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Rowing training assessment using smart sensors

Ana Catarina Rodrigues Gião Santos

Master Degree in, Telecommunications and Computer Engineering

Supervisor:
PhD Octavian Adrian Postolache, Associate Professor with Habilitation,
Iscte - Instituto Universitário de Lisboa

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TECNOLOGIAS
E ARQUITETURA

Department of Information Science and Technology

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Abstract

Technology is evolving, and the appearance of new smart sensors is increasing. The use of sensors to improve performance during sports activities is getting more relevant than ever. Thus, a system capable of obtaining real-time force metrics of a rowing machine's footplate and seat was developed. The force sensors on the footplate, connected to the Shimmer3 will obtain the heels and toes force information sent through a Bluetooth connection to the developed mobile application. In this application, the rower can understand during training how to improve his rowing technique. Additionally, it is possible to access the history information with more metrics and the evolution of all training sessions. Finally, this system can also detect the force exercised on the seat and the distribution of the centre of force, helping the athlete understand which side it tends to lean in all phases of the rowing stroke.

Keywords: Rowing, Ergometer, Smart Sensor, Force Mapping and Mobile Application.

Resumo

Com o desenvolvimento da tecnologia e aparecimento de novos sensores inteligentes, é cada vez mais imergente a utilização dos mesmos para melhorar a performance de atletas durante a atividade desportiva. Deste modo, foi desenvolvido um sistema capaz de obter em tempo real métricas de força do pau de voga e slide de uma máquina de remo. Os sensores de força no pau de voga, ligados ao Shimmer3 vão obter a informação de força dos calcanhares e ponta do pé que serão enviados através de uma ligação Bluetooth para a aplicação móvel desenvolvida. Nesta aplicação, o remador consegue perceber durante o treino como melhorar a sua técnica de remada. Adicionalmente, ainda é possível aceder a um histórico de informação onde se encontram mais métricas e a evolução de todos os treinos. Por fim, este sistema também consegue detetar a força exercida no slide bem como a distribuição do centro de força ajudando o atleta a perceber para que lado é exercida mais pressão em todas a fases da remada.

Palavras-chave: Remo, Ergómetro, Sensor Inteligente, Mapeamento de Força e Aplicação Móvel.

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CHAPTER 1

Introduction

Do you use the indoor rowing machine in the most effectively way possible? Do you realize which position you do when you row? Do you want to improve your pace?

In this chapter will be described the motivation, objectives, and research questions. Sports activities meet a broad range of needs linked to the multilateral development of the personality and improvement of skills increasing the quality of life [1]. In this project were involved six rowing athletes where their performance was improved while rowing in an indoor rowing machine.

1.1. Motivation

Sensing technology is advancing rapidly, gathering feedback from our body and the environment we constantly interact with, is demonstrating to be more relevant than ever. Athletes, whether professionals or amateurs, want to improve in the training, therefore there is the need to use new sensing technologies. The pilot study described gets insights, using various technologies, from an athlete rowing in an indoor rowing machine.

The indoor rowing machines, often known as ergometers, were initially developed to simulate the action of the watercraft rowers. Although the ergometer has been established as a different sport from rowing, the biomechanics of their exercises are very similar. Outdoor rowing training may not always be feasible since the performance of rowers can be affected by unpleasant weather conditions. Indoor training conducted with rowing machines offers a valuable alternative to outdoor practice, which has resulted in rowing clubs, teams, and associations often with large quantities of regularly used ergometers.

In rowing races, success is achieved by the minimum time to complete a pre-defined course track of commonly two kilometres. Thus, mathematically, the main performance metric for competitive rowers is the average boat speed to finish the course. Attaining a faster boat speed requires not only a physical effort but also an appropriate boat setup and a skilful technique to transfer the propulsion forces into speed. Therefore, fitness and technique are crucial for competitive rowers. The key to a powerful drive in rowing is an accurate application of power generated by the legs, trunk, and arms. However, the optimal application of power may vary between athletes due to differences in their biomechanical features. [2]

Although overuse and intense rowing training schedules can be a cause for injuries, a good technique is crucial to prevent injuries which can be very common in rowing, specifically, lower back pain, rib stress injury, shoulder injury, knee or forearm and wrist [3].

