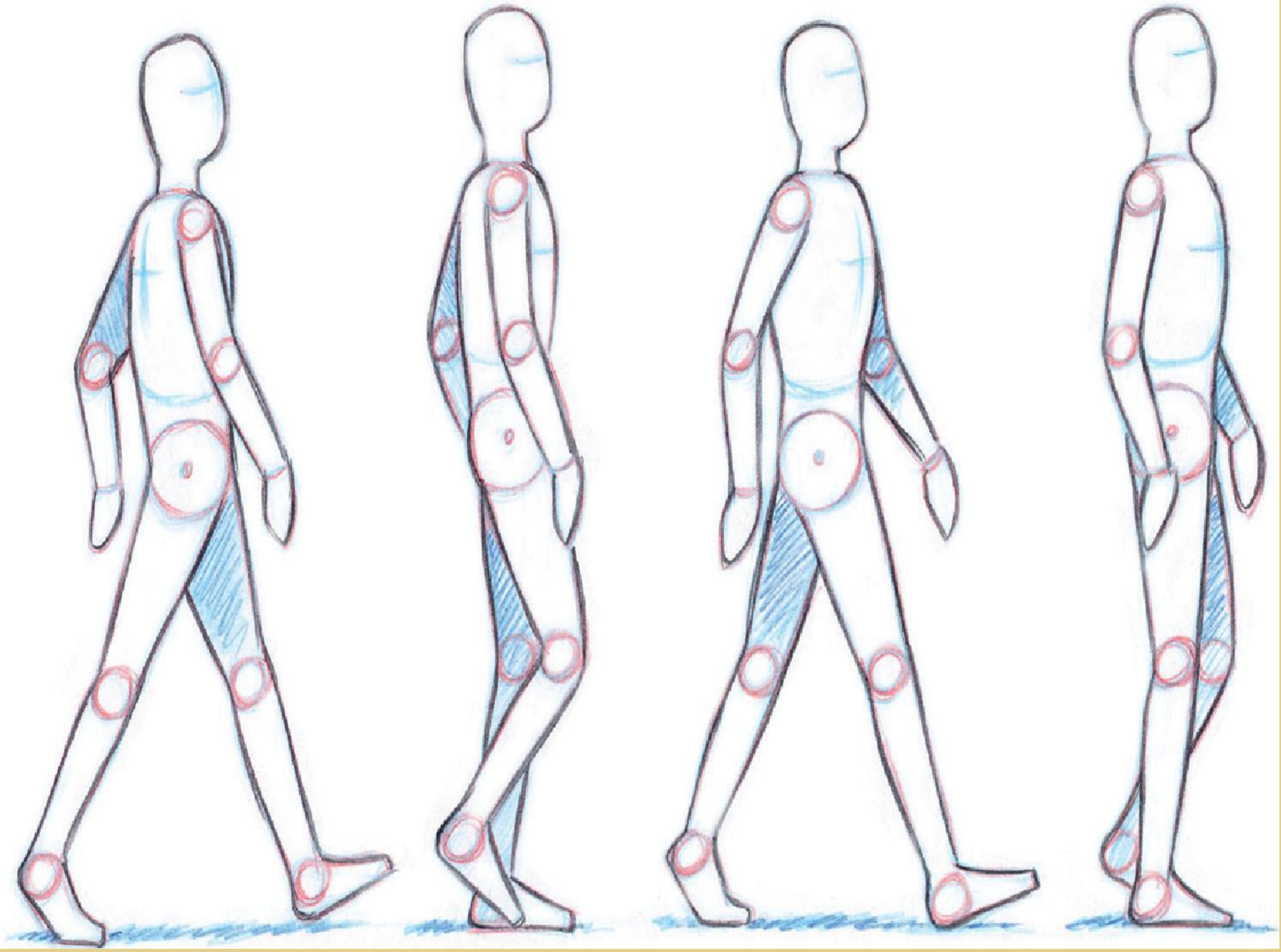

João Pedro Matos Santos

Gait analysis using instrumented shoes

Friction coefficients measurements

Coimbra 2018

Universidade de Coimbra

• U C •

FCTUC FACULDADE DE CIÊNCIAS
E TECNOLOGIA
UNIVERSIDADE DE COIMBRA

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Coimbra, September 2018

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To all my friends and colleagues that helped me throughout this five years.

To my family, especially my parents, that were always there for me when I needed the most.

Resumo

A análise da marcha humana é um campo amplamente investigado com aplicabilidade que vai para além da área da medicina. O desenvolvimento de novas tecnologias (sapatos instrumentados, sistemas de visão, plataformas de pressão) permite o desenvolvimento de novas formas de caracterizar a marcha humana com maior precisão e menor esforço. Com o aparecimento de robôs bípedes tornou-se importante para quem trabalha nesta área compreender a marcha humana para dar aos robôs um andar mais natural.

O principal objetivo deste projeto era verificar e corrigir quaisquer problemas existentes nos sapatos instrumentados e desenvolver uma aplicação Android capaz de realizar a aquisição de dados provenientes dos sapatos. Esta aplicação deveria utilizar uma ligação Bluetooth para estabelecer a comunicação com os dois sapatos em simultâneo. Os dados recolhidos devem ser guardados no dispositivo e devem estar disponíveis para transferência para um computador onde serão processados. Com recurso à aplicação desenvolvida foram realizadas um conjunto de experiências utilizando diferentes coeficientes de atrito com o solo. O processamento e a análise dos dados foram realizados utilizando uma aplicação existente para o Matlab. Os resultados obtidos são úteis para compreender o modo como os seres humanos se comportam em ambientes normais e em ambientes escorregadios (baixo coeficiente de atrito) onde é necessário um maior esforço para manter o equilíbrio. Esta informação é bastante útil para a programação de robôs bípedes.

Concluindo, foi possível corrigir os problemas encontrados nos sapatos instrumentados e verificar que os mesmos estão a funcionar corretamente. No que diz respeito à aplicação Android esta consegue fazer a aquisição e o armazenamento dos dados de forma correta e eficiente.

Palavras-chave: Marcha Humana, Sapatos Instrumentados, Forças de Reação do Solo, Coeficiente de Atrito, Aplicação Android

Abstract

The human gait analysis is a widely researched topic with applications that go beyond the medicine area. The development of new technologies (instrumented shoes, vision systems, pressure platform) allows the development of new ways to characterize the human gait with more precision and less effort. With the appearance of biped robots became important for those who work in this area to understand the human gait in order to give the robots a more natural walk.

The main goal of this project was to verify and correct any problems in the existing instrumented shoes and to develop an Android application capable of acquiring the data coming from the instrumented shoes. This application should use a Bluetooth connection in order to communicate with both shoes simultaneously. The gathered data should be stored on the device and should be available to be transferred to a computer to be processed. Using the developed application a set of experiments were carried out using different friction coefficients against the ground. The processing and analysis of the data were performed using an existing application for Matlab. The results are helpful to understand how humans behave in normal environments and in slippery environments (low friction coefficient) where a major effort is needed to keep balance. This information is quite useful to program biped robots.

In conclusion, it was possible to correct the problems found on the instrumented shoes and verify that they are working properly. Regarding the Android application it can acquire and store the data in a correct and efficient way.

Keywords: Human Gait, Instrumented Shoes, Ground Reaction Forces, Friction Coefficient, Android application

"The greatest enemy of knowledge is not ignorance, it is the illusion of knowledge."

— Stephen Hawking

"Strength doesn't come from what you can do. It comes from overcoming the things you once thought you couldn't."

— Rikki Rogers

Contents

List of Acronyms

APK	Android Application Package
API	Application Programming Interface
SDK	Software Development Kit
IDE	Integrated Development Environment
OS	Operating System
UI	User Interface
CoP	Center of Pressure
GRF	Ground Reaction Forces
ADC	Analog to Digital Converter
CR	Carriage Return
FCS	Frame Check Sequence
CRC	Cyclic Redundancy Check
CSV	Comma Separated Values
PVC	Polyvinyl chloride
ELM	Extreme Learning Machine

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1 Introduction

This document describes the work done in "Diagnosis of gait pathologies using instrumented shoes" project which took place in the Institute of Systems and Robotics, University of Coimbra. The main goal of this project is the development of a low cost human gait acquisition and analysis system using a pair of shoes equipped with force sensors.

This chapter presents this thesis motivation, main objectives and the outline.

1.1 Thesis Motivation

During the last decades the study of the human gait has been a subject of great interest in diverse areas such as biomechanics [7], psychology [8], medical sciences [9] and others [10] since the information that can be gathered from human gait analysis has immense applications.

With the advances in technology and robotics, new robots are being made to look, act and move very similarly to human beings. In order to do so, human behavior needs to be studied and understood. In the real world there is a vast diversity of materials with different friction coefficients affecting the slipperiness of the surfaces in which the robots will move. This will have a great impact on the robots balance and locomotion.

1.2 Main objectives

The first objective of this work was to verify if the existing prototype was working correctly and correct possible defective parts. The second objective was to develop an Android Application to ease the data acquisition since a mobile phone or a tablet are easier to carry than a computer. The third objective was to find materials with a low friction coefficient and acquire data using those materials as contacts with the floor surface.

1.3 Dissertation Outline

This document is divided in five main chapters. In the first chapter the context of the work, the motivation that lead to it and its main objectives are introduced. The second chapter presents some concepts that are needed to better understand the work done. The third chapter describes the hardware and software used in the data acquisition. Chapter four presents the experiments done to identify the friction coefficients and the experiments using the instrumented shoes for the different friction coefficients. In Chapter five are discussed the conclusions and future work.

2 Survey of the related work

In this chapter the most relevant theoretical concepts for this project are presented.

Firstly, a detailed explanation about the human gait cycle is presented. Then there is an explanation on how friction works. An overview of the Android operating system is presented as well as the official Integrated Development Environment(IDE) for Android. This chapter ends with a sample of current devices for gait acquisition.

2.1 Human Gait

Human gait refers to locomotion achieved through the movement of human limbs. 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 [11].

Gait Cycle

The gait cycle is a repetitive pattern involving steps and strides. A step corresponds to one single step, a stride is a whole gait cycle. The step time is the time from one foot hitting the floor to the other foot hitting the floor. Step width can be described as the mediolateral space between the two feet.

Classification of the gait cycle involves two main phases: the stance phase and the swing phase. 60% of the gait cycle is occupied by the stance phase while the swing phase occupies the remaining 40% of it.

The gait cycle can be decomposed into six phases: Heel Strike, Foot Flat, Mid-Stance, Heel-Off, Toe-Off and Mid-Swing. Another possible classification of the human gait involves eight phases: Initial Contact, Loading Response, Mid-stance, Terminal Stance, Preswing, Initial Swing, Mid Swing and Late Swing as seen in figure 2.1.

Heel strike, also known as initial contact, is a short period which begins the moment the foot touches the ground and is the first phase of double support. In foot flat, or loading

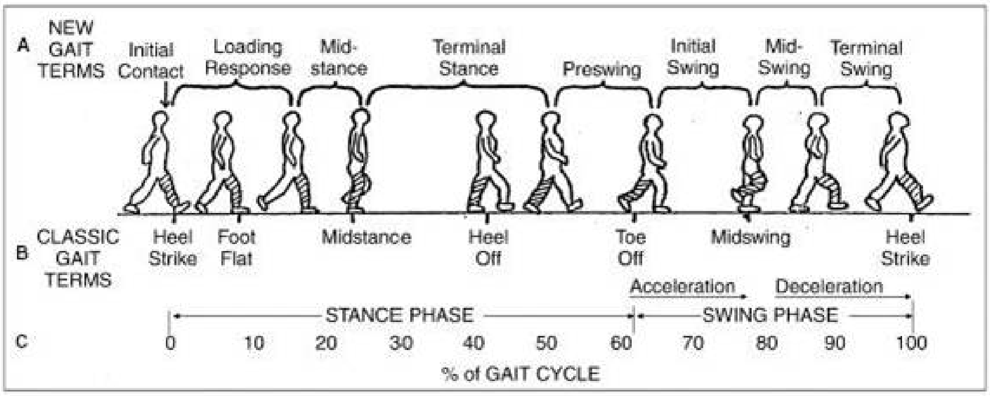


Figure 2.1: Human gait cyle [1]

response phase, the body absorbs the impact of the foot by rolling in pronation. In mid-stance, the body is supported by one leg. At this moment the body begins to move from force absorption at impact to force propulsion forward. Heel off begins when the heel leaves the floor. In this phase, the body weight is divided over the metatarsal heads. In toe-off the toes leave the ground. The mid-swing is the point at which the swinging leg passes the stance-phase leg and the two feet are side by side [12].

