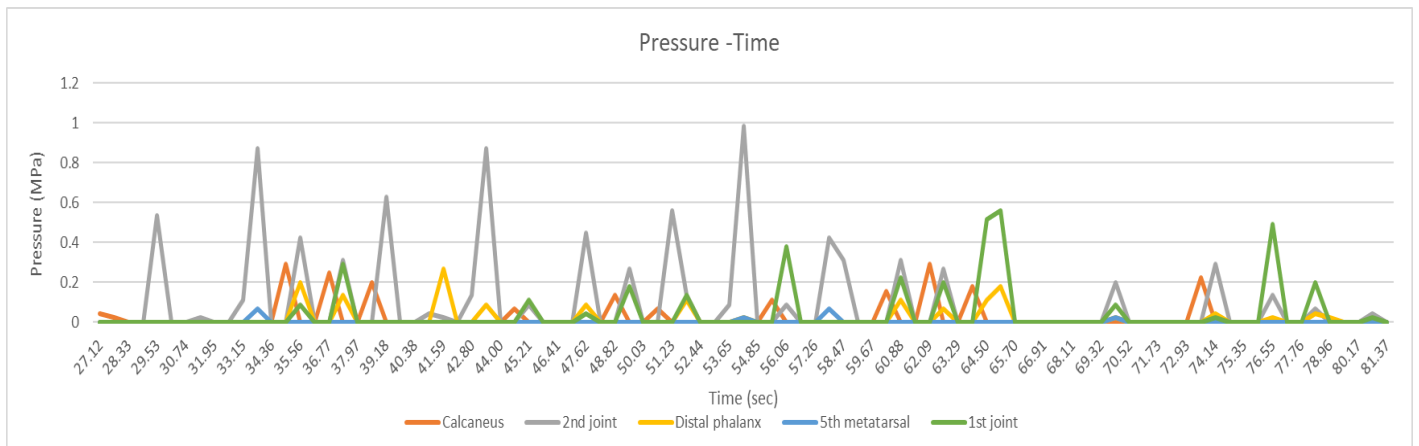


Figure 33. Each pressure along time. 'x' axis refers to time [s], meanwhile 'y' axis is the pressure made [MPa].

In Figure 33 it is possible to analyse the most significant parameters, such as: the maximum value, the activity duration, the order in which each sensor hits the ground and the sensors where the pressure is higher. The subject starts to walk near to second 30 and he finishes around the 80<sup>th</sup> second. However, between the second 65 and 73, the signal has lower values, which could be due to a disturbance in the gait cycle. Furthermore, it is seen that sensor 2 (joint between 2<sup>nd</sup> distal and proximal phalanx) is the one which suffers the highest pressure, reaching values near to 1MPa, which supposes 6.87kg (Equation 10). On the other hand, sensor 4 has recorded the lowest values, being imperceptible most of the time. Now the different values are going to be analysed individually.

At this point, it is important to remark that as the values are continuously changing and most of the time are null as it is possible to see in Figure 33, two kind of analysis can be made: the first one including all the values, which is not considered as 100% realistic; and the second one, which consists on taking only the values that are different to zero.

To make both analyses, 'Minitab' application has been used.

### 3.1.1 STUDY N°1: PART 1

Table 4. First analysis statistics variables. These values have been obtained from the data recorded in a 15-step gait by the subject. Q1 and Q3 are the first and third quartiles. Every value is represented in Pa.

Variable	N	N*	Mean	StDev	Variance	Minimum	Q1	Median	Q3	Maximum
S1	129	0	26218	61981	3841647095	0	0	0	0	291164
S2	129	0	72401	179404	32185832568	0	0	0	22408	985441
S3	129	0	17364	44377	1969317962	0	0	0	0	268757
S4	129	0	1389	8742	76414468	0	0	0	0	67178
S5	129	0	37676	100083	10016596932	0	0	0	0	559921

As it has been predicted, the median value (the median of a statistical distribution with distribution function  $D(x)$  is the value 'x' such  $D(x)=1/2$  (Robert V. Hogg, 1995). For a symmetric distribution, it is therefore equal to the mean. In other words, the median is the value of a distribution which has on one side half of the values and on the other side the other half distribution values. is zero for the five variables as shown in Table 4 . In any case it is possible to see how S2 has the highest mean and S4 the lowest. In addition, they have the highest and the lowest maximum respectively. In conclusion, it has to be mentioned that standard deviation and variance have a huge value due to the dispersion of the values as is it shown in Figure 34 and Figure 35 (Equation 12).

$$\text{Standard Deviation} = \sqrt{\frac{\sum(x-\bar{x})^2}{n-1}}$$

Equation 12. Standard deviation. It represents the sum of the distance of all values (x) from the mean ( $\bar{x}$ ), 'n' is the number of samples. (Triola, 2006)

It draws attention the low numbers different to zero that the sensor 4 has detected (only four values), but after all it agrees with the previously mentioned studies (2.8.2) and with (Skopljak, 2014), because the S4 is not considered as a significant pressure point.

To conclude, it is interesting to observe how the pressure changes along the time in each sensor, at least in the remarkable points. In Figure 33, it is possible to verify how around fifteen peaks have been detected (one for each step). Also, it is true that their values are changing due to the different movements that the subject makes in every step. Moreover, it is noticed that before every grey peak (sensor 2) there is an orange peak (sensor 1), which mirrors the fact that during the gait, the heel (calcaneus) is the first foot part in contact the floor.

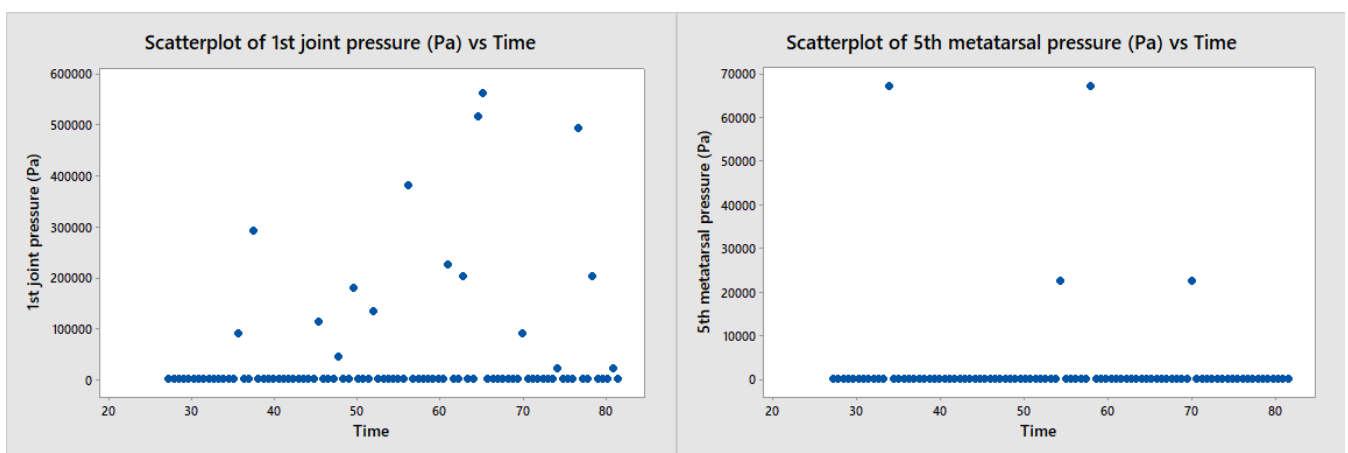


Figure 34. Sensor scatterplots. It shows the dispersion of every value recorded during a 15-step gait. 'y' axis represents the pressure that every sensor suffers [Pa] and 'x' axis the moment in the time when it suffers that pressure [s]. S1 is referred to calcaneus, S2 to the joint between the second distal phalanx and the second proximal phalanx.