This proposal uses metrics derived from sensors to improve the rower's technique. The results will be used to investigate if, and to which extent, information retrieved from the sensors may improve the technical skills of the athlete during the complex sport of rowing.

The author of this project is involved in rowing since 2008, with several participations in national championships and international regattas. It has allowed a depth knowledge in the sport.

1.2. Objectives

In this dissertation, the aim is to develop a sensing system for an indoor rowing machine in which several sensors have been considered and attached to the machine, providing the most benefit to the user. Such as, four force sensors to retrieve metrics from the footplates, also called as footstops, which will give real-time feedback to the athlete to know how his engaging their feet and legs with the ergometer. This fundamental knowledge will help develop and understand whether if the rower is using the rowing machine with the correct technique.

In addition, a CONFORMat system in the slide is used to store, analyse, and visualise the information. Therefore, improving the rower performance by allowing to understand the balance, position and force applied during the practice.

A mobile application was developed to present the information coming from the force sensors. The purpose of the system is to facilitate and improve the rower's technique in the train, introducing new metrics to evaluate the performance of the rower and improve their technique complementing the traditional training. Such information is also useful to coaches since they can evaluate the feedback after the training session.

1.3. Research questions

This research was not intended to answer specific questions about rowing, such as, decide what the optimal footplate force is, or the best way to row. Instead, it was intended to develop a tool that could be used to answer such questions. Specifically, the sensors used were designed to acquire or measure:

- The forces at the rower's feet
- The forces and the balance in the rower's seat

The main research question that will be answered is: 'How can force sensors can improve an indoor rower technique?'

To answer this question, the following sub-questions will also be answered:

1. How to design a sensor for giving feedback in rowing?
    a. What are the technological standards for sports sensor?
    b. What are the parameters for rowing?

c. How to measure rowing activities?

2. Does the information coming from the force sensor will be able to improve a rower technique?
3. Can rowing technique be analysed and corrected using force sensors and digital feedback.
4. Can be a mobile application used for giving feedback while rowing in a rowing machine

CHAPTER 2

State of the art

In this chapter, is presented a review of the existing projects and commercial products related to sensors in rowing and rowing itself.

2.1. Sensors

Sensor is defined as a device able to acquire, process and transmit/show data to users [4]. Here it will be present a research into the relevant sensors for this project.

Sensors can be divided into two categories. Wearable sensors that need to be attached to the human body. And non-wearable sensors that do not require contact with the human body.

2.1.1. Smart sensors in rowing

Smart sensors are identified by having their own communication decision-making system, which allows element sensor integration in a sensing network [5].

For example, the **EmPower Oarlock** developed by NK, attached in the boat is a system designed to provide technical feedback, such as, length, engagement and power while the user is training on the boat [6].

In this project, is also intended to use smart sensors to provide technical feedback. However, instead of measuring the information from the oars, it gets information from the footplate and the seat from an ergometer.

Figure 1 - EmPower Oarlock

BioRowTech system for ergometer helps correcting the rower technique by having a set of sensors added to the rowing machine. There is a handle sensor (1), seat positions sensor (2), a trunk positions sensor (3) and finally a data collector (4).

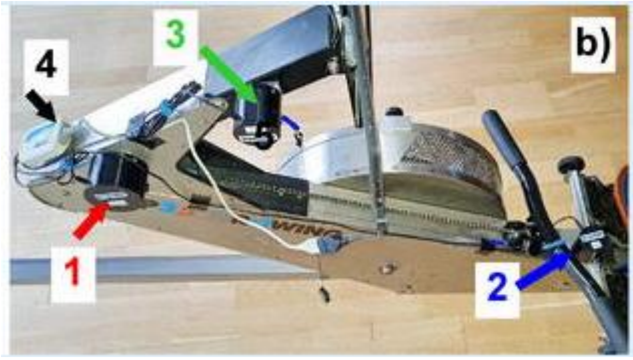

Figure 2 - BioRowTech System

Accordingly to BioRow, the system helps solve the most common problems in the rowing technique, such as opening the trunk at the catch, grabbing the arms and shoulders during the first part of the drive, and finally throwing the trunk when the handle has already changed direction. Measuring these three variables produces three indicators that are displayed instantly for the rower: Slide Shooting, Catch Factor and Roll back [7]. Although this system intends to improve the rower's technique, it does not focus either on the footplate or on the balance and centre of force from the seat.