2.2 Ground Reaction Forces

Ground reaction forces (GRF) are the forces exerted by the surface on the foot. GRF are composed by the vertical, anteroposterior and mediolateral components. In figure 2.2 it is possible to see the curves corresponding to the three components of the GRF. Positive values represent a lateral force and a posterior force, acting on the foot.

The vertical component of the GRF usually has one local minimum and two local maximums. The first local maximum occurs after the heel strike due to the impact of the foot on the surface and the transfer of weight from one leg to the other reaching values higher than the person's body weight. During mid-stance the force decreases to values lower than the person's body weight, reaching a local minimum. In the terminal stance the force reaches the second local maximum due to the force that is needed to impulse the foot off the ground. Finally the vertical force reaches zero when the foot looses contact with the surface, toe off, and the swing phase starts.

Regarding the antero-posterior component it has a positive peak as a result of the initial contact of the foot with the surface. During mid-stance the direction of the force is inverted which leads to a negative peak before the toe-off. This negative peak shows that in order to

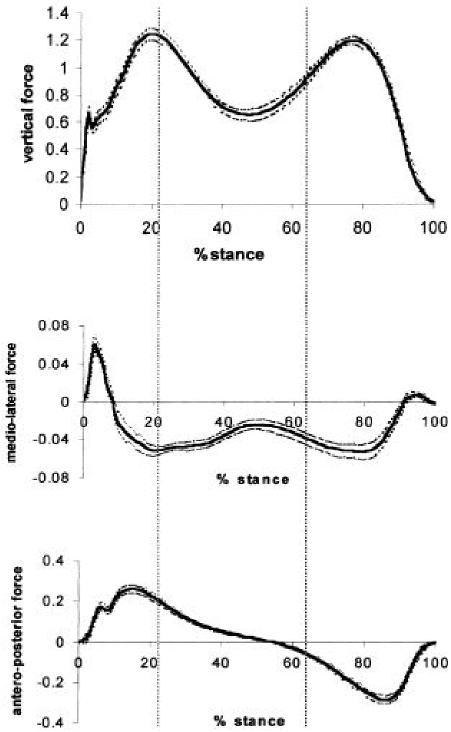


Figure 2.2: GRF: Vertical component (top), Medio-lateral component (middle), Antero-posterior component (bottom) in percentage of body weight, [2]

move forward we need to apply a force in the direction opposite to the movement.

The medio-lateral component represents the forces applied towards the inner part of the foot, medial forces, and forces applied towards the outer part of the foot, lateral forces.

The patterns described represent the curves expected for an healthy person to walk at a normal speed. These patterns change with the walking speed as can be seen in figure 2.3 for the vertical component.

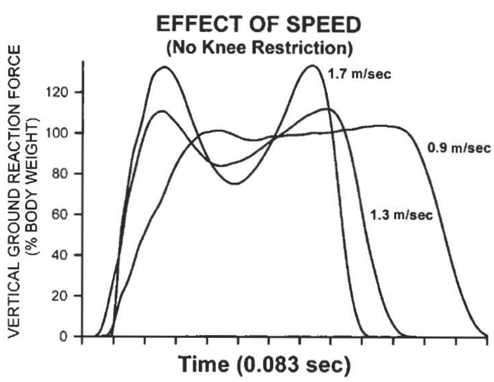


Figure 2.3: Effect of speed on the vertical component of GRF [3]

2.3 Center of Pressure

The center of pressure (CoP) location indicates the position of the vertical ground reaction force vector. The CoP is an average of all the forces applied on the contact points during the gait cycle. Studying the trajectory of the CoP throughout the gait cycle is an important factor to identify pathologic patterns.

For an healthy person walking barefoot at a normal speed, the CoP begins at the center of the heel, considering that the initial contact was made with the posterior part of the foot. The CoP progresses from the rear-foot, passing through the mid-foot and finally reaching the fore-foot where its progression speed suffers a deceleration as seen in figure 2.4.

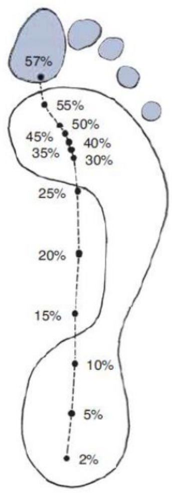


Figure 2.4: CoP trajectory with gait cycle percentage [4]

2.4 Friction

The behavior of friction is very complex and is still not completely understood.

Friction is always parallel to the contact surface between systems and in a direction that opposes motion or attempted motion of the systems relative to each other. If two systems are in contact and moving relative to one another, then the friction between them is called kinetic friction. When objects are stationary, static friction can act between them. The static friction is usually greater than the kinetic friction between the objects.

When there is no motion between the objects, the **magnitude of static friction** (f_s) is

$$fs \leq \mu_s N \tag{2.1}$$

where μ_s is the coefficient of static friction and N is the magnitude of the normal force (the force perpendicular to the surface).

Static friction is a responsive force that increases to be equal and opposite to whatever force is exerted, up to its maximum limit. Once the applied force exceeds $f_{s(max)}$, the object will move. Thus

$$f_{s(max)} = \mu_s N \tag{2.2}$$

Once an object is moving, the **magnitude of kinetic friction** (f_k) is given by

$$f_k = \mu_k N \tag{2.3}$$

where μ_k is the coefficient of kinetic friction. A system in which $f_k = \mu_k N$ is described as a system in which friction behaves simply [13].

2.5 Android

Android is a mobile operating system (OS) developed by Google that is based on a modified version of the Linux kernel and other open source software. Android was first launched in September 23, 2008 and it has been the best-selling OS worldwide on smartphones since 2011 and on tablets since 2013.

Android Versions

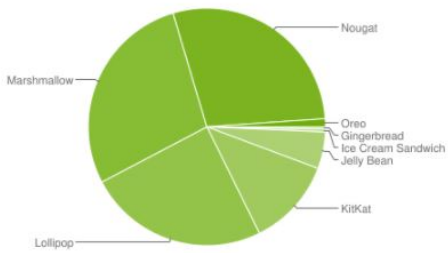
Since the first Android public release in 2008, Google has been releasing new Android versions that bring new features to the Android devices. As of May 2018 the latest version is Android Oreo 8.1 released on August 21, 2017 (figure 2.5), although Android Marshmallow 6.0 is the most widely used (figure 2.6).

Code name	Version number	Initial release date	API level
(No codename)[2]	1.0	September 23, 2008	1
(Internally known as "Petit Four")[2]	1.1	February 9, 2009	2
Cupcake	1.5	April 27, 2009	3
Donut[3]	1.6	September 15, 2009	4
Eclair[4]	2.0 – 2.1	October 26, 2009	5 – 7
Froyo[5]	2.2 – 2.2.3	May 20, 2010	8
Gingerbread[6]	2.3 – 2.3.7	December 6, 2010	9 – 10
Honeycomb[7]	3.0 – 3.2.6	February 22, 2011	11 – 13
Ice Cream Sandwich[8]	4.0 – 4.0.4	October 18, 2011	14 – 15
Jelly Bean[9]	4.1 – 4.3.1	July 9, 2012	16 – 18
KitKat[10]	4.4 – 4.4.4	October 31, 2013	19 – 20
Lollipop[12]	5.0 – 5.1.1	November 12, 2014	21 – 22
Marshmallow[13]	6.0 – 6.0.1	October 5, 2015	23
Nougat[14]	7.0 – 7.1.2	August 22, 2016	24 – 25
Oreo[15]	**8.0 – 8.1**	August 21, 2017	26 – 27
Android P	9?		

Legend: Old version | Older version, still supported | **Latest version**

Figure 2.5: Android version history [5]

Version	Codename	API	Distribution
2.3.3 - 2.3.7	Gingerbread	10	0.3%
4.0.3 - 4.0.4	Ice Cream Sandwich	15	0.4%
4.1.x	Jelly Bean	16	1.7%
4.2.x		17	2.6%
4.3		18	0.7%
4.4	KitKat	19	12.0%
5.0	Lollipop	21	5.4%
5.1		22	19.2%
6.0	Marshmallow	23	28.1%
7.0	Nougat	24	22.3%
7.1		25	6.2%
8.0	Oreo	26	0.8%
8.1		27	0.3%



Data collected during a 7-day period ending on February 5, 2018.
Any versions with less than 0.1% distribution are not shown.

Figure 2.6: Android versions distribution [6]

2.6 Android Studio

Android Studio is the official integrated development environment (IDE) for Google's Android operating system, built on JetBrains' IntelliJ IDEA software and designed specifically for Android development. It also has an integrated UI editor that allows programmers to drag and drop components into the UI activity without the concern of writing code. Android Studio divides the App files into three categories: Manifests, Java and Resources.

Manifests

Includes the file AndroidManifest.xml where the app permissions are defined as well as the app label, icon and activities used by the application.

Java

In this category are found all the java code files that are used by the application. Each activity needs to have its own file.

Resources

This category includes all the .xml files that are responsible for the graphical part of the application such as the layouts for the different activities, the app icons and strings that are displayed on the UI.

2.7 Devices for acquisition of the GRF of human gait

In this section some devices capable of measuring the GRF are described. As these devices are already on the market, they often include a software to analyze the data acquired. The most common devices are insoles due to their portability and easiness of use. Force plates are often more precise but restrict the area available for measuring forces.

2.7.1 Insoles

W-inshoe [14] is an in-shoe pressure analysis solution which has 9 sensors in each unit, figure 2.7a. It has a built in battery that allows 5 hours of measurements with an acquisition rate of 100 Hz. The data is sent in real time to a computer or android device using Bluetooth.

Pedar from Novel [15] is another insole measurement system, shown in figure 2.7b. It can be used with insoles that cover the entire plantar surface of the foot or with sensor pads for the dorsal, medial or lateral areas of the foot. This system also provides a data acquisition software capable of 2D and 3D representation of feet pressure, step selection, step timing analysis and determination of averaged and individual gait lines. The system has 256 sensors and can communicate with a computer using a USB cable or via Bluetooth. The data can also be stored in a SD card and later downloaded into a computer for analysis.

FlexinFit from Sensormedica [16] uses resistive sensors to perform a biomechanical and postural analysis, figure 2.7c. Each insole has 214 sensors that can be analyzed in real time and the data flow recorded up to 4 hours. The insoles communicate with Freestep software (from the same company) using a Bluetooth device at a sampling frequency in real time from 25 to 50 Hz.

(a) W-inshoe insole (b) Pedar insole system (c) Flexinfit insole

Figure 2.7: Insole systems

Medilogic Insoles from Noraxon [17], figure 2.8a, can be used to record the plantar pressure distribution. Their main applications are gait analysis for physical and occupational therapy practice, sports medicine, running health and injury prevention and fitting of Prosthesis and Orthotics. Each insole has a maximum of 240 sensors which can be sampled at 60 Hz or 300Hz (sports version) and communicates with the company software Noraxon Pressure wirelessly.

Wiisel (Wireless Insole for Independent & Safe Elderly Living) [18] is a project with the support of the Seventh Framework Programme and the European Union whose objective was to developed an insole to assess and research the fall risk in elderly people. The final product had 14 pressure sensors and inertial sensors entirely encapsulated in typical insole materials, figure 2.8b. It uses ultra-low power consumption components and can be wirelessly charged using Qi standard.

The Moticon Science [19] is a slim, robust and versatile insole, figure 2.8c. It has 13 pressure sensors combined with a 3-axis accelerometer that enables the user to see the pressures distribution, the overall ground contact force in normal direction and the center of pressure. The data can be streamed live to a PC or smartphone or it can be recorded and stored internally. The data acquisition can be made at 5 sample rates, 5, 10, 25, 50 and 100 Hz and the insole is powered by a rechargeable coin cell.