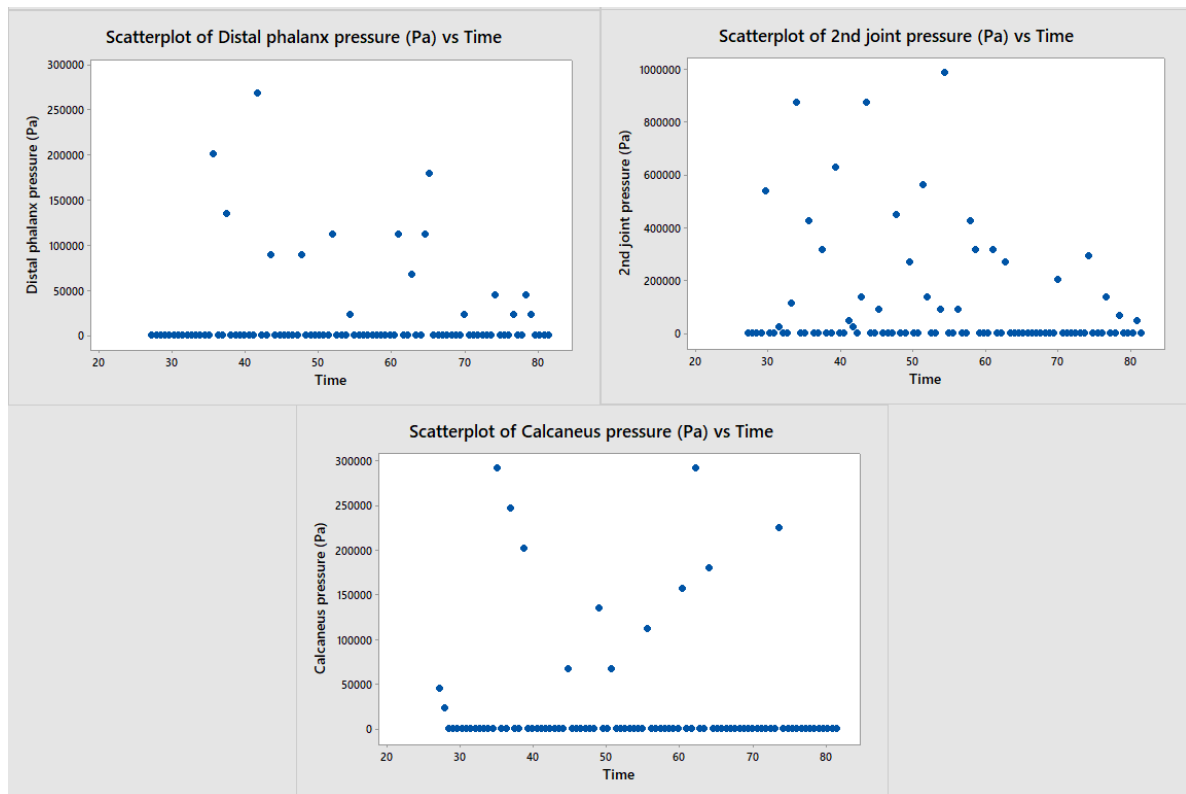


Figure 35. Sensor scatterplots. It shows the dispersion of every value recorded during a 15-step gait. 'y' axis represents the pressure that every sensor suffers [Pa] and 'x' axis the moment in the time when it suffers that pressure [s]. S3 refers to distal phalanx, S4 to the fifth metatarsal and S5 represents the joint between the first distal phalanx and the first proximal phalanx.

### 3.1.2 STUDY N°1: PART 2

Now, the second study is carried out deleting the null values (Table 5).

Table 5. Study without null values. It represents the same variables showed in Table 4, but in this case the null values have been deleted. Every value is represented in Pa.

Variable	N	N*	Mean	StDev	Variance	Minimum	Q1	Median	Q3	Maximum
S1	27	90	125262	77647	6029075034	22408	67178	111993	179171	291164
S2	38	91	245781	259962	67580337063	22408	44816	134401	341559	985441
S3	27	99	82960	63592	4043968385	22408	22408	89586	111993	268757
S4	4	107	44793	25848	668113234	22408	22408	44793	67178	67178
S5	26	103	186931	149226	22268533271	22408	89586	145582	229577	559921

It is considered that the current values are more significant. Analysing the non-zero values, it is possible to see in Table 5 how S2 continues being the point where the pressure is the highest as mean and maximum value are concerned. In addition, the joint between first distal phalanx and first proximal phalanx has the second maximum value, which has been reached

about the second 60 as it is possible to see in Figure 33. Although it is observed that the rest of the values of this sensor are lower, as the mean represents, so this specific value could be considered as an outlier. Applying Equation 10 as it has been made before (2.8.5), the weight that each point on average suffers is obtained and shown in Table 6.

Table 6. Average weight in each sensor, calculated from the mean pressure recorded. The relationship is around 125181Pa by 1kg

Sensor	Pressure (Pa)	Voutput (mV)	Weight (Kg)
1	125262	25.82	0.86
2	245781	50.66	1.69
3	82960	17.10	0.57
4	44793	9.23	0.31
5	186931	38.53	1.28

In this case, instead of making a scatterplots analysis to see the data dispersion, a box graphic is going to be studied. In Figure 36, it is seen how S1, S3 and S4 have their data more compacted, meanwhile the sensors which register greater values show bigger dispersion in their data. This fact agrees with the standard deviation in Table 5.

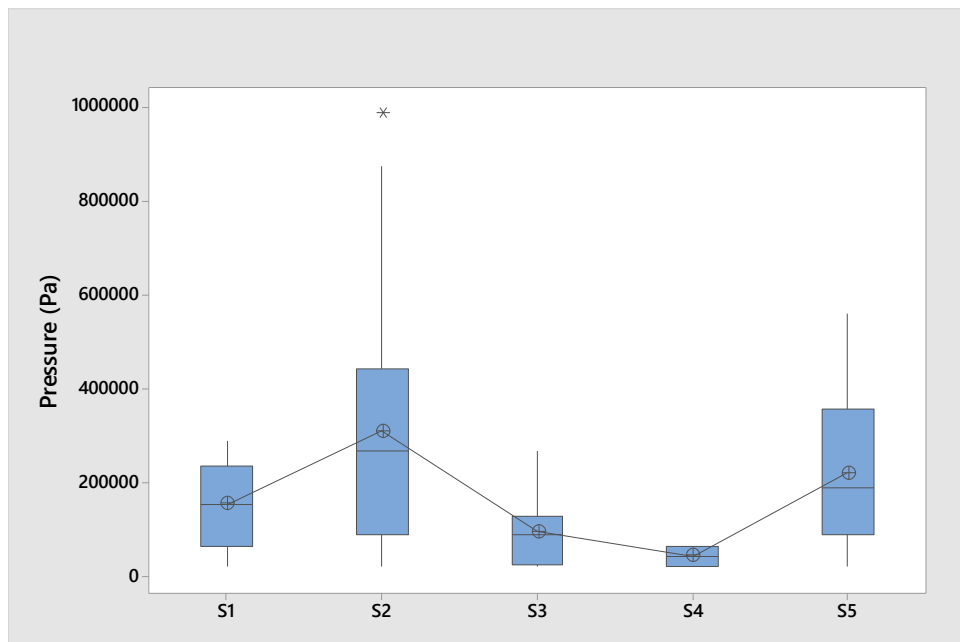


Figure 36. Study one, part two box plot. The line connects every mean sensor. 'y' represents every pressure recorded and 'x' axis represents the sensor to which this pressure refers.

At last, the mean values have been introduced in 'Pressure\_Points' program (2.8.6), obtaining the following result (Figure 37):

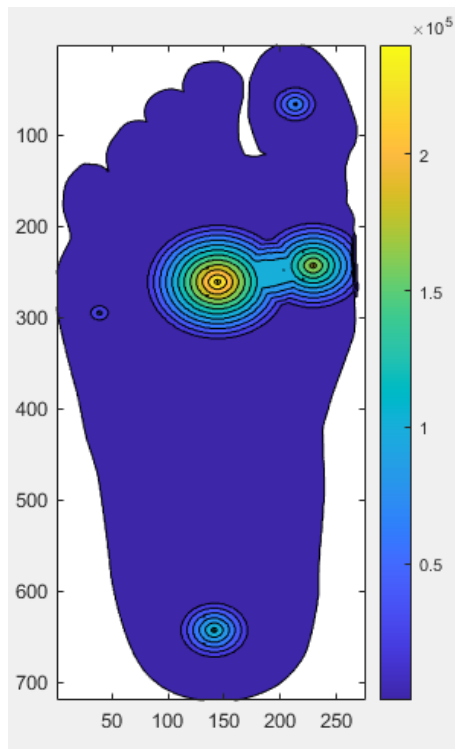


Figure 37. Mean values pedobarography obtained along the subject's gait of 15 steps.

This image has been processed following the same steps that in 2.8.2 to compare the obtained points with the ones in Figure 26. Although it is true that the sensors have been in these coordinates because of the first result, the other point added (sensor 4) is not represented in the final image because its value is not significant. This could mean that the board designed and the software, work properly in concordance with the objectives previously established (1.2).

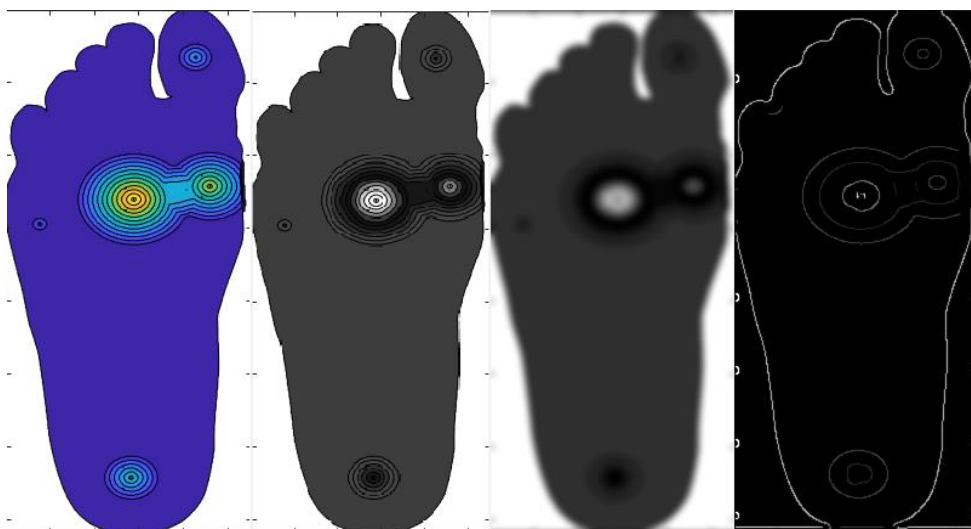


Figure 38. Pedobarography of the means. It has been processed in order to know where the most significant points are.