2.1.2. Wearable sensors

The **Polar** [8] and **Garmin** [9] smartwatches are commonly used in rowing. These devices can be used to measure the heart rate, speed, time, distance, or stroke per minute. Some of the integrated sensors in these devices are gyroscope, accelerometer, or GPS.

Figure 3 - Wearable smartwatches

The wearable metabolic system **K5** developed by COSMED is a wearable designed for measuring the oxygen intake of athletes during the training, showing how fit the athletes are, and it can indicate how fast they can row. This device uses Bluetooth or ANT+ to transmit the information. An advantage of using ANT+ trackers instead of Bluetooth is that it can communicate with multiple devices at once. However, it is less secure and slower transferring the data.

Figure 4 - COSMED - K5 system

The *Shimmer3* platform comprises a baseboard that gives the sensors computational, data storage, communications and daughterboard connection capabilities. The core functionality of *Shimmer3* extends via a range of daughterboards which provide various . This sensor includes internal and external connectors for expansion, two accelerometers and a SD data bypass [10].

The mainly advantage of using this microcontroller in this project is that it is extremely low power during periods of inactivity.

Figure 5 - Shimmer3 sensor

2.1.3. Non-wearable sensors

BTH-1208LS by microDAQ is a data acquisition device that communicates using Bluetooth or a USB connection to a computer. This microcontroller has eight single-ended (SE) or four differential (DIFF) analogue inputs, two 12-bit analogue outputs, eight digital I/O’s, and one 32-bit counter input. When using Bluetooth, it is possible to have continuous data scanning to the DAQ software [11].

Figure 6 - BTH-1208LS data acquisition with Bluetooth communication

ForSite SS developed by XSENSOR is a pressure imaging system that helps therapists and clinicians prevent pressure injuries. This system gives accurate, reliable, and durable sensors, high-resolution images, and easy-to-use software design. The communication between sensor and handheld tablet is via Bluetooth [12].

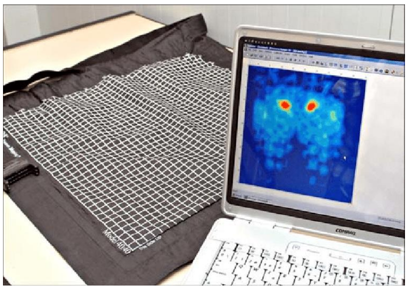

Figure 7 – ForSite SS system [13]

F-Scan system by Tekscan is ultra-thin, in-shoe sensors that capture timing and pressure information for the foot function and gait analysis. Displays the information such as force, pressure, position and trajectories for the centre of force (CoF) in real-time. This system could be used for orthotics, offloading diabetic feet and evaluating footwear and techniques in elite athletes [14].

It would be interesting to use the F-Scan system in this project. Unfortunately, due to budget constraints, it was not possible to acquire. Nevertheless, the created system does fulfil the purpose of this dissertation.

Figure 8 - F-Scan system

2.1.3.1. Piezoresistive force sensor

Piezoresistive force sensors, are strong polymer thick film (PTF) devices that display a reduction in resistance with an addition in the force applied to the sensor's surface.