(a) Medilogic insole (b) Wiisel project (c) Moticon insole

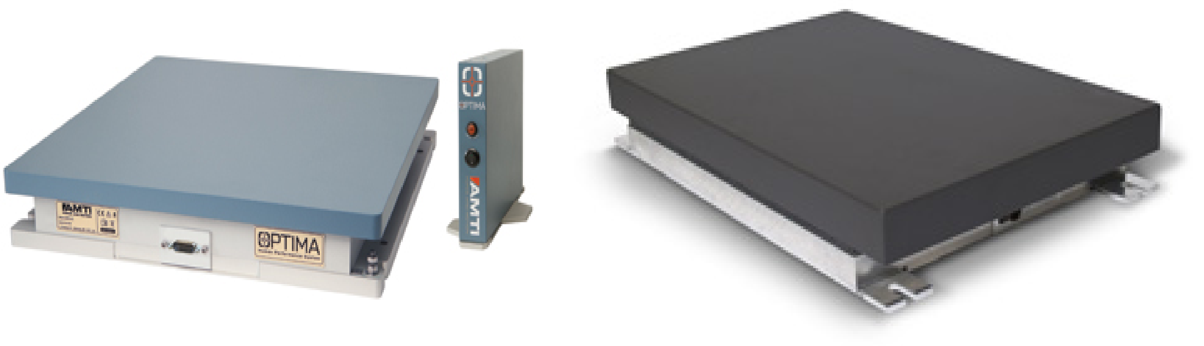
Figure 2.8: Insole systems

2.7.2 Force plates

AMTI's force plates [20] have an average CoP accuracy of just a fraction of a millimeter (typically less than 0.2), crosstalk values typically ±0.05% of applied load and measurement accuracy typically ±0.1% of applied load, figure 2.9a.

Bertec force plates [21] offer a variety of sizes and load ranges and can be used with any motion analysis system. It has 0% cross-talk with no signal interference from outside sources with 100% digital encoding. The force plate signal is fed into a variety of amplifiers — digital, analog or dual digital/analog output.

Bertec Force Plates simultaneously measure three force components along the x, y, and z axes and three moment components about the x, y, and z axes for a total of six outputs. Balance and jump plates measure the vertical force and two moments which can be used to compute the Center of Pressure (CoP), figure 2.9b.



(a) Optima force plate (b) Bertec force plate

Figure 2.9: Force Plate systems

3 GRF Acquisition

In this chapter is explained the work that was done throughout this project. The first part is relative to what was done at the hardware level and the second part to what was developed at the software level.

Throughout this chapter the sensors that measure vertical forces are referred as vertical sensors and the sensors that measure horizontal forces are referred as horizontal sensors despite the sensors being placed horizontally and vertically respectively, on the shoes.

3.1 Hardware

This section describes what hardware was used for this project and how it was prepared for the experiments that were made.

3.1.1 Instrumented shoes

To acquire the patient's gait a pair of previously built instrumented shoes were used. The shoes are capable of measuring the three components of the GRF and the CoP trajectory for the human gait analysis. The device was developed to acquire data in different places, inside and outside, and at different activities like walking or climbing stairs.

Each shoe is constituted by 2 parts. The front part is in contact with the fore-foot and the back part is in contact with the mid-foot and the rear-foot. Each part is made out of a top and bottom platform. The sensors are fixed on the bottom platform which are then covered by the top platform. The top platform has a sandal that supports feet with a shoe size up to number 46, figure 3.1.

Each foot has 16 sensors, 8 arranged horizontally to measure the vertical component of the GRF, and 8 arranged vertically placed in the corners of the shoes at a 45º angle in order to use a single sensor to decompose the forces applied horizontally into two distinct components. The location of the sensors can be seen in figure 3.3. The sensors used are

Figure 3.1: Instrumented shoe

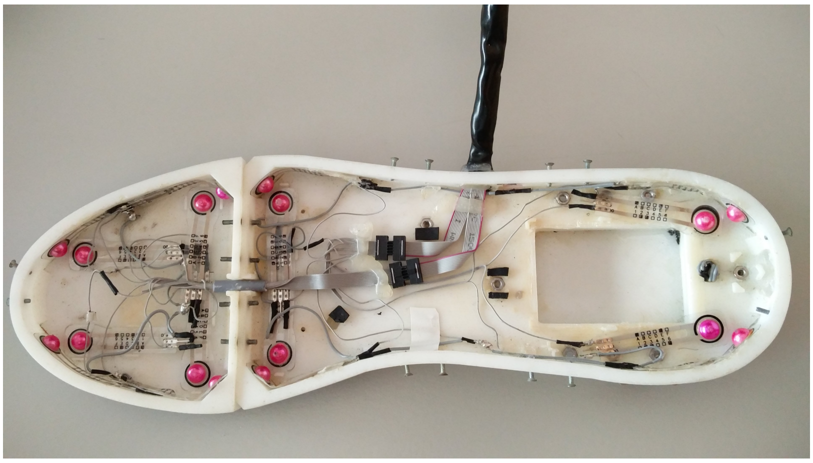


Figure 3.2: Bottom part of the instrumented shoe

Tekscan Flexiforce A201 with a 0–440 N (0–100 lb) force range for the vertical sensors and with a 0–110 N (0–25 lb) force range for the horizontal sensors.

The shoes were not functioning correctly and some changes were made in order to get them to work properly. There were some sensors that were broken and had to be taken off and replaced by new ones. Some of the wires that connected to the sensors were disconnected because they were too short and they would break from the solder, which connected the wires to the sensors, while walking with the shoes. This problem was fixed by soldering a wire extension to the existing wire and the sensor, creating a slack that allowed the wire to move without breaking during the walking experiments.

To connect the shoes to the acquisition boards flat cable is used. The flat cable that comes from the shoes connects to a flat cable extension that in turn connects to the flat cable that is attached to the acquisition board. These connections were made using a male to female connectors that needed to be secured using small rubber bands otherwise they

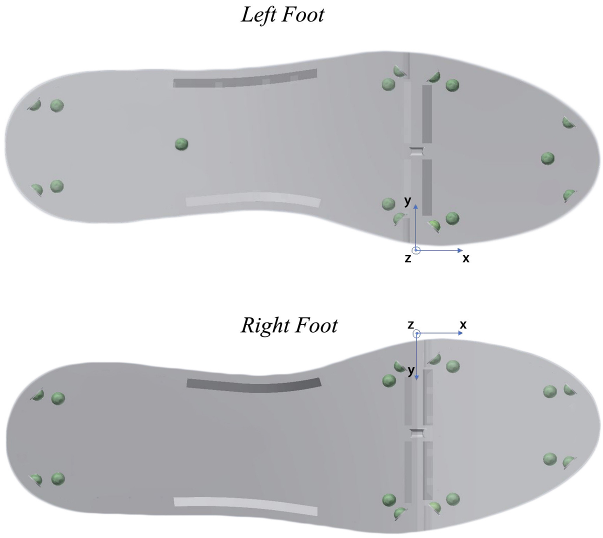


Figure 3.3: Sensors location in each feet

would disconnect. Even with the rubber bands there was some slack between the male and female connectors that sometimes would interrupt the connection between some wires. To solve this problem the male connector was replaced by a new one that has grapples which hold the female connector in place, securing a tight fit between the two.

3.1.2 Acquisition Module

The acquisition module includes an Arduino Mega 2560 board, a Bluetooth module and a 7.4 V, 2250 mAh rechargeable battery. The module is responsible for reading the sensors values and transmitting them over Bluetooth to the user device. During the experiments the modules are carried inside a bag that is secured to a waist belt not interfering with the normal human gait.

3.1.3 Force Sensors Calibration

Calibration is an important step because it helps obtaining more accurate results and neutralizing the drift of the sensors.

The sensors were calibrated to convert the voltage read by the board into the force applied to the sensor. This process consisted in applying different weights with a known mass to the sensor and reading the voltage. To have more accurate results the sensor should be calibrated in the circuit were it is going to be used. For this reason the sensor was connected to the acquisition module and the voltage was also read from the module. With all the results from this experiment a linear regression was made to obtain an equation that would fit best the behavior of the sensor. Since three types of sensors were used in the project, one type of horizontal sensors and two types of vertical sensors, this process needed to be done for all types of sensors. To obtain more precise results this process was made for each acquisition module. The assembly used for this calibration can be seen in figure 3.4.

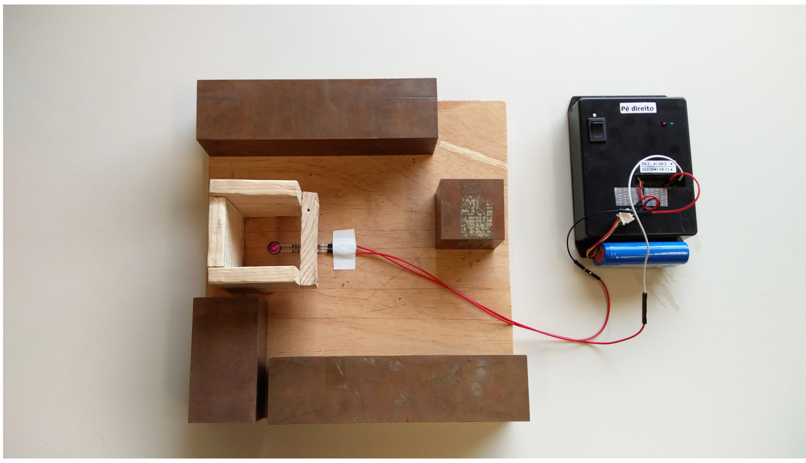


Figure 3.4: Sensors' calibration rig using the acquisition module

After the experiments a linear regression between Force and Voltage was obtained for every set of experiments. Figures 3.5, 3.7 and 3.9 represent the linear regression graphics for the sensors on the left shoe and figures 3.6, 3.8 and 3.10 represent the linear regression graphics for the sensors on the right shoe.

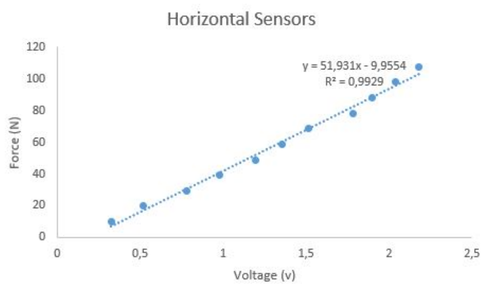


Figure 3.5: Linear regression for horizontal sensors AC136 (left)

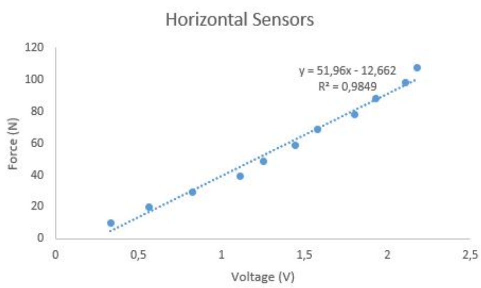


Figure 3.6: Linear regression for horizontal sensors AC136 (right)

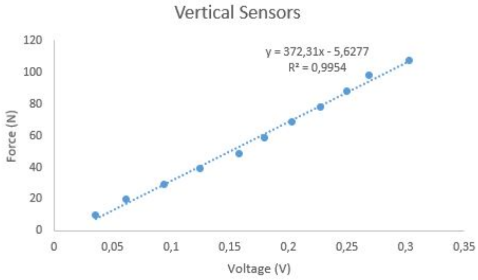


Figure 3.7: Linear regression for vertical sensors AE236 (left)

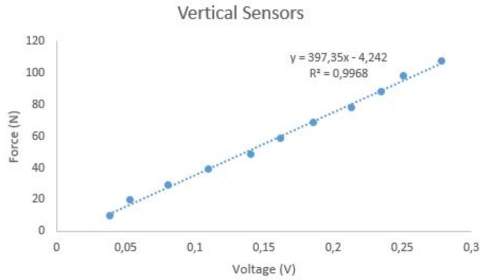


Figure 3.8: Linear regression for vertical sensors AE236 (right)

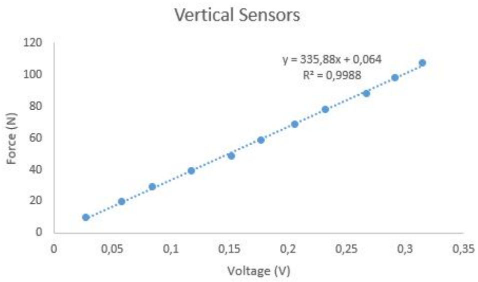


Figure 3.9: Linear regression for vertical sensors AE456 (left)

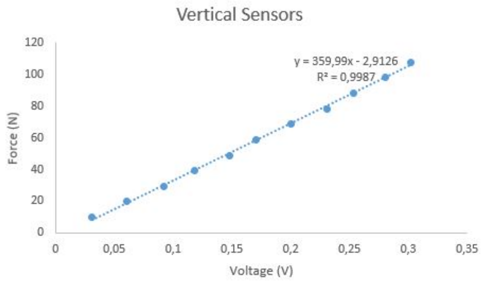


Figure 3.10: Linear regression for vertical sensors AE456 (right)

Having obtained equations for the three types of sensors it was considered that all sensors of the same type had similar behavior.