## 3.2 STUDY N<sup>o</sup>2

For the second study, it has been selected the same subject than in the previous one (Table 3). In this case the subject has walked for approximately 60 seconds on a treadmill, while its slope was increasing. The test has started with 0% slope and it has finished at 12%, recording data every 2% and always with a 1.5km/h speed. First, every slope is going to be studied individually and then a combined analysis will be carried out.

In contrast to the study made before (3.1), only non-zero data will be analysed in each case.

### 3.2.1 STUDY N<sup>o</sup>2: PART 1

#### SLOPE 0%

Data recorded and processed in 3.1 could be useful also in this test, but it has been decided to take new values in order to apply the same external condition.

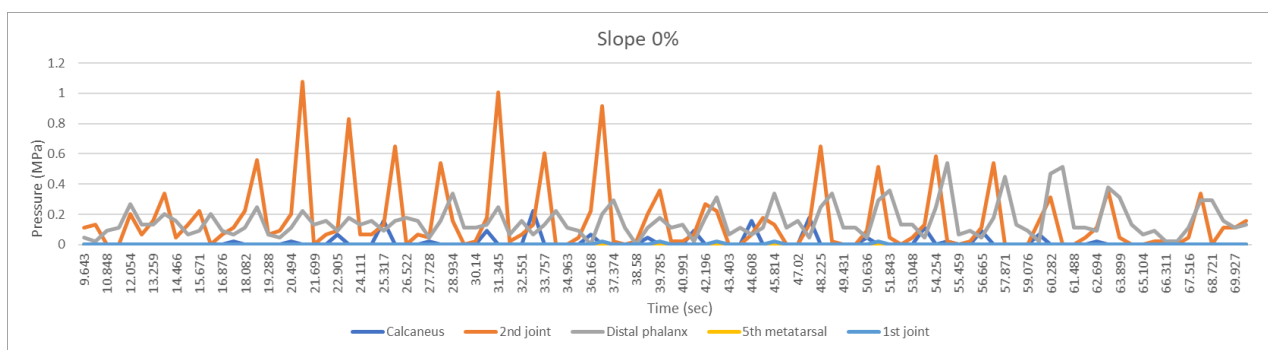


Figure 39. Slope 0% data recorded along the time. 'y' axis represents the pressure recorded in each sensor in MPa and 'x' axis the time during which the activity has been carried out

As It has happened before (3.1), the 2<sup>nd</sup> sensor has detected the highest pressure, followed by sensor 3 and to conclude sensor 1. Meanwhile sensors 4 and 5 have much lower values.

Table 7. Slope 0% statistics values. These values have been obtained from the data recorded in a 60 seconds gait by the subject. Q1 and Q3 are the first and third quartiles. Every value is represented in Pa.

#### Statistics

Variable	Mean	StDev	Variance	Minimum	Q1	Median	Q3	Maximum
Calcaneus	83369	60876	3705917875	22408	22408	67178	123186	223987
2nd joint	211594	243160	59126544055	22408	50406	123197	223987	1075026
Distal phalanx	156781	108463	11764306036	22408	89586	134401	195977	537513
1st joint	22408	0,000000	0,000000	22408	22408	22408	22408	22408

As it was predicted in Figure 39, statistics data obtained in Table 7 mirrored the fact that 2<sup>nd</sup> sensor has the greater mean and maximum value, having also the biggest standard deviation, as its mean is about 200.000Pa meanwhile the maximum value recorded reached more than 1.000.000Pa. In addition, 5<sup>th</sup> metatarsal does not have any statistics because its values are always zero and finally another significant event is that the last sensor has always recorded the same value, this could be caused because it is recording the footwear pressure. In any case its value is 22408Pa, which implies (Equation 10) 0.154kg.

To continue, it has been analysed the gait process shown in Figure 5. For that purpose, time period from 30.74 and 34,96 has been selected, as it is documented in Table 8. Then each pedobarography has been calculated with these values, and they have been compared with a filmed gait (Figure 40).

Table 8. Gait processed data, between the second 30.74 and 34.96, with a slope of 0%

Time (Sec)	30.74	31.35	31.95	32.55	33.15	33.76	34.36	34.96
Calcaneus (Pa)	89585.53	0	0	0	223986.73	0	0	0
2nd joint (Pa)	179171.06	1007848.66	22407.84	67177.69	134401.21	604690.86	0	0
Distal phalanx (Pa)	134401.21	246348.75	67177.69	156763.22	67177.69	134401.21	223986.73	111993.37
5th metatarsal (Pa)	0	0	0	0	0	0	0	0
1st joint (Pa)	0	0	0	0	0	0	0	0

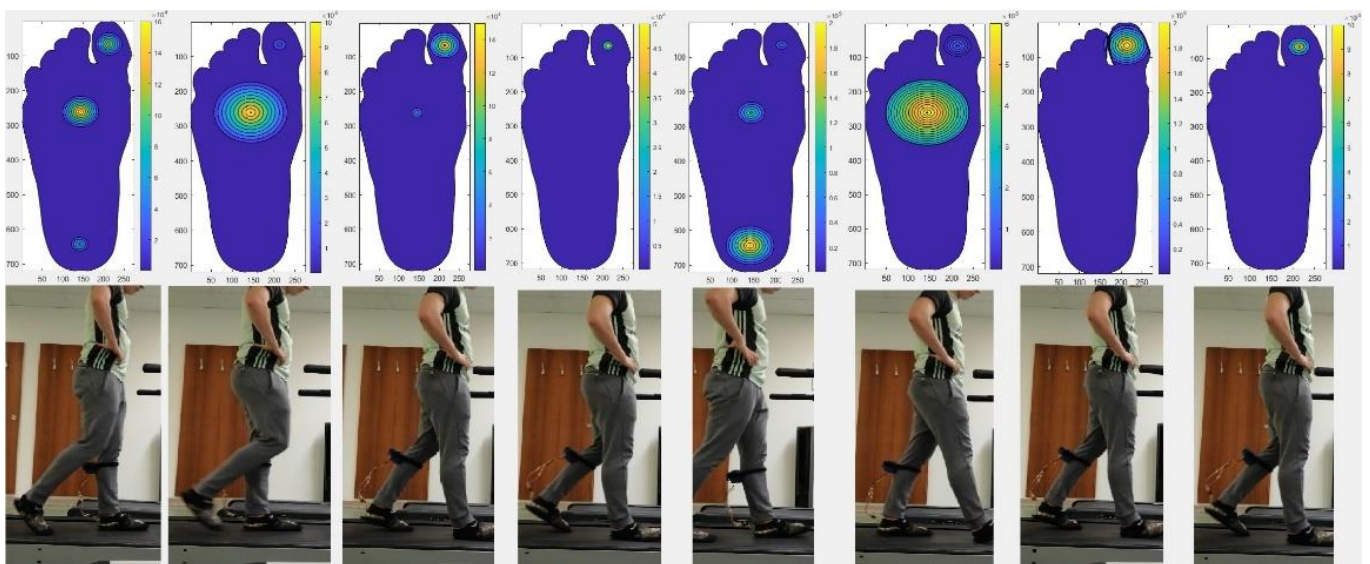


Figure 40. Recorded gait. Each value of the Table 8 has been analysed with the program developed, obtaining the pedobarography for each moment. It allows to see the moment where the subject is during the gait. Then it has been compared with a video recorded

Figure 40 shows an example about how the developed device works. It is fixed to the left leg via a 'Velcro' strip and is directly connected with the insole.

## SLOPE 2%

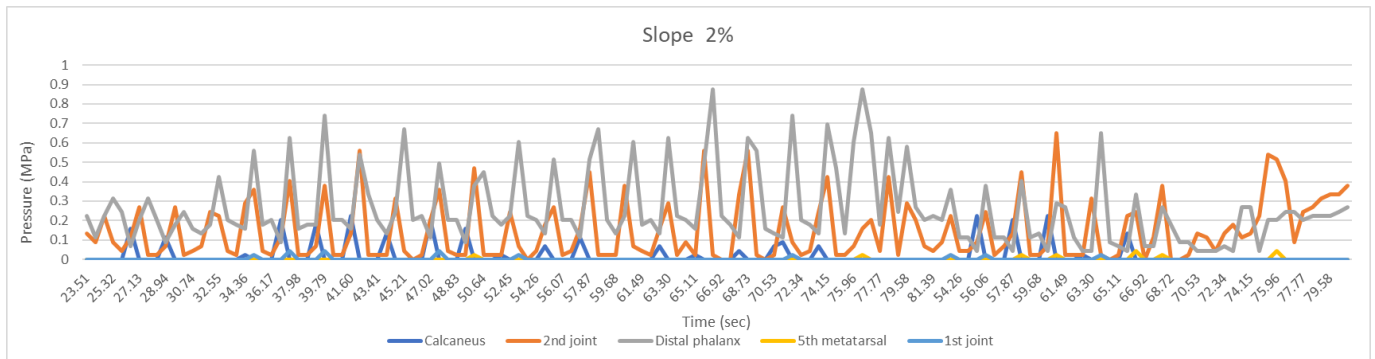


Figure 41. Slope 2% data recorded along the time. 'y' axis represents the pressure recorded in each sensor in MPa and 'x' axis the time during which the activity has been carried out.