Table 1 - Force sensors comparison

	FSR 402	FlexiForce A201	DF9-40@10kg
Force Range	0.1-10 Newtons	4.4-445 Newtons	0-10 Kg
Thickness Range	0.2 - 1.25 mm	0.203 mm	< 0.3 mm
Repeatability	± 2%	< ±2.5%	< ±5.8%
Precision	-	< ±3% of full scale	±2.5% (85% of force range)
Durability	10 Million	≥ 3 Million actuations	＞1 Million times
Response Time	<3ms	< 5µsec	< 1ms
Working Temp	-30°C - 70°C	-40°C - 60°C	-20°C - 60°C

Film pressure sensor **DF9-40@10kg** is based on nanometre pressure-sensitive materials, supplemented by ultrathin film substrate of Young's modulus and disposable pater. It has both waterproof and pressure-sensitive functions [15].

The **FSR 402** model is a single-zone Force Sensing Resistor optimized for human touch control of electronic devices such as automotive electronics, medical systems, and industrial and robotics applications. Its active area is 14.7mm in diameter, and the sensor is available with four connection options [16].

The **A201** is a thin and flexible piezoresistive force sensor that is available off-the-shelf in various lengths for easy proof of concept. These ultra-thin sensors are ideal for non-intrusive force and pressure measurement in a variety of applications [17].

Figure 9 - FSR 402 piezoresistive force sensor

2.2. Indoor rowing machine or ergometer

The ergometer is largely used in rowing clubs it can be also found in gyms. The ergometer is used as an endurance training machine which attempts to increase fitness and improve rowing technique. In addition, it can help beginners learn the basic rowing movements before experiencing a real racing boat. The machine attempts to achieve these ends by its movement similarity to a boat on the water.

2.2.1. Concept 2 ergometer

The current **Concept 2** rowing machine includes the PM5 performance monitor. The monitor allows setting up a variety of workouts and shows a wide range of data such as the pace, watts, stroke rate, time, distance, and calories. Furthermore, it is possible to connect the monitor to a smartphone or tablet via Bluetooth and adjust the footplate for quick and easy sizing to fit many shoe sizes [18].

Figure 10 – Concept 2 ergometer

2.2.2. RP3 ergometer

The **RP3** ergometer is connected to the RP3 application. The application tracks and generates performance stats and creates challenges accordingly to the rower by giving feedback based on precise and accurate data, such as the pace, stroke count, power, average power, stroke rate, average stroke rate, time, stroke length, distance, distance per stroke, energy per stroke, energy sum, calories sum, average energy per stroke, heartrate, work per pulse, peak force, position, and relative position, drive time, recovery time, drive/recovery ratio and speed. It is possible to view potential areas for improvement visible on the force curve [19].

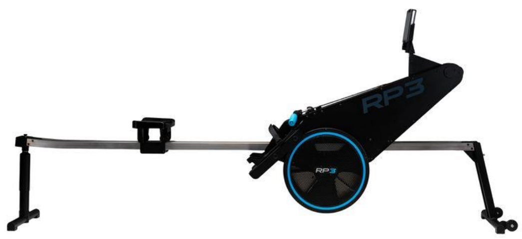

Figure 11 - RP3 ergometer

2.2.3. Skillrow ergometer

TechnoGym produces **Skillrow** ergometer that allows users to select the rowing mode for a cardiovascular workout or power mode. The machine includes a console useful to view performance data such as the pace, time, stroke rate, distance, calories, watts, resistance and heart rate. Furthermore, the user can also connect to a mobile app that provides a more motivating experience with challenges, training together with other rowers and real-time feedback on performance metrics [20].

Figure 12 - Skillrow ergometer

Even though, the force applied with the legs is one of the most used elements in the rowing stroke, as Dr. Kleshnev stated in 2000, legs contribute 46.4% of the stroke power, with the trunk being responsible for 30.9% and the arms and shoulders with the remaining 22.7% [2]. None of the ergometers described data focuses on the footplate or seat of the machine.

2.3. Communication protocols

There are several wireless and wired communication protocols, but since it is a wireless sensor network it is mandatory to use wireless protocols. The most common protocols used in short-range wireless networks communications are the IEEE 802.11 (Wi-Fi), IEEE 802.15.1 (Bluetooth) and IEEE 802.15.4 (ZigBee) standards.