3.2 Hardware and Software communication

To establish a communication between the hardware and the software a Bluetooth connection was used. The data is sent by the acquisition module in 47 bytes frames. Each frame is initiated with 5 characters 'A' and it is terminated with 5 characters 'U' followed by a Carriage Return(CR) at the end. All the information is sent between these sets of characters starting with the time and then the values read from the 16 sensors. All values, including the time, are followed by the respective FCS (Frame Check Sequence) which was a result from the CRC (Cyclic Redundancy Check), figure 3.11.

Field	Beginning ("A")x5	Time	FCS	Sensor 1	FCS	...	Sensor 16	FCS	End ("U")x5	CR
Bits	40	26	6	10	6	...	10	6	40	8

Figure 3.11: Communication frame

This communication protocol was already developed in [22].

3.3 Software

The Android application was developed in Android Studio and its principal objective is to make it more practical to collect data from the instrumented shoes using an Android device (tablet or smartphone) instead of a computer. The existing Matlab application was improved and updated and new scripts were made in order to use the data collected with the Android app in Matlab.

In the existing Matlab application it is possible to acquire data at a 1 Hz rate and see in real time the values that are being read. It is also possible to set the acquisition rate to 100 Hz but the data acquired can't be seen in real time. The data is stored in a .mat file. The application also has the functionality of loading the .mat created during the acquisition and show different graphics of the GRF and the CoP along with the values obtained from each sensor at any instant.

3.3.1 Android application

This Android application was developed to read and store the data sent from the acquisition modules of the shoes. This application is useful since it can be installed on any Android device with Bluetooth running Android 4.0.3 Ice Cream Sandwich (API 15) or higher. The application was tested on Android 6.0.1 Marshmallow (API 23). Since a mobile phone is smaller and lighter than a laptop is also more practical to carry whenever a new person's gait needs to be measured.

The *BluetoothConnection* class used in this application was adapted from an application called BluetoothChat which is available on Android Developers' official GitHub website [23].

The developed application has two main options. In the first option the data are sent at a 1 Hz rate and in the second one the same data are sent at a 100 Hz rate. The first one will be used mainly to verify the correct operation of the sensors and the Bluetooth connection. The second one is recommended to be used to register the data while the patient is walking with the shoes. In both cases the data received is stored in a *.txt* file.

The user should pair the acquisition boards with the Android device in order for them to be recognized by the application. Paired devices have already made a connection and a code was used to approve that same connection. Connected devices implies that the devices are paired and with an active connection.

The acquisition modules Bluetooth names are "Pe_Direito" for the right foot and "Pe_Esquerdo" for the left foot.

Operating Mode

When the user starts the application, if the Bluetooth is turned off the application asks for permission to turn Bluetooth on, otherwise nothing is showed. The user should authorize this action because without Bluetooth the application is useless. The application also asks for permission to read and write files from and into the device, which once more the user should authorize. The last request only happens the first time that the application is used.

In the main page, figure 3.12, there are only two buttons that correspond to the two options described before. Each button will redirect the user to a new page once it is pressed.

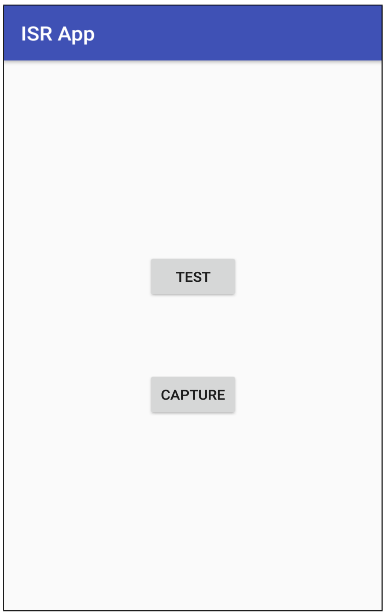


Figure 3.12: Main page of Android app

By pressing the "Test" button the acquisition rate is set to 1 Hz. A page similar to the one shown in figure 3.13 will appear in which it is possible to see all the devices that are paired with the Android device. The user should select the devices to connect ("Pe_Direito" and "Pe_Esquerdo") by tapping on the correspondent item on the screen. After a successful connection the green LED on the acquisition module will light up and it will be waiting to start sending the data. Once the second acquisition module is connected the user can press the start button to start receiving the GRF data. The stop button will stop the transmission of data and it will disconnect the acquisition modules from the Android device. The received data will be stored in the "Downloads" folder in two separated files, one for each foot, named "Ficheiro_de_teste_dir.txt" and "Ficheiro_de_teste_esq.txt".

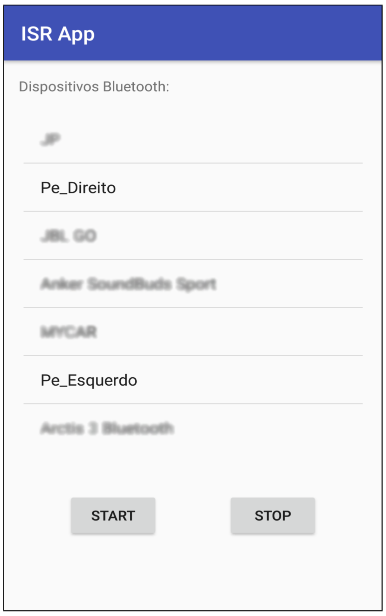


Figure 3.13: Test page of Android app

To capture data the "Capture" option should be used. The acquisition rate is then set to 100 Hz. After pressing the "Capture" button a question is prompted to the user asking how many acquisition boards are being used. This is important because it allows the user to use the application even if one of the acquisition boards is not operational. Thereafter it is shown to the user a page similar to the testing page but with fields that need to be filled, figure 3.14.

Before connecting to the acquisition modules the fields Name, Age, Weight, Height and Foot size must be filled and the Sex and Dominant foot options be selected. If one of these fields is not filled a message will appear on the screen informing the user that a field is empty. The file to store the data is created only after all the fields are completed.

In order to connect to the acquisition modules the user should proceed the same way it was described for the "Test" option.

In both options, Test and Capture, a small pop-up appears in the bottom of the screen indicating whether or not the device was able to connect with the acquisition modules.

At the end of each capture a message is displayed asking the user whether or not the fields should be maintained, figure 3.15. If the answer is affirmative the fields are left as they were and a new capture can be made by pressing the "Start" button again, otherwise all fields are cleared and must be filled again before a new capture. This functionality is useful because it eliminates the need for the user to rewrite all the fields when consecutive captures of the same person need to be made.

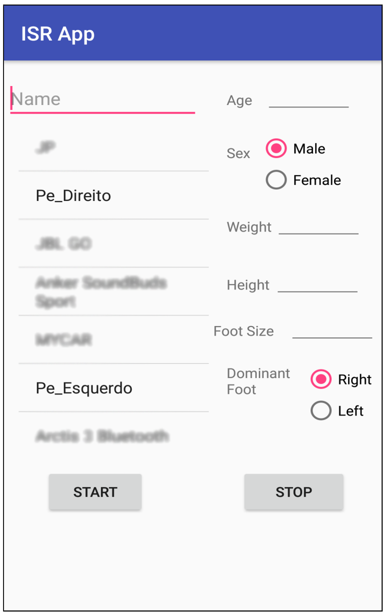


Figure 3.14: Capture page of Android app

Similar to what happens in the "Test" mode, the data sent by each acquisition module is stored in the "Downloads" folder. The name of the files will include the information about the patient as well as the date in which the capture was made. The file name will have the format "Name_Age_Sex_Weight_Height_FootSize_DominantFoot_Date" followed by "esq.txt" or "dir.txt" if it is the left or right foot.

When a new file is created if there is already a file with the same name, the new file name will have the format "NameVi_Age_Sex_Weight_Height_FootSize_DominantFoot_Date", where "i" is incremented for each file with the same name.

Memory space won't be a problem since a 2.5 minutes long experiment produces 2 files with approximately 750 kB each.

This application is available in both Portuguese and English.

3.3.2 Matlab application upgrade

In order to decode and use the data that was captured by the Android application on the existing Matlab application, the function *conv_txt_mat* was created. This function extracts the sensors data and the time data from one or two .txt files, depending on the number of acquisition modules that were used with the Android application.

This function is used in the *conversor.m* script and uses the values returned by the function *conv_txt_mat* to verify and correct the time values. When this script is executed

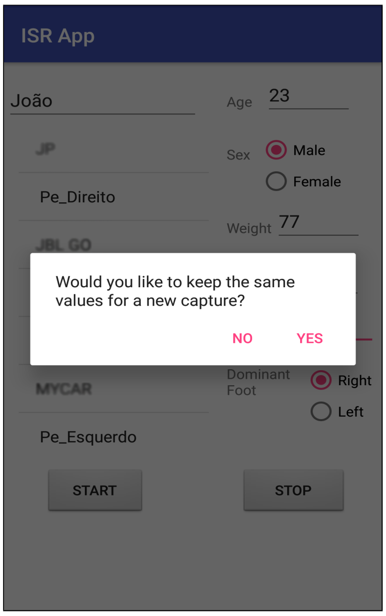


Figure 3.15: Displayed message after pressing Stop button

it is asked to the user to open two files. The user must open the file corresponding to the right foot first and then the file from the left foot. Afterwards the file name is parsed to obtain the patient's details as well as the date in which the capture was made.

Finally, all the information is stored in a .csv file and in a .mat file which can be used in the existing Matlab application.

In the existing Matlab application some changes were made to take in account possible transmission errors on the Android application. The script verifies if the time received is always different from zero. In the event that there was an error and the time is zero, the script checks if the time sequence was spaced for more than 2 time intervals and eliminates the stride in which the error took place. The duration between loading a file and its graphical representation was reduced in a third due the use of a more efficient Butterworth filter that is applied to the data.

Regarding the use of neural networks with the Extreme Learning Machine (ELM) method, developed in [24] to predict a patients gait some changes were also made. The train and test sets were completely separated with 75% of the data being used to train the neural network and the remaining 25% to test the network.

In order to utilize more data from each person a script was developed to not only use the average stride as an input to the neural network, but all the strides from each person. This will allow for a better training of the neural network since it will provide more data to the network.

4 Experimental Results

This chapter first describes how the friction coefficient was determined and the results obtained using different materials. It also describes various experiments using some of the friction coefficient analyzed and also a set of weights on one of the legs. All the experiments described in this section were performed by a 23 years old male with 1.79 m and 76 kg.

4.1 Friction coefficient readings

To determine the friction coefficient the friction force was measured and then divided by the normal force applied to the shoe.

To measure the friction force the Sauter FK10 force gauge was used, figure 4.1a. This device has a maximum range of 10 N and a precision of 0.005 N. In order to read forces bigger than 10 N a force lever was made, figure 4.1b, which had a 1:5 force ratio. Different materials were used to find out which combinations would provide a smaller friction coefficient. The different materials were fixed on the shoe sole using double sided duct tape.

In the beginning the shoe was weighted to know the normal force applied on the shoes. The normal force and the weight have the same value but opposite directions. The shoe weighted 9.030 N.

For each combination of materials several weights were added to the shoe. For each weight 5 measurements of the friction force were made and the mean was used to calculate the friction coefficient.

Different experiments were made combining the materials that were available. In the first experiment the rubber sole was tested with the granite floor, table A.1. In the second experiment a cardboard from a cereal box was attached to the sole and was again tested with the granite floor, table A.2. Using the same cardboard material an experiment was made between the rubber sole and the cardboard, table A.3. The next experiment was between the rubber sole and a 0.25 mm PVC sheet, table A.4. It was also measured the friction

(a) Sauter FK10 force gauge

(b) Force lever used in the experiments

Figure 4.1: Force gauge and force lever used

force between the sole with the PVC sheet attached and the granite floor, table A.5 and also between the sole with the PVC sheet and a PVC floor made of the same material as the PVC sheet, table A.6. Finally a 0.8 mm aluminium sheet was tested against the granite floor, table A.7.

With these results the friction coefficient was obtained for each combination using equation 2.2. The friction coefficients calculated can be seen in table 4.1.