As it is possible to see in Figure 41, the recorded data are quite different. In this case the highest value is reached by sensor 3. It needs to be considered that the peaks order is always the same, in every step the first value is the blue one (calcaneus), then orange peak appears (2nd joint) and finally a grey peak is registered. At the end, from the second 70 on, an anomalous behaviour can be detected, since it does not follow the pattern of the rest of the values taken, so it could be assumed that they are outliers.

Table 9. Slope 2% statistics values. These values have been obtained from the data recorded in a 60 seconds gait by the subject. Q1 and Q3 are the first and third quartiles. Every value is represented in Pa.

### Statistics

Variable	Mean	StDev	Variance	Minimum	Q1	Median	Q3	Maximum
Calcaneus_1	108254	66195	4381822014	22408	61587	100789	162365	223987
2nd joint_1	141936	151632	22992309583	22408	22408	67178	246349	559921
Distal phalanx_1	303074	205076	42056110426	67178	173569	201579	475937	873493
1st joint_1	33612	12273	150633364	22408	22408	33612	44816	44816

Table 9 shows how Sensor 3 has registered the highest value, this is a pressure about 873493Pa, which means (Equation 10) 6kg, and in addition its mean has a value about 303074Pa (2.082kg). In this case, data collected by sensor 4 has been deleted because of the same reason that has been previously mentioned (slope 0%). To conclude, it is possible to see again how in the minimum column the most repeated value is 22408Pa.

## SLOPE 4%

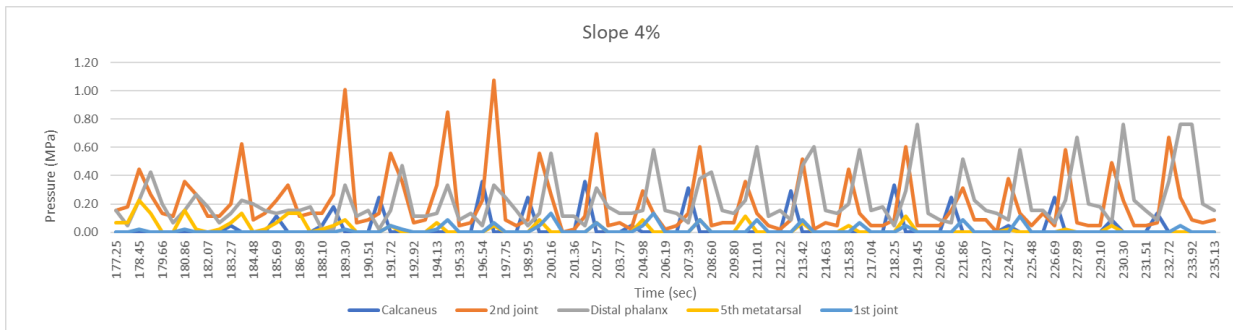


Figure 42. Slope 4% data recorded along the time. 'y' axis represents the pressure recorded in each sensor in MPa and 'x' axis the time during which the activity has been carried out

Table 10. Slope 4% statistics values. These values have been obtained from the data recorded in a 60 seconds gait by the subject. Q1 and Q3 are the first and third quartiles. Every value is represented in Pa.

### Statistics

Variable	Mean	StDev	Variance	Minimum	Q1	Median	Q3	Maximum
Calcaneus_2	196304	115259	13284547105	44816	78393	246349	296766	358342
2nd joint_2	208178	223176	49807706537	22408	67178	111993	268757	1075026
Distal phalanx_2	227433	185371	34362522669	22408	111993	156763	251951	761500
5th metatarsal_2	77648	47995	2303499227	22408	44816	67178	111993	223987
1st joint_2	65065	35603	1267575868	22408	39214	67178	89586	134401

Despite the fact that at the beginning of Figure 42 sensor 2 values were bigger than sensor 3 values, as it is mirrored by the maximum value in Table 10, the mean value of sensor 3 is higher than the 2<sup>nd</sup> one again. Nevertheless, the standard deviation is lower, which indicates the proximity between its data. In this test it is also possible to observe how sensor 4 has detected some significant data reaching a maximum of 223987Pa (1.53kg). It is true that is not as big as the recorded by other sensors, but it may indicate a growing change as slope increases. The highest values of sensor 4 match in time with sensor 2 lowest values, which it could mean a different lean in these steps.

## SLOPE 6%

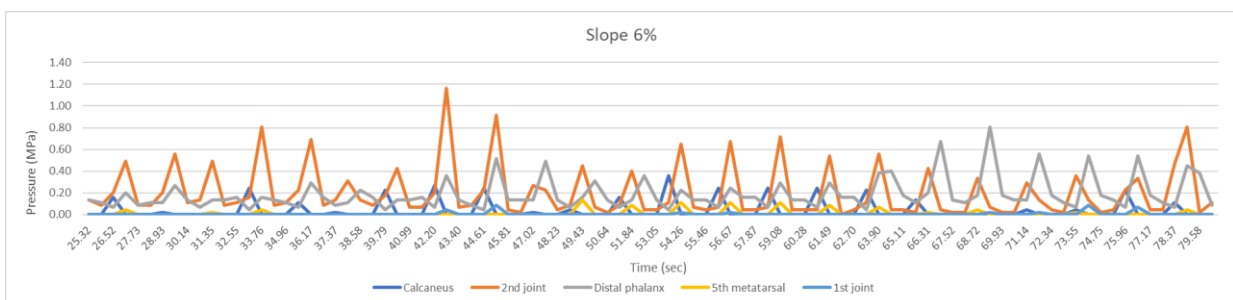


Figure 43. Slope 6% data recorded along the time. 'y' axis represents the pressure recorded in each sensor in MPa and 'x' axis the time during which the activity has been carried out

Observing the Figure 43, it is seen how sensor 2 has the highest values again, reaching the maximum value until now, 1164612Pa (8kg) as it is possible to see in Table 11. In addition, despite the slope is increasing it does not affect the gait process, being always first the calcaneus peak in every step. It is also true that there are some sensor 4 values at the middle of the record.

Table 11. Slope 6% statistics values. These values have been obtained from the data recorded in a 60 seconds gait by the subject. Q1 and Q3 are the first and third quartiles. Every value is represented in Pa.

### Statistics

Variable	Mean	StDev	Variance	Minimum	Q1	Median	Q3	Maximum
Calcaneus_3	162114	100628	10125991331	22408	44816	156763	246349	358342
2nd joint_3	209043	239409	57316847032	22408	44816	89586	296766	1164612
Distal phalanx_3	187301	146845	21563406787	44816	111993	134401	201579	806270
5th metatarsal_3	68801	38755	1501916654	22408	39214	55997	111993	134401
1st joint_3	47599	30367	922169684	22408	22408	33612	83984	89586

Data mirrored in Table 11 show how in this case sensor 2 mean has the greatest value. Nevertheless, sensor 3 has the biggest minimum being 44816Pa (0.30kg). Moreover, sensor 2 standard deviation shows a huge data dispersion in comparison with the other sensors, being almost 100.00Pa above the next one (sensor 3). In fact, it is possible to detect how Q1 (first quartile), median value and Q3 (third quartile) are closer in the 3<sup>rd</sup> than in the 2<sup>nd</sup> one.

### SLOPE 8%

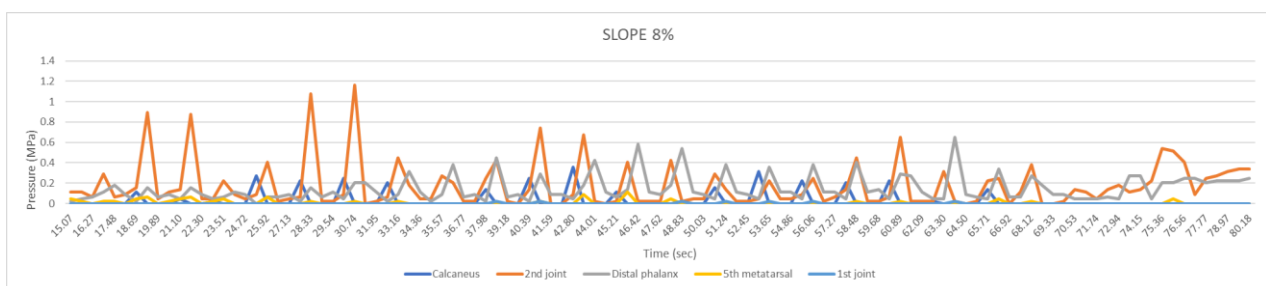


Figure 44. Slope 8% data recorded along the time. 'y' axis represents the pressure recorded in each sensor in MPa and 'x' axis the time during which the activity has been carried out

In this case it is possible to see (Figure 44 and Table 12) the same trend, sensor 2 has the maximum value, near to the previous one. Its mean is also the highest and their data are the most irregular. At last, sensor 5 has only detected a pressure about 22408Pa, so it could be concluded that these data are not relevant.

Table 12. Slope 8% statistics values. These values have been obtained from the data recorded in a 60 seconds gait by the subject. Q1 and Q3 are the first and third quartiles. Every value is represented in Pa.