Table 2 - Wi-Fi, Bluetooth and Zigbee comparison [21]

	Wi-Fi	Bluetooth	ZigBee
Frequency band	2.4 GHz; 5 GHz	2.4 GHz	2.4 GHz
Max signal rate	54 Mb/s	1 Mb/s	250 Kb/s
Nominal range	100 m	10 m	10 – 100 m
Channel bandwidth	22 MHz	1 MHz	2 MHz
Basic cell	BSS	Piconet	Star

2.3.1. Wi-Fi based on IEEE 802.11

Wi-Fi is the most used consumer and enterprise wireless TCP/IP network solution. Wi-Fi is short for Wireless Fidelity and is a standard used to identify WLAN (Wireless Local Area Network) devices.

Wireless LAN sites will see significant improvements in the number of clients supported by an Access Point (AP), a better experience for each client, and more available bandwidth for a higher number of parallel video streams. Users see a benefit even when the network is not fully loaded: their file downloads and email sync happen at low lag gigabit speeds. Also, device battery life is extended since the device’s Wi-Fi interface can wake up, exchange data with its AP, and then revert to dozing that much more quickly [22].

2.3.2. Bluetooth based on IEEE 802.15.1

Bluetooth is a low-cost, low-power, robust, short-range wireless communication protocol which was initially founded by Ericsson in 1994 to replace traditional mobile phone and computer cables with wireless links. It operates in each device's license free 2.4 GHz ISM (industrial, scientific, medical) band with a short range (power-class-dependent: 1 metre, 10 metres, 100 metres) transceiver. This range of applications is known as wireless personal area network (WPAN).

Two connectivity topologies are defined in Bluetooth: the piconet and scatternet. A piconet is a WPAN formed by a Bluetooth device serving as a master in the piconet and one or more Bluetooth devices serving as slaves. A frequency-hopping channel based on the address of the master defines each piconet. All devices playing in communications in each piconet are synchronized using the clock of the master. Slaves communicate only with their master in a point-to-point mode under the control of the master. The master's transmissions may be either point-to-point or point-to-multipoint. Also, besides in an active way, a slave device can be parked or standby modes to reduce power consumption. A scatternet is a collection of operational Bluetooth piconets overlap in time and space. Two piconets can be connected to form a scatternet. A Bluetooth device may participate in different piconets simultaneously, thus allowing for the possibility that information could progress beyond the coverage area of the single piconet. A device in a scatternet could be a slave in several piconets, but master in only one of them [23].

2.3.3. ZigBee based on IEEE 802.15.4

Zigbee is a low-power, low-bandwith and cost-effective wireless radio standard that allows different protocols to be built on top of the standard radio. The Zigbee protocol allows data transmission over long distances by passing information through a mesh network of intermediate nodes to reach distant ones. Zigbee's protocol is designed for quick turn-on and turn-off, thereby saving power. Several other protocols have been built on top of 802.15.4, including ISA100, WirelessHART and 6LoWPAN [24].

2.4. Mobile Applications

Currently there are several applications for sports in the market. In this sub-chapter are described some that can be useful in rowing or in sport in general.

2.4.1. Mobile applications used in rowing

ErgData is a mobile application developed by Concept 2, able to connect the ergometer monitor with the smartphone application providing additional information such as drive length, drive time, average force, peak force or stroke count to the athlete while he is training. In addition, it is possible to access all detailed information from all the practices [25].

Figure 13 - ErgData application example

Float mobile application connects to a Concept 2 rowing machine via Bluetooth to track the workouts. It finds patterns of how the user performs, correlates data with performance output and achieves continuous improvement. The HR data helps the user to understand how he is progressing in the rowing stroke [26].

Figure 14 - Float application example

RowVigor mobile application connects to a Concept 2 rowing machine via Bluetooth to offer video workouts both on and off the rowing machines. The instructors in the video give techniques and training advice. It is also possible to track progress and challenge friends [27].