Table 4.1: Friction coefficients

Materials	Friction coefficient
Rubber & PVC	0.67 ± 0.05
Rubber & cardboard	0.63 ± 0.04
Rubber & granite	0.47 ± 0.02
Cardboard & granite	0.31 ± 0.01
PVC & PVC	0.30 ± 0.01
PVC & granite	0.27 ± 0.01
Aluminium & granite	0.26 ± 0.03

4.2 Walking experiments

These experiments were performed in an approximately 18 meters granite corridor. The experiments consisted in walking at different speeds in order to acquire the patient's GRF and CoP. At the beginning of each experiment the patient had to stand on each feet for a few seconds in order to use the total registered force as the person's weight reference. Then the patient had to walk six times the corridor starting with a normal speed, then a little faster and then even a faster speed. During the fourth walk the patient should walk at a normal speed again followed by a slower speed and finally an even slower speed.

In the experiment three friction coefficient from previous readings were used. 0.47 corresponding to the shoe without any attachment, 0.27 corresponding the shoe with a PVC sheet attached to the sole and 0.26 corresponding to the shoe with an aluminium sheet attached to the sole.

This experiment was also carried out using a 3 kg ankle weights in the left leg, corresponding to 21% of the leg weight [25], which restricted the freedom of movement on the knee joint, similar to what happens in meniscus tears and knee arthritis.

All the data gathered from the experiments was acquired using the developed Android Application.

The coordinates referential shown in figure 3.3 was used on these experiments and the graphics shown in this section respect that referential.

To calculate the vertical component of the GRF (Fz) the forces obtained from the 8 vertical sensors were summed as follows:

$$F_{zD} = F_{2D} + F_{3D} + F_{6D} + F_{7D} + F_{9D} + F_{11D} + F_{14D} + F_{15D} \tag{4.1}$$

$$F_{zE} = F_{2E} + F_{3E} + F_{6E} + F_{7E} + F_{10E} + F_{11E} + F_{13E} + F_{16E} \tag{4.2}$$

The antero-posterior (Fx) and medio-lateral (Fy) components of the GRF are calculated in a similar ways but with the horizontal sensors, as it can be seen in the following equations:

$$F_{xD} = [(F_{5D} + F_{8D} + F_{10D} + F_{12D}) - (F_{1D} + F_{4D} + F_{13D} + F_{16D})] \times \frac{\sqrt{2}}{2} \tag{4.3}$$

$$F_{xE} = [(F_{1E} + F_{4E} + F_{9E} + F_{12E}) - (F_{5E} + F_{8E} + F_{14E} + F_{15E})] \times \frac{\sqrt{2}}{2} \tag{4.4}$$

$$F_{yD} = [(F_{4D} + F_{8D} + F_{10D} + F_{16D}) - (F_{1D} + F_{5D} + F_{12D} + F_{13D})] \times \frac{\sqrt{2}}{2} \tag{4.5}$$

$$F_{yE} = [(F_{1E} + F_{5E} + F_{9E} + F_{15E}) - (F_{4E} + F_{8E} + F_{12E} + F_{14E})] \times \frac{\sqrt{2}}{2} \tag{4.6}$$

The CoP trajectory is calculated based on the value and position inside the shoe of the 8 vertical sensors:

$$CoP_x = \frac{\sum_{i=1}^{8} x_i F_i}{\sum_{i=1}^{8} F_i} \tag{4.7}$$

$$CoP_y = \frac{\sum_{i=1}^{8} y_i F_i}{\sum_{i=1}^{8} F_i} \tag{4.8}$$

where x_i and y_i are the position of the i^{th} sensor on the x and y axes.

Due to a problem on the acquisition board assigned to the right foot the data presented next is only from the left foot.

All the curves obtained were filtered using a 2^{nd} order Butterworth filter with a 2.1 Hz cut off frequency.

4.2.1 Vertical component of the GRF

Experiment without weights

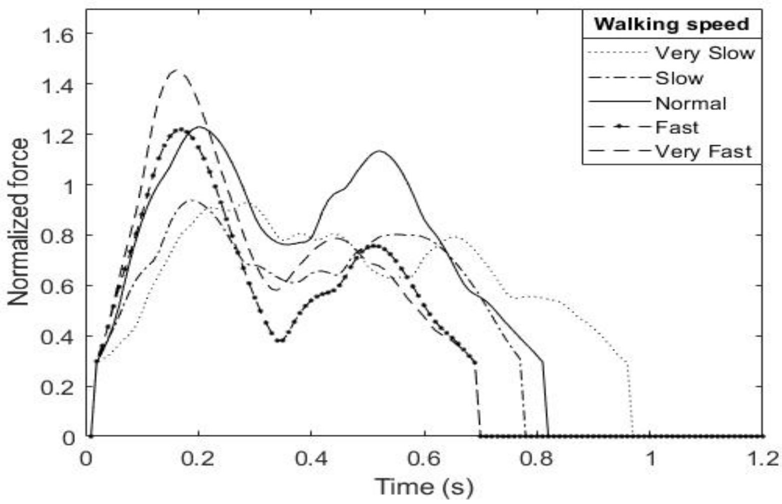


Figure 4.2: Coefficient of friction - 0.47

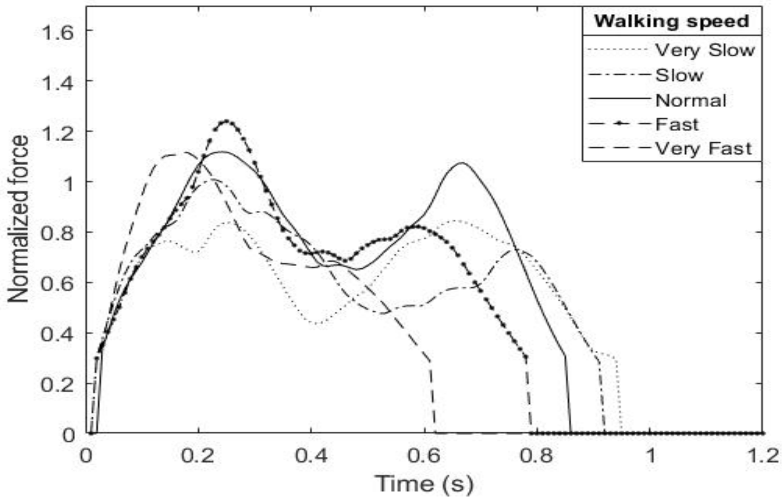


Figure 4.3: Coefficient of friction - 0.27

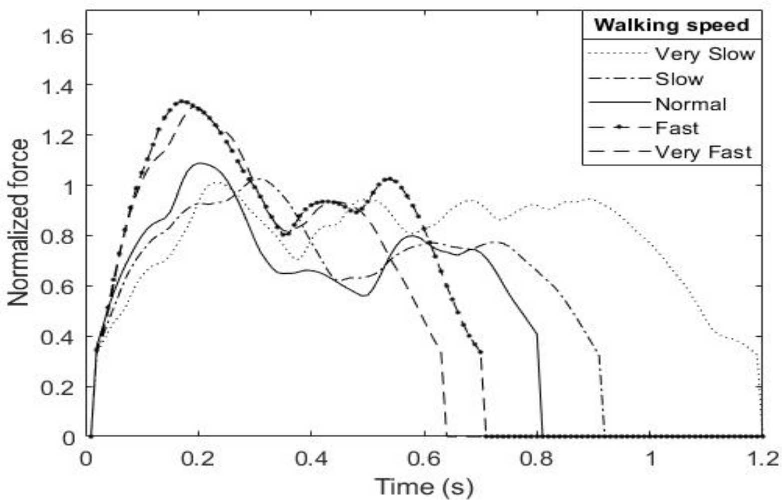


Figure 4.4: Coefficient of friction - 0.26

In figures 4.2, 4.3 and 4.4 it is possible to see the vertical component of the GRF for the five speeds with different friction coefficients. All the graphics were normalized for the person's weight.

It is noticeable from the graphics that the faster the walking speed was, the higher is the first peak corresponding to the contact of the heel on the ground. Regarding the second peak it is usually lower than expected as it should reach the same value as the first peak according to [2]. This can be due to only having one vertical sensor on the front of the shoe which might be insufficient to properly capture the forces that are applied on that area. It is also visible that the faster the person walked the shorter is the duration of the step.

Comparing the duration of the steps with different friction coefficients is possible to see some difference but that difference can be attributed to a non precise walking speed on each experiment. In general the curves are similar to what it was expected.

Experiment with weights

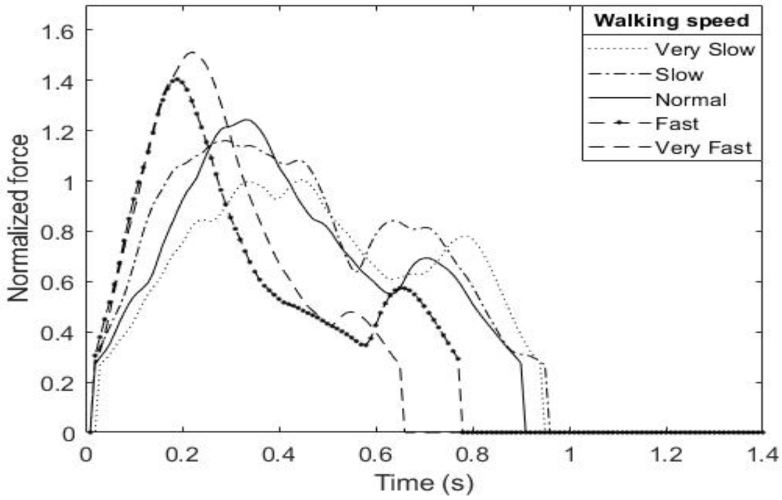


Figure 4.5: Coefficient of friction - 0.47

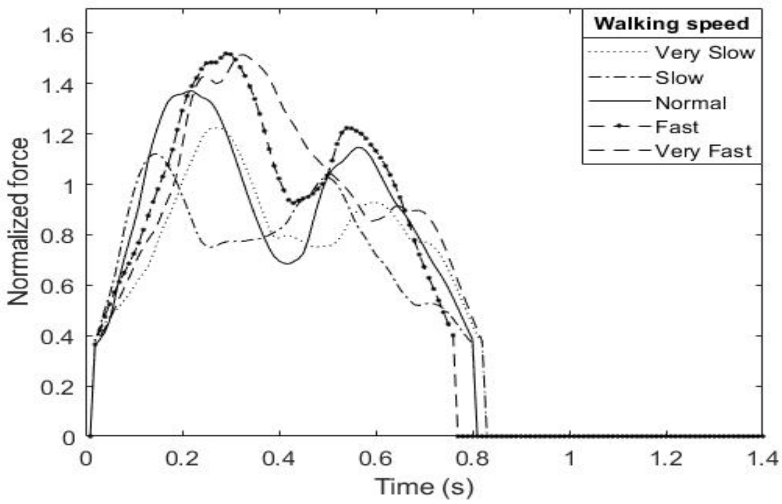


Figure 4.6: Coefficient of friction - 0.27

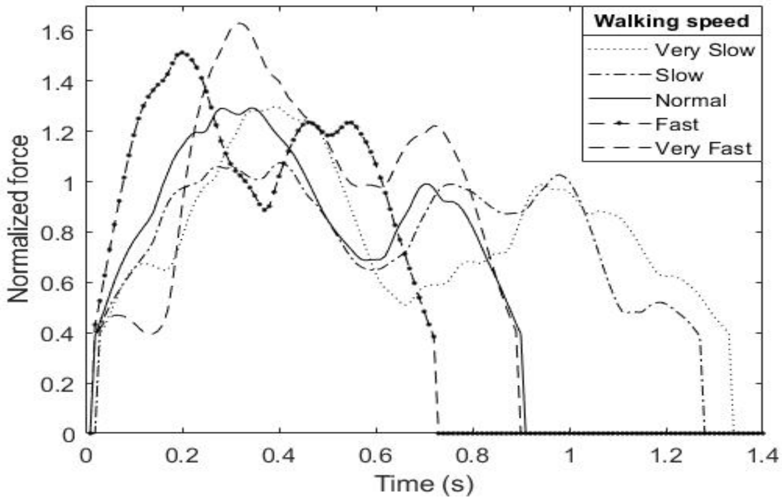


Figure 4.7: Coefficient of friction - 0.26

Figures 4.5, 4.6 and 4.7 represent the curves obtained for the vertical components of the GRF while using a 3 kg ankle weight. It is noticeable that the curves are similar to the curves presented without weights, but the peak values are slightly higher and the duration of the steps is also bigger than without weights. This results were expected since that the subject had more weight which results in higher forces and a higher difficulty to move the leg increasing the step duration.