### Statistics

Variable	Mean	StDev	Variance	Minimum	Q1	Median	Q3	Maximum
Calcaneus_4	180426	95473	9115039096	22408	111993	201579	246349	358342
2nd joint_4	192297	232666	54133644788	22408	44816	100789	263155	1154832
Distal phalanx_4	145998	126858	16092963095	22408	67178	89586	201579	649507
5th metatarsal_4	41071	24412	595923527	22408	22408	33612	44816	111993
1st joint_4	22408	0,000000	0,000000	22408	22408	22408	22408	22408

### SLOPE 10%

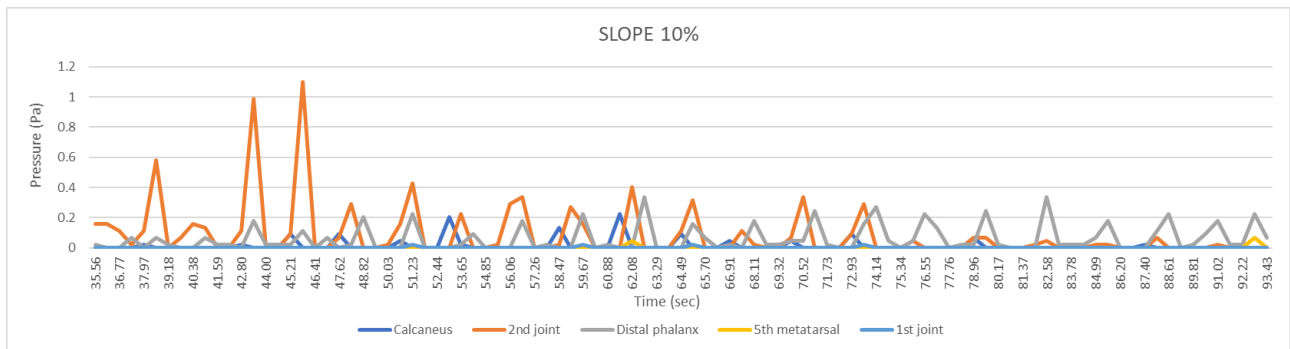


Figure 45. Slope 10% data recorded along the time. 'y' axis represents the pressure recorded in each sensor in MPa and 'x' axis the time during which the activity has been carried out

Looking at the means in Table 13, it is observed a decrease, while the maximum values registered are similar in the 2<sup>nd</sup> sensor. By contrast, in Figure 45, it is possible to see how, although sensor 2 have great values at the beginning, in the end it is practically null, being bigger the pressure in sensor 3. Finally, as it happened before (slope 8%), the last sensor has recorded every time the same value, so it could be deleted.

Table 13. Slope 10% statistics values. These values have been obtained from the data recorded in a 60 seconds gait by the subject. Q1 and Q3 are the first and third quartiles. Every value is represented in Pa.

### Statistics

Variable	Mean	StDev	Variance	Minimum	Q1	Median	Q3	Maximum
Calcaneus_5	80638	63234	3998584206	22408	22408	67178	89586	223987
2nd joint_5	190634	231535	53608488791	22408	44816	111993	291164	1097434
Distal phalanx_5	98087	91124	8303547284	22408	22408	67178	179171	335934
5th metatarsal_5	55997	15812	250029844	44816	*	55997	*	67178
1st joint_5	22408	0,000000	0,000000	22408	22408	22408	22408	22408

## SLOPE 12%

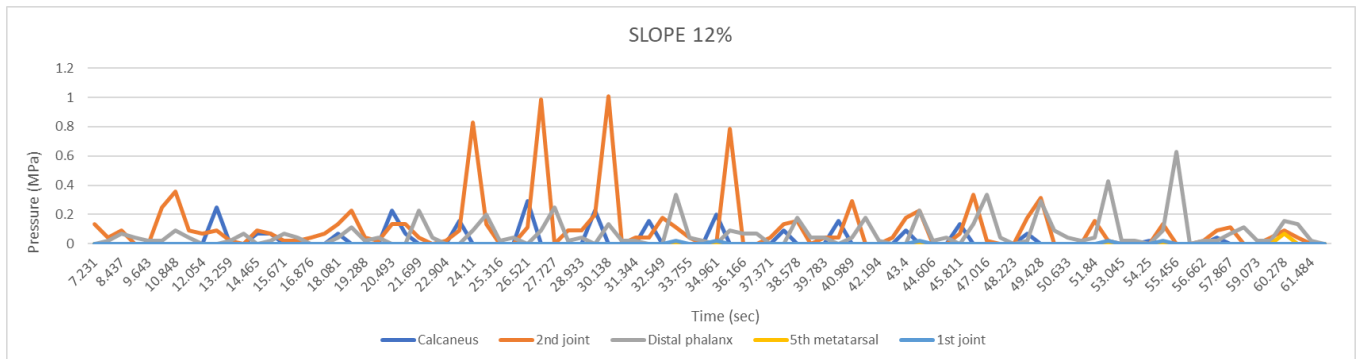


Figure 46. Slope 12% data recorded along the time. 'y' axis represents the pressure recorded in each sensor in MPa and 'x' axis the time during which the activity has been carried out

Table 14. Slope 12% statistics values. These values have been obtained from the data recorded in a 60 seconds gait by the subject. Q1 and Q3 are the first and third quartiles. Every value is represented in Pa.

### Statistics

Variable	Mean	StDev	Variance	Minimum	Q1	Median	Q3	Maximum
Calcaneus_6	131891	79052	6249275128	22408	67178	111993	207181	291164
2nd joint_6	160090	215278	46344769566	22408	44816	89586	167967	1007849
Distal phalanx_6	92604	109984	12096577607	22408	22408	44816	111993	627099
5th metatarsal_6	67178	*	*	67178	*	67178	*	67178
1st joint_6	22408	0,000000	0,000000	22408	22408	22408	22408	22408

In this last case, it is possible to see in Figure 46, four high orange peaks (sensor 2) in the middle of the data recorded, but then the rest of the data are lower, which causes a data dispersion, also shown in the standard deviation (Table 14). This sensor has the maximum value and the greatest mean again. Finally, although sensor 4 has a mean, minimum and maximum value, it is the result of only one data, so there are not another values. This data recorded is at the end of Figure 46, where a yellow value is shown. Due to its insignificant value (67178Pa) and the fact announced, it has been decided to delete it, considering it as an outlier (Manish Gupta, 2014).

### 3.2.2 STUDY N°2: PART 2

To carry out this study each sensor is going to be compared with each slope, trying to observe any relationship between the slope and the pressure that a point suffers.

## SENSOR 1: CALCANEUS

Table 15. Sensor 1 statistics values. These values have been obtained from the data recorded in a 60 seconds gait by the subject. Q1 and Q3 are the first and third quartiles. It compares the recorded data in the same point but with different slope. Every value is represented in Pa.

### Statistics

Variable	Mean	StDev	Variance	Minimum	Q1	Median	Q3	Maximum
Calcaneus 0%	83369	60876	3705917875	22408	22408	67178	123186	223987
Calcaneus 2%	108254	66195	4381822014	22408	61587	100789	162365	223987
Calcaneus 4%	196304	115259	13284547105	44816	78393	246349	296766	358342
Calcaneus 6%	162114	100628	10125991331	22408	44816	156763	246349	358342
Calcaneus 8%	180426	95473	9115039096	22408	111993	201579	246349	358342
Calcaneus 10%	80638	63234	3998584206	22408	22408	67178	89586	223987
Calcaneus 12%	131891	79052	6249275128	22408	67178	111993	207181	291164

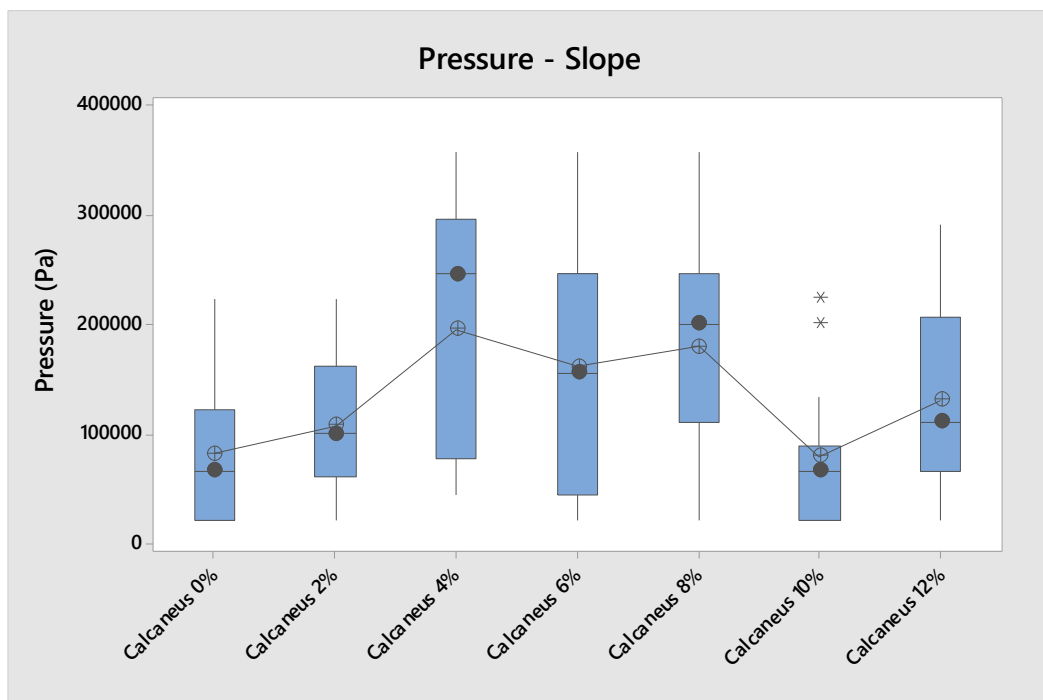


Figure 47. Sensor 1 boxplot. The values recorded in different slopes are shown [Pa]. The line connects every sensor mean.