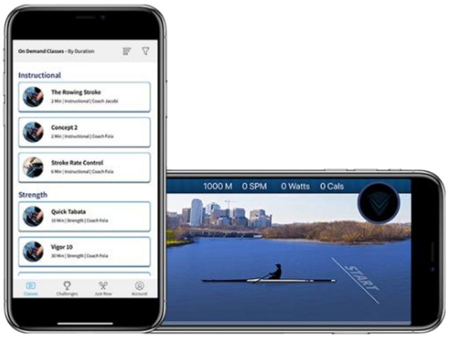

Figure 15 - RowVigor application example

2.4.2. Mobile applications used for sport monitoring

Garmin Connect allows the user to monitor, analyse and share health and fitness results collected with the Garmin device. Users can install several applications on Garmin devices. For example, the ErgIQ allows the user to connect the device to a Concept 2 ergometer and collect the information from the rowing training session [28].

Figure 16 - Garmin Connect application example

Strava is not an application mainly focused on rowing. However, it is possible to connect with other applications such as ErgData or connect garmin allowing the transfer of rowing training to the application stats. It motivates the athletes by working like a social network where it is possible to communicate with other people and see their activities [29].

Figure 17 - Strava application example

Google Fit is a Google tool that allows the user to track various items such as mobility and calories burned. It is possible to connect multiple health bracelets and other monitoring applications [30].

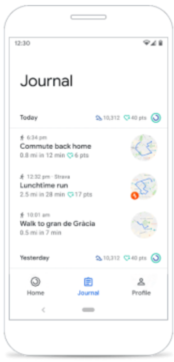

Figure 18 - Google Fit application example

Although there are many applications to track training and give feedback to the user, none of them focuses on giving charts with force from the heels or toes and they do not differentiate the force produced from each leg. Additionally, none of these applications presents detailed information on the force applied in the footplate.

Table 3 - Available Operating Systems

Operating System	Android	iOS
ErgApp	Yes	Yes
Float	Yes	Yes
RowVigor	No	Yes
Garmin Connect	Yes	Yes
Strava	Yes	Yes
Google Fit	Yes	Yes

In Table 3 is possible to see that most of the available mobile application work both on Android and iOS Operating Systems.

2.5. Mobile application development tools

Mobile applications frameworks can be classified into five different categories as it possible to see a comparison on table 4 Native, Web, Hybrid, Interpreted and Widget Based:

Table 4 - Categories comparison [31]

	Native	Web	Hybrid	Interpreted	Widget Based
UI/UX	Excellent	Moderate	Moderate	Fairly Good	Very Good
Implementation Complexity	High	Low	Moderate	Low to Moderate	Moderate
App Security	Very High	Very Low	Low	Moderate	High
Access to Native APIs	Yes	Yes, but only with HTML5	Yes, through plugins	Yes	Yes
Ease to Update	Low	High	Varying	varying	Moderate

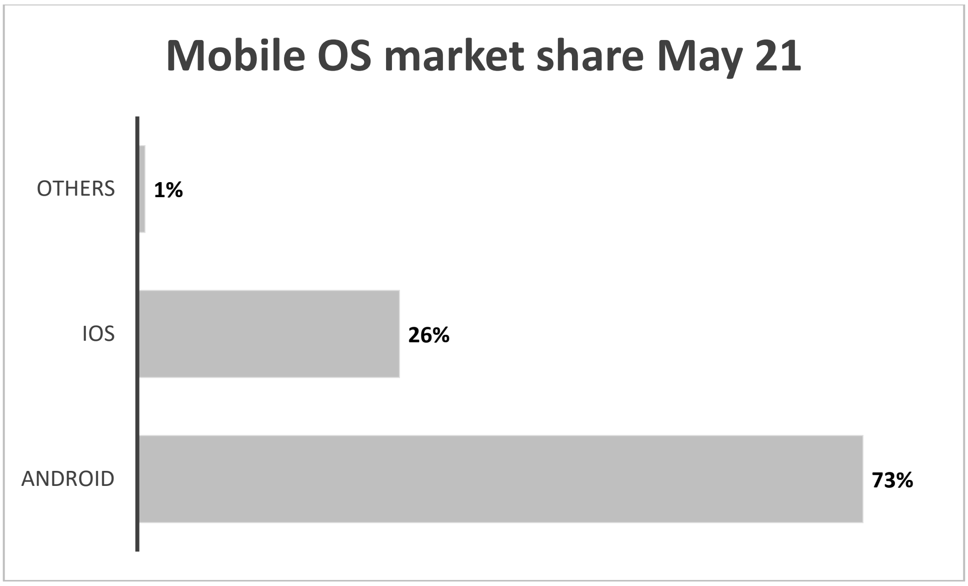

Figure 19 – Mobile operating systems market share worldwide in May 2021 [36]