4.2.2 Antero-posterior component of the GRF

Experiment without weights

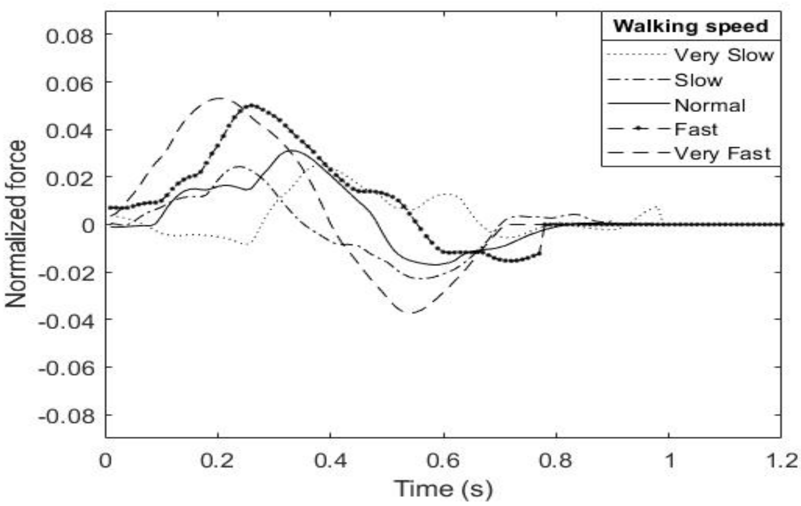


Figure 4.8: Coefficient of friction - 0.47

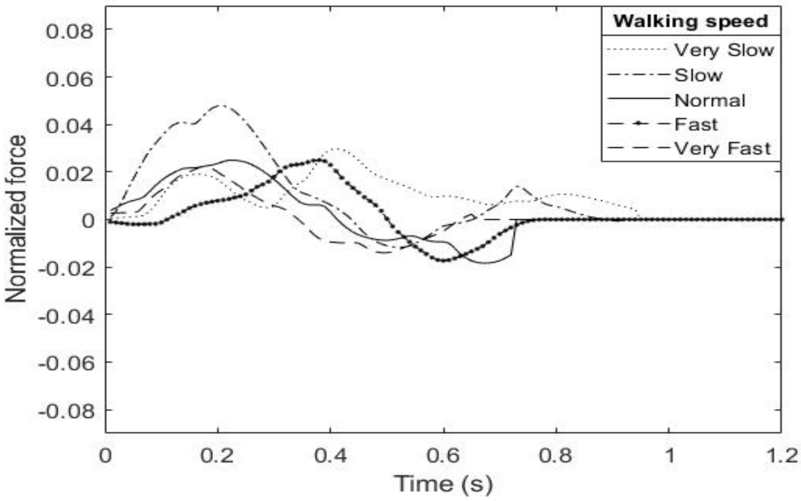


Figure 4.9: Coefficient of friction - 0.27

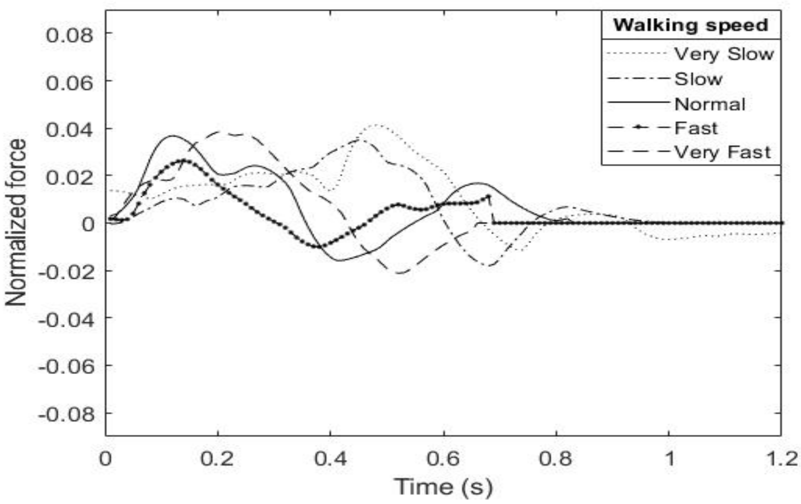


Figure 4.10: Coefficient of friction - 0.26

In figures 4.8, 4.9 and 4.10 are represented the results of the antero-posterior component of the GRF. In all the three cases studied the amplitude of the forces is between 3 and 4 times smaller than it is supposed to be.

In figure 4.8 the curve corresponding to the fastest walking speed is a good representation of the antero-posterior component of the GRF. At slower speeds the curves aren't as perfect because at lower speeds the forces absorbed on the heel strike and created on toe-off are also smaller causing more imperfect readings.

Since in figures 4.9 and 4.10 the friction coefficient is significantly lower than in figure 4.8 the curves that represent the higher speeds are less perfect, even though it is still possible to see some similarity with the standard curves for the different speeds.

Experiment with weights

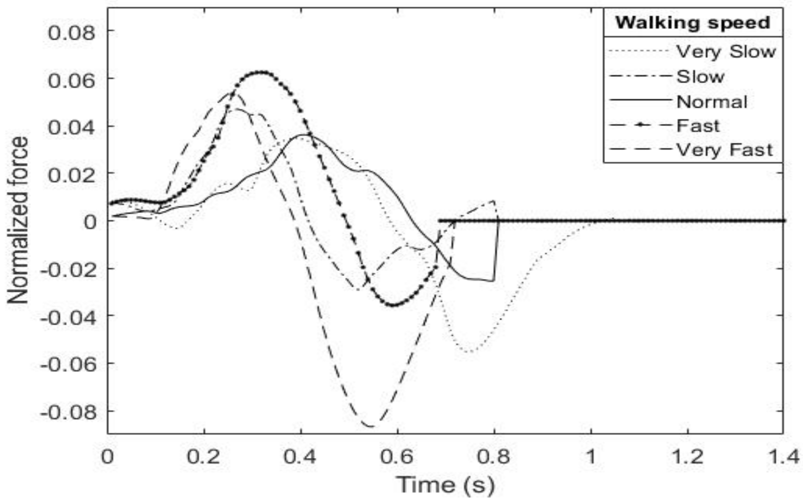


Figure 4.11: Coefficient of friction - 0.47

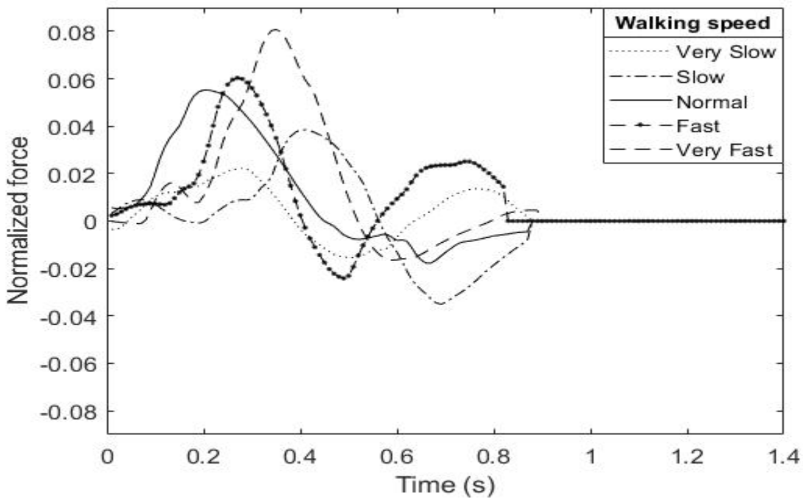


Figure 4.12: Coefficient of friction - 0.27

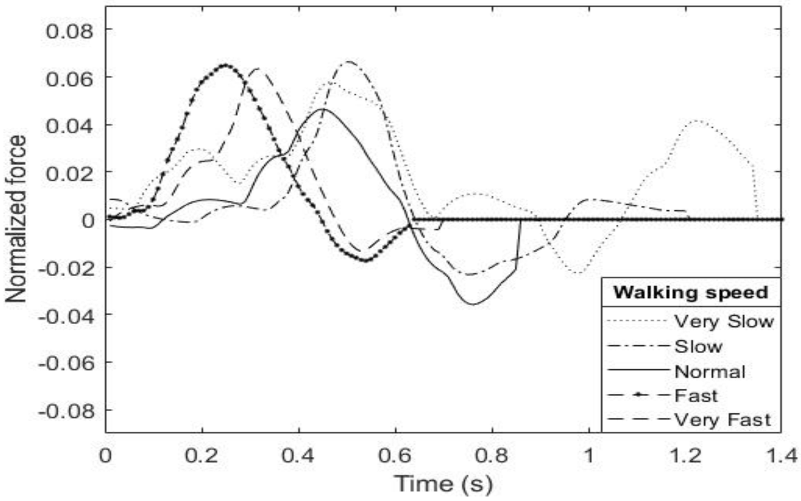


Figure 4.13: Coefficient of friction - 0.26

The curves representing the antero-posterior component of the GRF, figures 4.11, 4.12 and 4.13, maintain the same peak values on most of the cases. In figure 4.11 the negative peak on the fastest walking peak is more than double the same value on the experiment without weights which indicates that, in this case, twice the force was used to move forward. On the other speeds the force needed was similar to the experiment without weights.

With lower friction coefficients, figure 4.12 and figure 4.13 the force values are generally higher with weights.

4.2.3 Medio-lateral component of the GRF

Experiment without weights

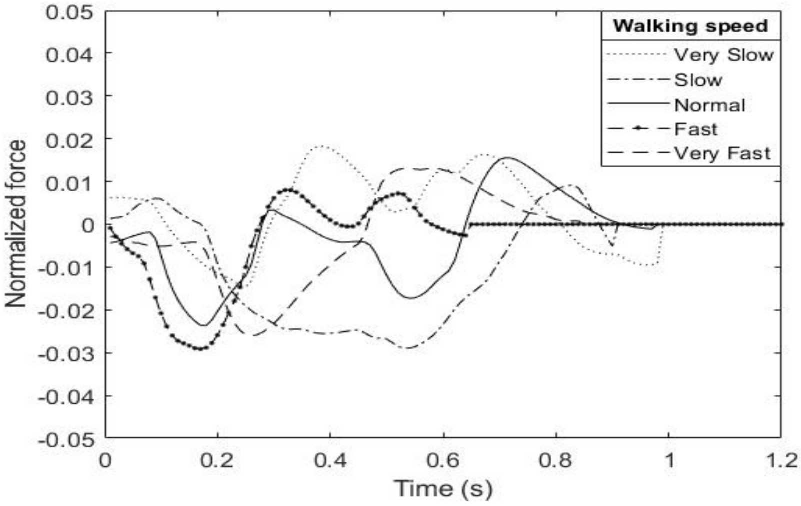


Figure 4.14: Coefficient of friction - 0.47

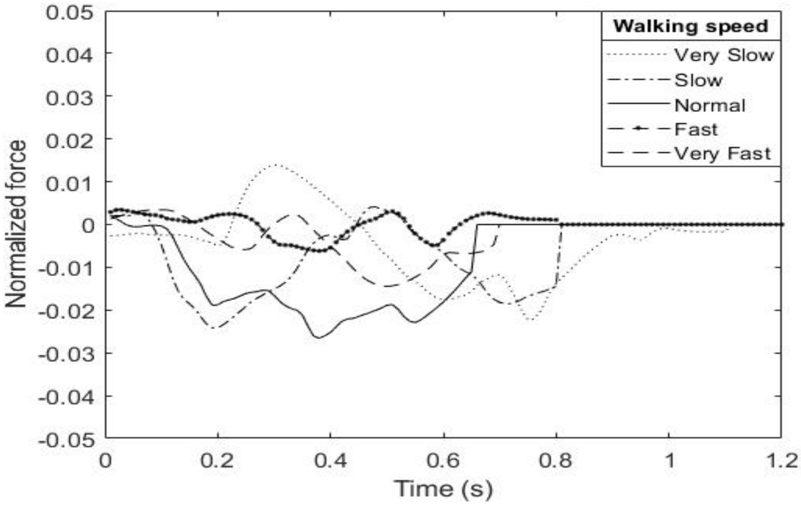


Figure 4.15: Coefficient of friction - 0.27

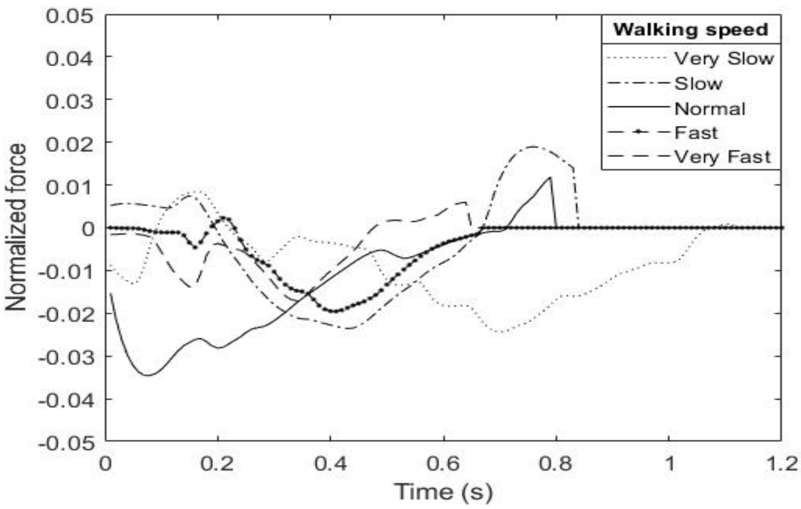


Figure 4.16: Coefficient of friction - 0.26

The medio-lateral component of the GRF was the most inaccurate of all the components. The experiment with the higher friction coefficient, figure 4.14, has the worst results from the three different components with the majority of the curves having positive values. The experiments with the lower friction coefficients, figures 4.15 and 4.16, have more similarity with the expected curve with most of the speed curves having a negative value on the majority of the graphic.