Analysing Table 15 and Figure 47, it is possible to affirm that the data recorded are between 89586Pa (0.61kg) and 358342Pa (2.46kg) which has been recorded in three different slopes, so there is a data variation of 268756Pa. A priori there is not any relationship between the slope and the values, the means are increasing and decreasing with no apparent pattern. In addition, in the 6<sup>th</sup> test there are two points that attract attention, not for their values, because there are similar values in other tests, but for its remoteness in respect of the data recorded for this slope.



## SENSOR 2: 2<sup>nd</sup> JOINT

Table 16. Sensor 2 statistics values. These values have been obtained from the data recorded in a 60 seconds gait by the subject. Q1 and Q3 are the first and third quartiles. It compares the recorded data in the same point but with different slope. Every value is represented in Pa.

### Statistics

Variable	Mean	StDev	Variance	Minimum	Q1	Median	Q3	Maximum
2nd joint 0%	211594	243160	59126544055	22408	50406	123197	223987	1075026
2nd joint 2%	141936	151632	22992309583	22408	22408	67178	246349	559921
2nd joint 4%	208178	223176	49807706537	22408	67178	111993	268757	1075026
2nd joint 6%	209043	239409	57316847032	22408	44816	89586	296766	1164612
2nd joint 8%	192297	232666	54133644788	22408	44816	100789	263155	1154832
2nd joint 10%	190634	231535	53608488791	22408	44816	111993	291164	1097434
2nd joint 12%	160090	215278	46344769566	22408	44816	89586	167967	1007849

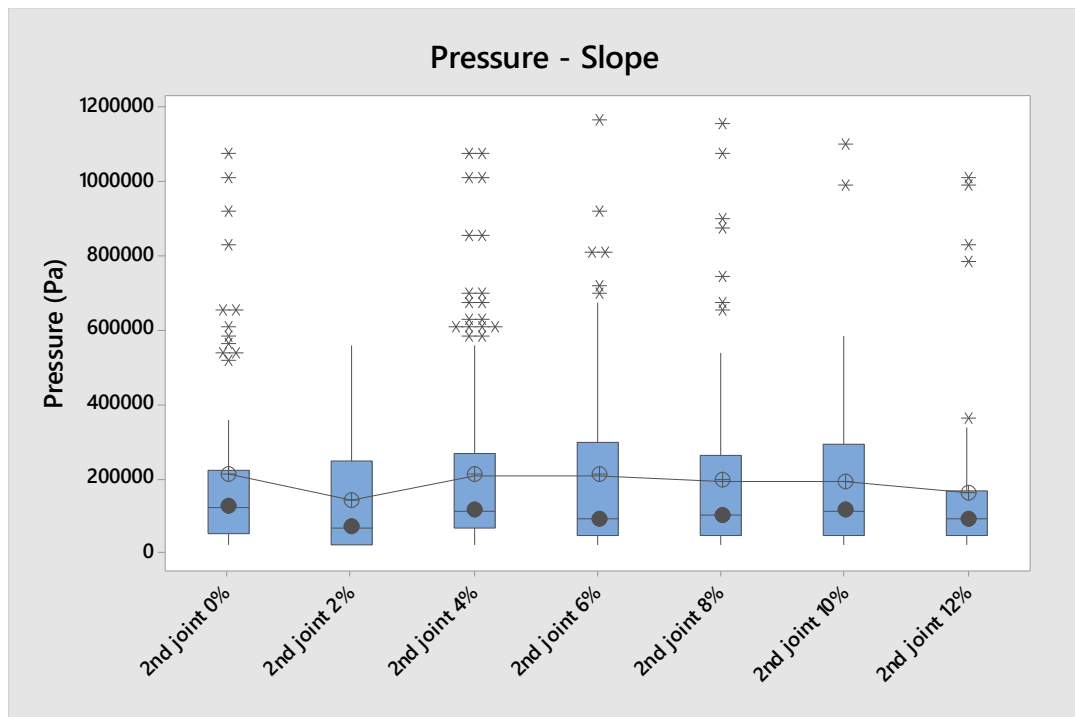


Figure 48. Sensor 2 boxplot. The values recorded in different slopes are shown [Pa]. The line connects every sensor mean.

In this case the data recorded seem more constant, in fact the line that can be observe in Figure 48 connects every mean and it shows a certain horizontal linearity. Figure 48 and Table 16 show how data are compacted, the differences between Q1 and Q3 are not big, even the maximum difference between them is lower than in the previous slope, but there are several points far from the mean of each test. 1164612Pa is the maximum value reached by this sensor, which means (Equation 10) a weight about 8kg and the lower maximum is 559921Pa (3.84kg). Finally, the lower value recorded in every test is always the same,

probably because of the contact between the insole and the foot, even if there is no a pressure as such.

### **SENSOR 3: DISTAL PHALANX**

Table 17. Sensor 3 statistics values. These values have been obtained from the data recorded in a 60 seconds gait by the subject. Q1 and Q3 are the first and third quartiles. It compares the recorded data in the same point but with different slope. Every value is represented in Pa.

#### **Statistics**

Variable	Mean	StDev	Variance	Minimum	Q1	Median	Q3	Maximum
Distal phalanx 0%	156781	108463	11764306036	22408	89586	134401	195977	537513
Distal phalanx 2%	303074	205076	42056110426	67178	173569	201579	475937	873493
Distal phalanx 4%	227433	185371	34362522669	22408	111993	156763	251951	761500
Distal phalanx 6%	187301	146845	21563406787	44816	111993	134401	201579	806270
Distal phalanx 8%	145998	126858	16092963095	22408	67178	89586	201579	649507
Distal phalanx 10%	98087	91124	8303547284	22408	22408	67178	179171	335934
Distal phalanx 12%	92604	109984	12096577607	22408	22408	44816	111993	627099

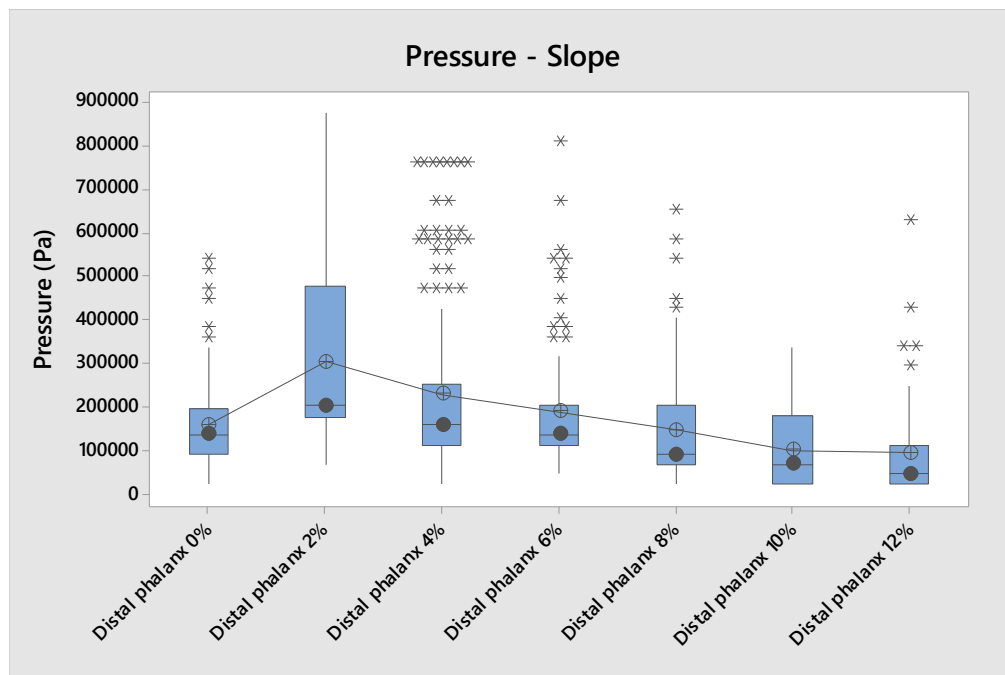


Figure 49. Sensor 3 boxplot. The values recorded in different slopes are shown [Pa]. The line connects every sensor mean.

Figure 49 and Table 17 shows how, despite a first data increasing, its mean decreases continuously in each slope. Regarding the 2<sup>nd</sup> test, it could be wrong since its values are not in concordance with the other tests. It is true that its maximum value is not extremely high, and the next one is only at 67223Pa below, but Q3 shows a higher value in comparison with the same one in other slopes. Finally, there are many points far from the mean, which could

be caused because even though most of the values are not recorded when the distal phalanx contacts the floor, when it makes contact the pressure values are increased, giving these higher data.

### **SENSOR 4: 5<sup>TH</sup> METATARSAL**

Table 18. Sensor 4 statistics values. These values have been obtained from the data recorded in a 60 seconds gait by the subject. Q1 and Q3 are the first and third quartiles. It compares the recorded data in the same point but with different slope. Every value is represented in Pa.

#### **Statistics**

Variable	Mean	StDev	Variance	Minimum	Q1	Median	Q3	Maximum
5th metatarsal 2%	22408	0,000000	0,000000	22408	*	22408	*	22408
5th metatarsal 4%	77648	47995	2303499227	22408	44816	67178	111993	223987
5th metatarsal 6%	68801	38755	1501916654	22408	39214	55997	111993	134401
5th metatarsal 8%	41071	24412	595923527	22408	22408	33612	44816	111993
5th metatarsal 10%	55997	15812	250029844	44816	*	55997	*	67178
5th metatarsal 12%	67178	*	*	67178	*	67178	*	67178

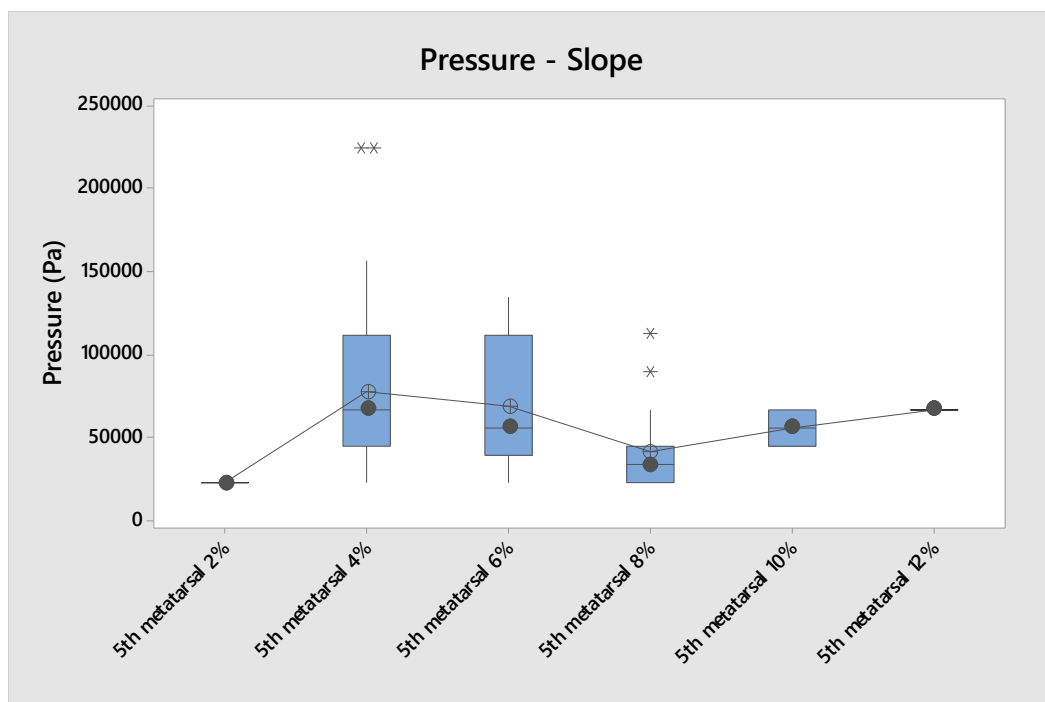


Figure 50. Sensor 4 boxplot. The values recorded in different slopes are shown [Pa]. The line connects every sensor mean.

Sensor 4 was added to the analysis despite the results obtained in 2.8.2. It has been considered that because of its position it could be interesting to include it. Once the data have been recorded and analysed, it is possible to see (Figure 50 and Table 18) how even

though sometimes there are some relevant points, 1<sup>st</sup> test result has been deleted because there was not any value, and 2% and 12% of slopes show only one value each one. As standard deviation shows, every test has compacted values, due to the low number of points. Furthermore, the maximum value registered is 223987Pa, which is far above the other ones, being more exactly a 66% more than the second maximum (134401Pa). It may be caused due to a different strike against the floor.

### **SENSOR 5: 1<sup>ST</sup> JOINT**

Table 19. Sensor 5 statistics values. These values have been obtained from the data recorded in a 60 seconds gait by the subject. Q1 and Q3 are the first and third quartiles. It compares the recorded data in the same point but with different slope. Every value is represented in Pa.

#### **Statistics**

Variable	Mean	StDev	Variance	Minimum	Q1	Median	Q3	Maximum
1st joint 0%	22408	0,000000	0,000000	22408	22408	22408	22408	22408
1st joint 2%	33612	12273	150633364	22408	22408	33612	44816	44816
1st joint 4%	65065	35603	1267575868	22408	39214	67178	89586	134401
1st joint 6%	47599	30367	922169684	22408	22408	33612	83984	89586
1st joint 8%	22408	0,000000	0,000000	22408	22408	22408	22408	22408
1st joint 10%	22408	0,000000	0,000000	22408	22408	22408	22408	22408
1st joint 12%	22408	0,000000	0,000000	22408	22408	22408	22408	22408

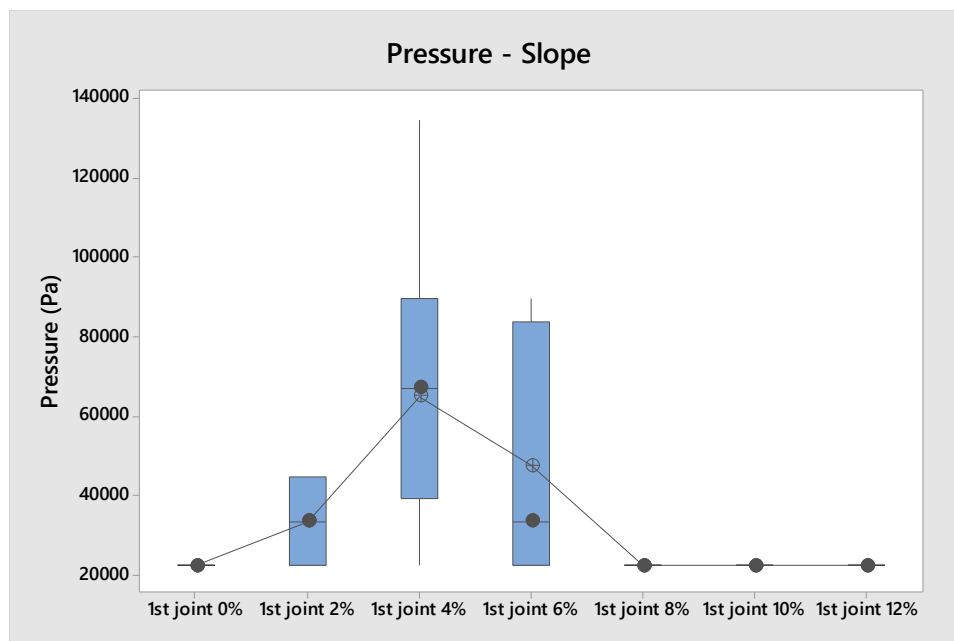


Figure 51. Sensor 5 boxplot. The values recorded in different slopes are shown [Pa]. The line connects every sensor mean.

In reference to the last sensor, despite it seems an important pressure point in Figure 25 and in Figure 38, according to the data recorded in four out of seven slopes there is only one

value (Figure 51 and Table 19), being always 22408Pa (data related with footwear pressure). The maximum value registered is 134401Pa (0.92kg), which is far from the other values, so it could be considered as an outlier.