Experiment with weights

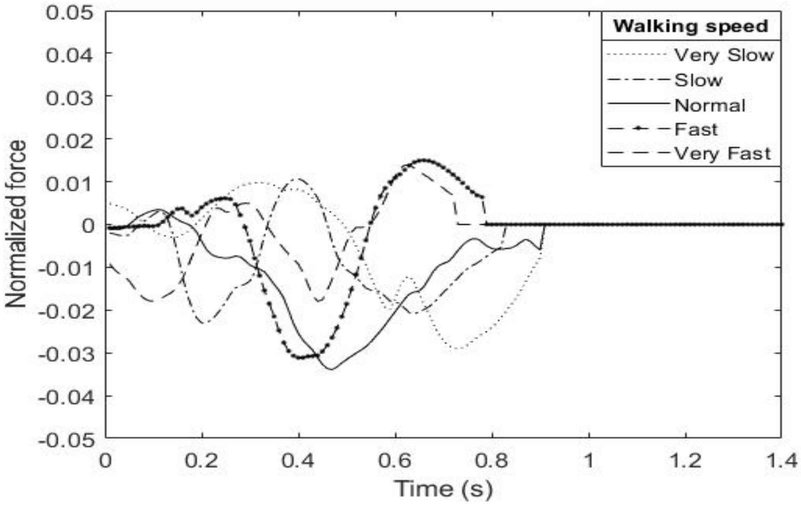


Figure 4.17: Coefficient of friction - 0.47

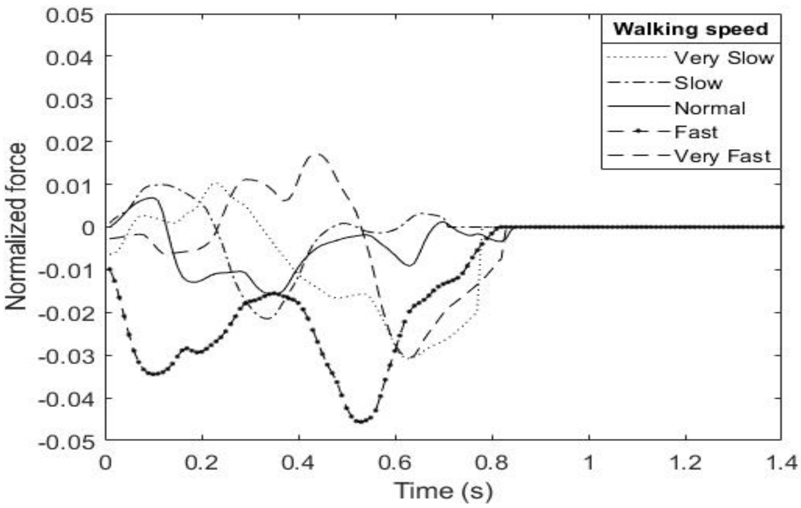


Figure 4.18: Coefficient of friction - 0.27

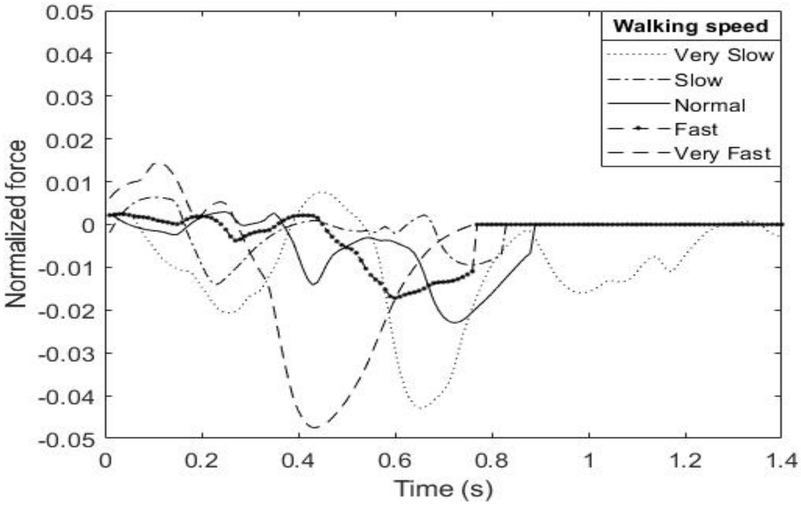


Figure 4.19: Coefficient of friction - 0.26

Figures 4.17, 4.18 and 4.19 represent the medio-lateral component of the GRF acquired while using weights. A reduction of positive values is noticeable in all graphics. The curves are now more similar to the standard curve. This also means that there is more stability on the y axis due to the weights strapped around the ankle.

4.2.4 CoP

Experiment without weights

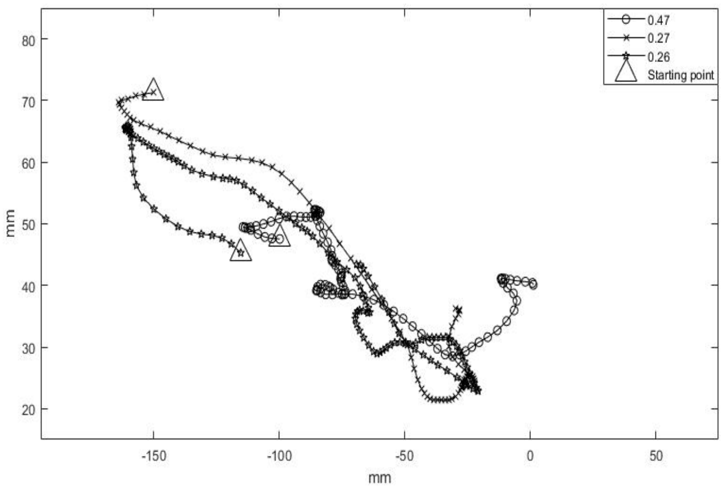


Figure 4.20: Very slow walking speed

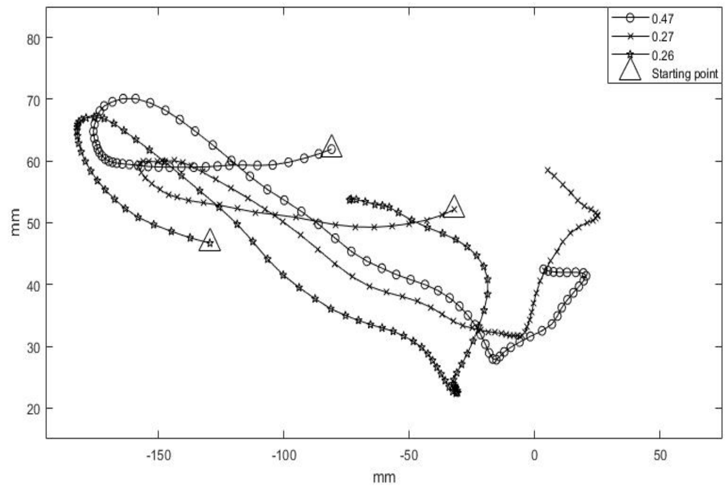


Figure 4.21: Normal walking speed

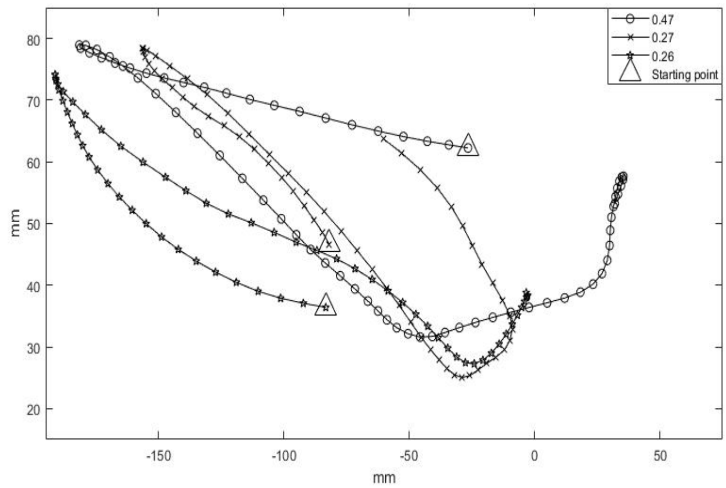


Figure 4.22: Very fast walking speed

From figures 4.20, 4.21 and 4.22 it is noticeable that the sensors on the fore-foot are not being activated as well as they are supposed to be because the CoP along the x axis does not surpasses 40 mm and the most forward vertical sensor is located at 75 mm.

Regarding the movement of the CoP along the x axis, CoP_x, the graphics, figure 4.21 and figure 4.22, show that it starts at a negative value and then reduces to around -160/-180 mm. This is normal since when no forces are being applied it is not possible to calculate the CoP. To overcome this problem an interpolation is made which puts the CoP around the center of the shoe. The CoP_x then moves towards the heel as the heel strike is registered. Finally the CoP_x moves towards the fore-foot when the toe off occurs. In figure 4.20 since the walking speed is slower than the other graphics, at the higher friction coefficient the

CoP_x does not go below -130 mm and with a friction coefficient of 0.26 the CoP_x doesn't surpasses -20 mm. This is explained for the fact that at slower speed the foot as a more flat contact with the ground with a more contact surface at every moment.

The movement of the CoP along the y axis, CoP_y, shows that it moves from the lateral to the medial part of the foot and tends to return to the middle of the foot, around 50 mm. The return to the middle of the y axis was expected since the last vertical sensor to acquire data is centered on the middle as can be seen in figure 3.3.

Experiment with weights

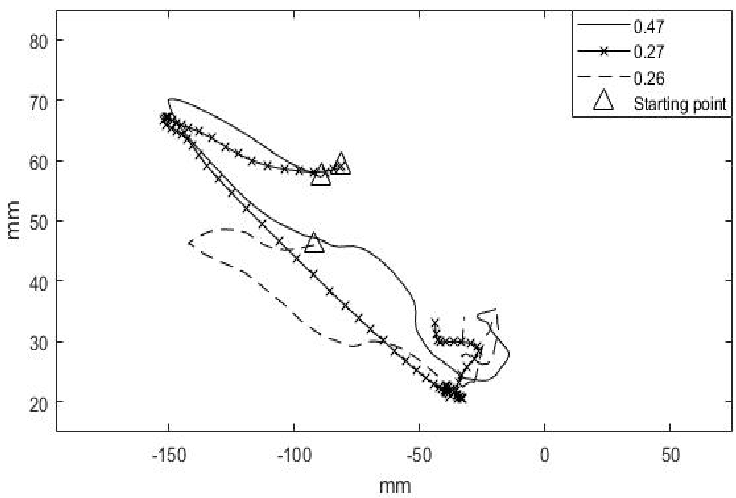


Figure 4.23: Very slow walking speed

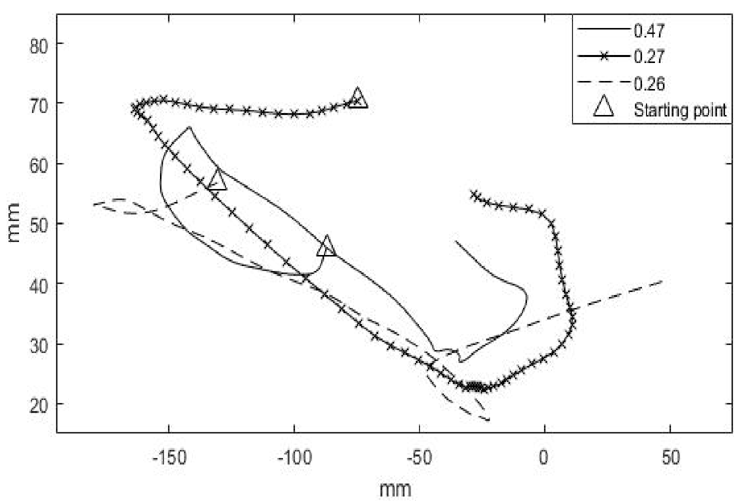


Figure 4.24: Normal walking speed

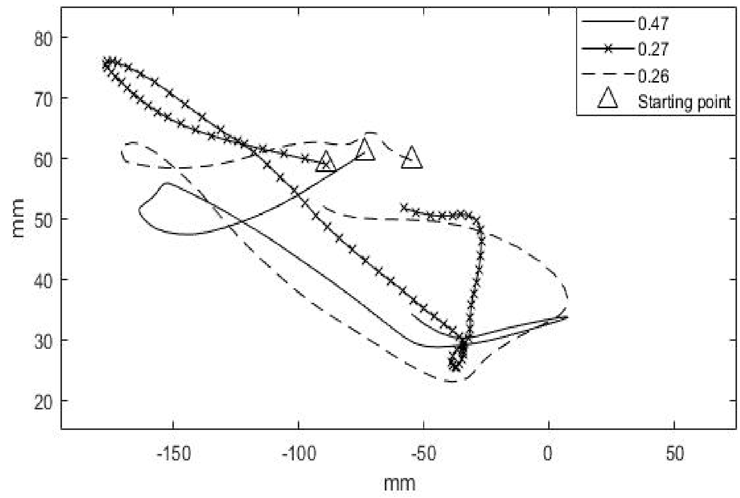


Figure 4.25: Very fast walking speed

The curves displayed on the 3 CoP graphics in figures 4.23, 4.24 and 4.25 have a similar behaviour as the ones obtained without the use of weights.

5 Conclusion and future work

In order to complete the proposed objectives different areas of study were involved.

The first objective was completed by leaving the prototype shoes working. This was a crucial objective because the rest of the work was dependant on the good operation of the shoes, otherwise no data could be collected. Both acquisition boards were working properly until the beginning of the experiments, at which point the board assigned to the right foot stopped working and there was no time to order all the necessary materials and build a new one.

The development of the Android application was completed for its main use, acquiring data at a 100 Hz rate. For this purpose the application works properly, taking in consideration the use of one or two acquisition boards and having the necessary restrictions to not let the user start the acquisition without filling all the parameters.

Even though it was not a defined objective, the Matlab scripts created became an important piece of this work providing an easy way to convert the acquired data using the Android application into a file that could be interpreted using the Matlab application.

In the end all of the work done allowed to acquired and analyze the various GRF components as well as the CoP using different friction coefficients. To better validate the results the experiments should have been carried out with more people.

Regarding the experiments with the two lower friction coefficients, 0.27 and 0.26, even though the values are close to one another the results weren't that similar since the materials involved have different properties, a 0.25 mm PVC sheet and a 0.8 mm aluminium sheet.

In the future, with the second acquisition module working, new data can be acquired and be used to train the neural networks. The number of people who's gait will be acquired should be large. The physical characteristics of those people should also be diverse so that after training the network it could be used to correctly predict any people's gait.

The Android application can also be improved by using the Test option to display a matrix corresponding to the 32 sensors of both feet that will indicate if any sensor is not acquiring data. This will be a great improvement because, as for now, it requires the use of a computer to see if a sensor is working or not.

With the integration of a screw behind each horizontal sensor that would move the sensor towards or away from the top part of the shoes, a better contact with the sensor would be achieved improving the quality of the acquired data.

New materials can also be tested to try to reduce the friction coefficient to an even lower value.

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Appendix A

Friction Coefficient measurements

Table A.1: Rubber sole vs granite floor

Shoe	Shoe + 1kg
4.115 N	9.025 N
4.015 N	9.255 N
4.035 N	9.525 N
4.265 N	8.515 N
3.980 N	8.575 N

Table A.2: Cereal box cardboard sole vs granite floor

Shoe + 1kg	Shoe + 8kg	Shoe + 9kg
5.665 N	25.700 N	31.400 N
6.110 N	28.500 N	30.525 N
5.715 N	28.175 N	28.750 N
5.960 N	27.450 N	32.375 N
6.000 N	29.350 N	32.050 N

Table A.3: Rubber sole vs Cereal box cardboard

Shoe
5.310 N
6.035 N
5.690 N
6.190 N
5.410 N

Table A.4: Rubber sole vs PVC sheet

Shoe
5.705 N
6.635 N
5.560 N
6.550 N
5.875 N

Table A.5: PVC sheet sole vs granite floor

Shoe + 8kg	Shoe + 9kg	Shoe + 10kg	Shoe + 11kg
21.675 N	25.050 N	28.925 N	30.9250 N
22.975 N	27.650 N	30.075 N	32.5750 N
23.975 N	26.550 N	29.450 N	33.6250 N
24.150 N	26.200 N	29.250 N	31.7750 N
23.800 N	26.425 N	30.025 N	32.5000 N

Table A.6: PVC sole vs PVC floor

Shoe + 8kg	Shoe + 9kg	Shoe + 10kg
27.300 N	27.875 N	32.725 N
26.350 N	28.775 N	31.750 N
24.400 N	30.875 N	32.625 N
25.675 N	29.250 N	31.900 N
25.050 N	28.875 N	31.775 N

Table A.7: Aluminium sheet sole vs granite floor

Shoe + 8kg	Shoe + 10kg	Shoe + 11kg
22.775 N	25.500 N	31.775 N
22.625 N	27.100 N	30.175 N
21.625 N	28.000 N	28.775 N
24.975 N	28.025 N	31.100 N
23.275 N	27.600 N	31.925 N

Appendix B

Matlab scripts

Listing B.1: conv_txt_mat function

```
function [filename, tempo, dados] = conv_txt_mat()
% first we ask to open the file
filename = uigetfile({'*.txt';'*.*'},'File Selector');

% open the file
fileID = fopen(filename,'r');

if (fileID < 0)
        printf('Error:could not open file\n');
end

% put the info inside the file into an array
A = fscanf(fileID,'%c');

% convert to integers
A=unicode2native(A);
A=uint32(A);

% close the file
fclose(fileID);

% pattern to look for
B = [13 65 65 65 65 65];
% indexes where 13(\n) is
K = strfind(A,B);
```

```
data = zeros(size(K,2), 36);
tempo = zeros(size(K,2), 1);
dados = zeros(size(K,2),16);

% clear data
for i=1:size(K,2)
    data(i,:) = A(K(i)-41:K(i)-6);
end

% extract data
for i=1:size(K,2)
    %------ TIME -------
    tempo(i,1)=typecast(uint8(data(i,(1:4))), 'uint32');

    %------- DATA -------
    index1=5;
    for j=1:16
        dados(i,j)=bitor(bitshift(data(i,(index1+1)),8),data(i,(index1)));
        index1=index1+2;
    end
end

end
```

Listing B.2: conv_txt_mat function

```
clc, clear

missing_dir = false;
missing_esq = false;

% para o caso de apenas uma das placas estar a funcionar
try
    [filename, tempo_dir, dados_dir] = conv_txt_mat(1);
catch ERROR
    if strcmp(ERROR.identifier, 'MATLAB:badfilename_mx')
        missing_dir = true;
    end
end
```

```
try
    [filename, tempo_esq, dados_esq] = conv_txt_mat(0);
catch ERROR
    if strcmp(ERROR.identifier, 'MATLAB:badfilename_mx')
        missing_esq = true;
    end
end

% se nao for selecionado nenhum fcheiro
if missing_dir == true && missing_esq == true
    return
end

if missing_dir
    tempo_dir = tempo_esq;
    dados_dir = zeros(size(dados_esq));
end

if missing_esq
    tempo_esq = tempo_dir;
    dados_esq = zeros(size(dados_dir));
end


size_dir = size(tempo_dir,1);
size_esq = size(tempo_esq,1);

if (size_dir ~= size_esq)
    if size_dir > size_esq
        tempo_dir = tempo_dir(1:size_esq,:);
        dados_dir = dados_dir(1:size_esq,:);
    else % size_dir < size esq
        tempo_esq = tempo_esq(1:size_dir,:);
        dados_esq = dados_esq(1:size_dir,:);
    end
end

% retirar os diferentes valores do nome do ficheiro
C = strsplit(filename,'_');
```

```
if size(C,2) < 8

    filename=filename(1:end-8);

    save(filename,'dados_dir','dados_esq','tempo_dir','tempo_esq');

else

nome = C{1};
idade = C{2};
sexo = C{3};
peso = C{4};
altura = C{5};
tamanho_pe = C{6};
pe_dominante = C{7};
date = C{8};

offset_dir = zeros(1,16);
offset_esq = zeros(1,16);
fa = 100;
fc = 6;

% caso a aplicacao seja usada em ingles
if strcmpi(sexo, 'Male')
    sexo = 'Masculino';
elseif strcmpi(sexo, 'Female')
    sexo = 'Feminino';
end

if strcmpi(pe_dominante, 'Right')
    pe_dominante = 'Direito';
elseif strcmpi(pe_dominante, 'Left')
    pe_dominante = 'Esquerdo';
end

filename=strcat(nome,'_',idade,'_',sexo,'_',date);

% gravar em ficheiro .mat
save(filename,'peso','altura','dados_dir','dados_esq','offset_dir', ...
    'offset_esq','fa','fc','tempo_dir','tempo_esq','tamanho_pe',...
```

```
    'pe_dominante');

% gravar em ficheiro .csv
Tabela = [dados_dir(:,1),dados_dir(:,2),dados_dir(:,3),dados_dir(:,4),..
    dados_dir(:,5),dados_dir(:,6),dados_dir(:,7),dados_dir(:,8),...
    dados_dir(:,9),dados_dir(:,10),dados_dir(:,11),dados_dir(:,12),...
    dados_dir(:,13),dados_dir(:,14),dados_dir(:,15),dados_dir(:,16),...
    dados_esq(:,1),dados_esq(:,2),dados_esq(:,3),dados_esq(:,4),...
    dados_esq(:,5),dados_esq(:,6),dados_esq(:,7),dados_esq(:,8),...
    dados_esq(:,9),dados_esq(:,10),dados_esq(:,11),dados_esq(:,12),...
    dados_esq(:,13),dados_esq(:,14),dados_esq(:,15),dados_esq(:,16),...
    double(tempo_dir),double(tempo_esq),
    repmat(str2double(altura),size(dados_dir,1),1),...
    repmat(str2double(peso),size(dados_dir,1),1),...
    repmat(str2double(idade),size(dados_dir,1),1),...
    repmat(str2double(tamanho_pe),size(dados_dir,1),1)];

Header = {'Sensor1_dir' 'Sensor2_dir' 'Sensor3_dir' 'Sensor4_dir' ...
    'Sensor5_dir' 'Sensor6_dir' 'Sensor7_dir' 'Sensor8_dir' ...
    'Sensor9_dir' 'Sensor10_dir' 'Sensor11_dir' 'Sensor12_dir' ...
    'Sensor13_dir' 'Sensor14_dir' 'Sensor15_dir' 'Sensor16_dir',...
    'Sensor1_esq' 'Sensor2_esq' 'Sensor3_esq' 'Sensor4_esq' ...
    'Sensor5_esq' 'Sensor6_esq' 'Sensor7_esq' 'Sensor8_esq' ...
    'Sensor9_esq' 'Sensor10_esq' 'Sensor11_esq' 'Sensor12_esq' ...
    'Sensor13_esq' 'Sensor14_esq' 'Sensor15_esq' 'Sensor16_esq',...
    'Tempo_dir', 'Tempo_esq', 'Altura', 'Peso', 'Idade', 'Tamanho do pe'};
textHeader = strjoin(Header, ',');

%write header to file
fid = fopen(strcat(filename,'.csv'),'w');
fprintf(fid,'%s\n',textHeader);
fclose(fid);

%write data to end of file
dlmwrite(strcat(filename,'.csv'),Tabela,'-append');

end


end
```