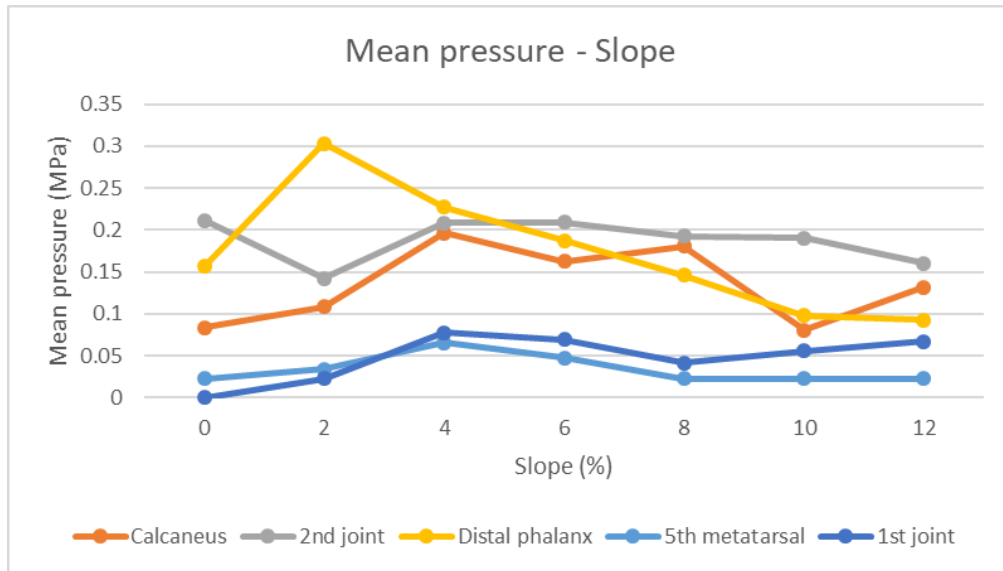


Figure 52. Mean pressure evolution -Slope

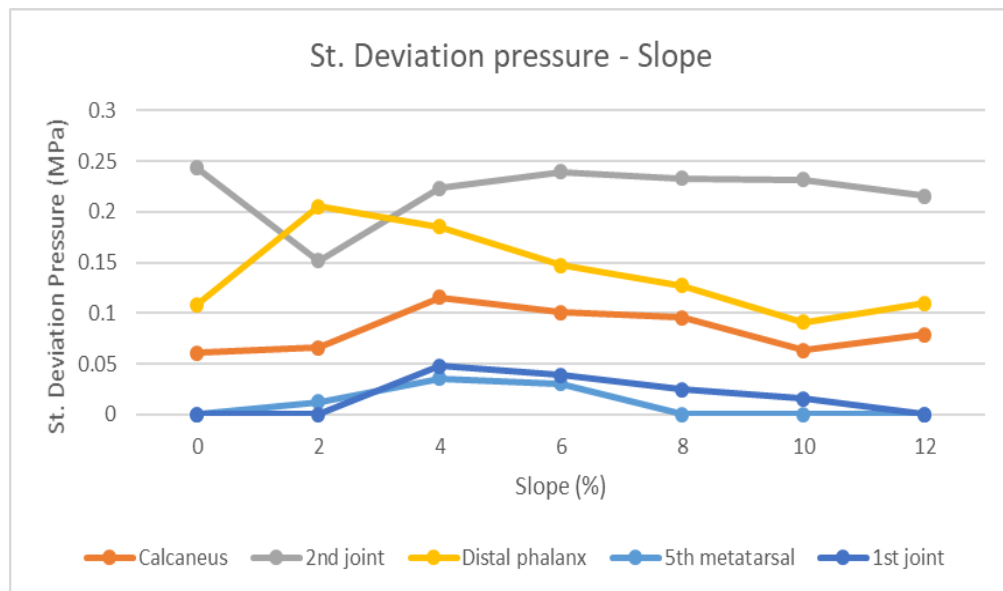


Figure 53. Standard deviation evolution -Slope

To sum up, in these two last figures (Figure 52 and Figure 53), mean and standard deviation evolution are shown. As it has been said, in the previous two studies the highest values belong to sensors 2 and 3. No sensor except the 3<sup>rd</sup> one show a relationship between the slope increase and change in pressure values, so it could be interesting to check if this fact continues with greater inclinations. It seems clear that when distal phalanx pressure

increases, pressure in the 2<sup>nd</sup> joint decreases as it is possible to see in the second test. Moreover, both figures demonstrate that the greater the mean pressure, the bigger the standard deviation value.

In any case, although it seems that there is not a relationship between the pressure and an increasing slope, this study should be made in more subjects in order to corroborate this affirmation.

Table 20. The average of each sensor on all the slopes has been calculated. From these values by means of Equation 9 the average weights suffered by each point analysed of the foot have been calculated.

Sensor	Pressure (Pa)	Voutput(mV)	Weight (Kg)
Calcaneus	134713.71	27.76	0.93
2nd joint	187681.71	38.68	1.29
Distal phalanx	173039.71	35.66	1.19
5th metatarsal	33701.14	6.95	0.23
1st joint	47586.14	9.81	0.33

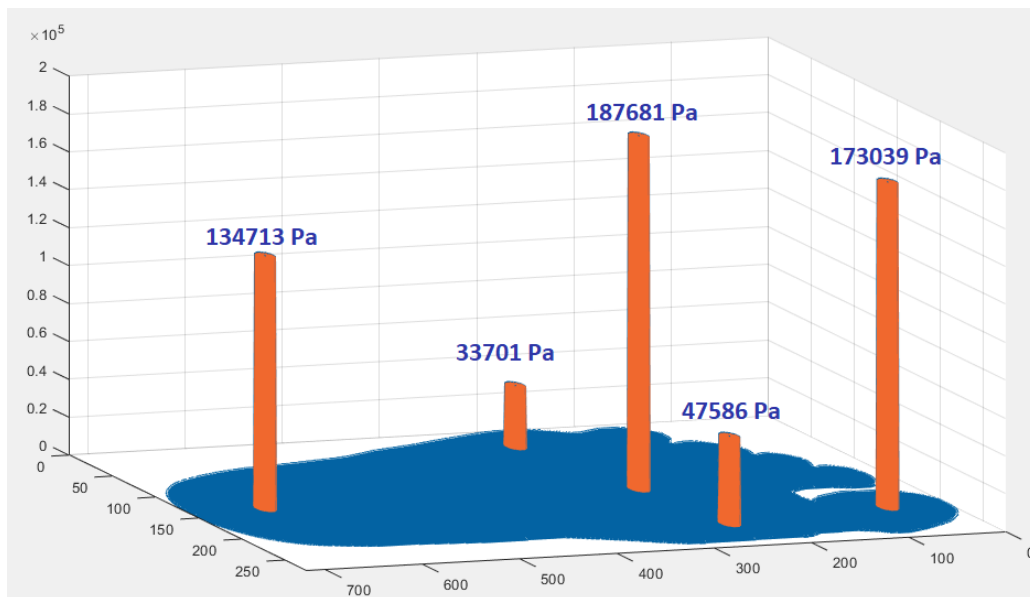


Figure 54. Study n<sup>o</sup>2 mean pressures. Each one is in the position where its sensor is placed.

To conclude, the mean of each sensor has been calculated (Table 20) and they have been compared with the ones obtained in study n<sup>o</sup> 1 (3.1), showing slight differences. Although sensor 1 and 3 show an increase the other sensors have lower values, being significant the difference in the last sensor, where the force made decreases almost one kg. It is possible to see how independently of the study the pressure in sensor 4 is always insignificant and in 2<sup>nd</sup> sensor has the highest value.

## 4 DISCUSSIONS AND FUTURE WORK

### 4.1 DISCUSSIONS

According to studies carried out, the following discussions are reached:

1. It seems clear that the part of the foot that registers the greatest pressure during the gait is the union between the 2<sup>nd</sup> distal phalanx and the 2<sup>nd</sup> proximal phalanx, followed by the 1<sup>st</sup> distal phalanx. In addition, it can be affirmed that the last point added to have a better pedobarography representation does not suffer significant pressure along the activities made (Figure 54).
2. It has been possible to observe the complete process of the tread. Calcaneus is the first foot point to make contact against the floor, then the union between the 2<sup>nd</sup> distal phalanx and 2<sup>nd</sup> proximal phalanx does. The last point that kicks the ground is the 1<sup>st</sup> distal phalanx.
3. Looking at the second study results, there is no significant evidence to affirm that the increase in the slope (at least 12% of inclination) affects the tread in some way, since Figure 52 and Figure 53 show very regular lines.

These discussions are based on studies developed on a single subject (Table 3), so in bigger populations they could be totally different.

### 4.2 FUTURE WORK

As it has been mentioned throughout the paper, since it is such a broad project and it is limited by the length of the 'Erasmus' scholarship, there are several aspects where the work carried out could be continued. Some of these ideas had been studied and tested, but due to the lack of time, they have not been implemented.

Firstly, a right foot insole could be developed, analysing the most important pressure points. To measure the force made by a subject with both feet, it would also be necessary to modify the program developed in order to show the whole gait cycle.

In addition, as the board used to design the circuit is a generic one with holes, it would be interesting to design the specific PCB (Printed Circuit Board), in order to optimise it and make it smaller, being more comfortable to make the studies.

In third place, another interesting improvement could be adding more sensors to the insole, to generate a better and more specific pedobarography, which allows to measure the pressure in the whole tread.

Finally, more subjects should be studied in order to have more realistic values and to compare them between different demographic groups, allowing to observe certain trends depending on age, weight, gender or other variables.

## 5 CONCLUSION

To sum up, the main points developed in the project are the following:

Study of the main anatomical principles, emphasizing the shape and bone composition of the foot. In addition, the consequences that this distribution has on human gait have been analysed, looking at the different equations that define it. Furthermore, several pedobarographies were analysed with the purpose of knowing the greatest pressure points of the foot and thus being able to design an insole that allows to measure the forces that the foot suffers during the gait.

From there, it was developed an electronic card which allows to measure the pressure generated in five different sensors in voltage units, thus being able to interpret the weight exerted on each of them, this creating the hardware part of the project. As software concerns, it was programmed in 'Arduino' application a code capable of reading the data generated on the electronic board and sending it to a computer through a Bluetooth connection. Moreover, it was also developed a MATLAB code which allows to interpret and to process data received through the Bluetooth connection, generating a real-time pedobarography. Finally, MATLAB graphic interface was designed, which facilitates the pedobarographic data interpretation, as well as the storage of such data for later analysis.

Then two studies have been carried out in order to measure and compare the pressure exerted at each point of the designed insole in different situations.

Summarizing, the project has achieved the main objectives proposed, being able to measure the pressure that a subject makes throughout the gait and interpreting these data.



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