2.5.1 Native applications

Native Apps use a software program developed for use on a particular platform or device and its operating system.

Native apps are a better choice for performance-related parameters like access to native device APIs, ease of update, rendering UI and providing a better user experience. These apps, however, require platform-specific specialization and often are cost-intensive [31].

2.5.2 Web applications

Web Apps use an Internet Brower to run and has limited access to the underlying of the mobile device. Examples of frameworks can be Angular, jQuery and Django.

Web apps are a better choice if ease of implementation and the development time is the developer's primary concern, but they have to keep in mind that the app cannot get published in the app marketplace [31].

Angular is an open-source TypeScript-based front-end web app framework. It is possible to build features quickly with simple, declarative templates [33]. Forbes and PayPal web applications are some of the examples built with Angular [32].

2.5.3 Hybrid applications

Hybrid Apps are embedded inside software called containers. Like Apache Cordova.

Hybrid apps also can access native device APIs, but on the downside, they are not as easy to develop [31].

Apache Cordova, much like other cross-platform tools, is an open-source mobile development framework which makes use of web standards such as HTML, CSS, and JavaScript [34]. Pacifica – Stress and Anxiety Relief and Sworkit – Personal Workout Trainer are some of the applications built with Apache Cordova.

2.5.4 Interpreted applications

Interpreted Apps emulate native apps by allowing users to interact with the user interface components that are specific to a particular platform. Like React Native.

Interpreted apps have better security than web and hybrid apps and have better access to device hardware as they are native apps generated from cross-platform tools. Interpreted apps often use web development technologies like JavaScript and are easier to develop than purely native apps [31].

React Native is an open source technology released by Facebook in March 2015 and is based on their approach to "learn once, write anywhere". The apps are built using JavaScript but are indistinguishable from natively developed apps in Android or iOS [35]. Facebook and Instagram integrate React Native into their native application.

2.5.5 Widget Based applications

Widget Based Apps all components are widgets meaning that they serve as the building blocks to form the application user interface. For example, Flutter [31].

Flutter is an open source UI framework and mobile software development kit (SDK) created by Google that not only provides cross-platform support but also enhances the application performance. Google Ads and Cryptograph are some of the applications built with Flutter.

Flutter is a widget-based application with several advantages:

a) It has almost complete access to the underlying device hardware, similar to native applications
b) It uses Dart, which is easy to implement close to although not exactly as simple as web apps
c) It generates its widgets compared to analysed app tools like React Native that are dependent on the device original equipment manufacturer (OEM) widgets
d) Ensures high-security standards and maintenance since is developed by Google

Considering the above factors and the mobile OS market share in May 2021 (Figure 19), it is possible to deduce that Flutter combines the advantages of almost all application development tools. Although it cannot wholly offer the amount of hardware integration like purely native apps, it seems to be the best choice among all cross-platform alternatives.

CHAPTER 3

Hardware system description

In this chapter, a description of the developed system hardware components will be assembled. First, an overview of the entire system architecture will be described follow by a section where each of the components is described in detail.

3.1. Overview system architecture

The system developed, intends to help athletes during the practice. Includes a Concept 2 indoor rowing machine [37], a Tekscan computer software and CONFORMat system [38], four channel measurement channels associated with force measurements that combines flexiforce sensors, conditioning circuits and Shimmer 3 characterized by 4 analogue input channels [39], and a mobile app. The Figure 20 illustrates the hardware components architecture and how they communicate with each other.

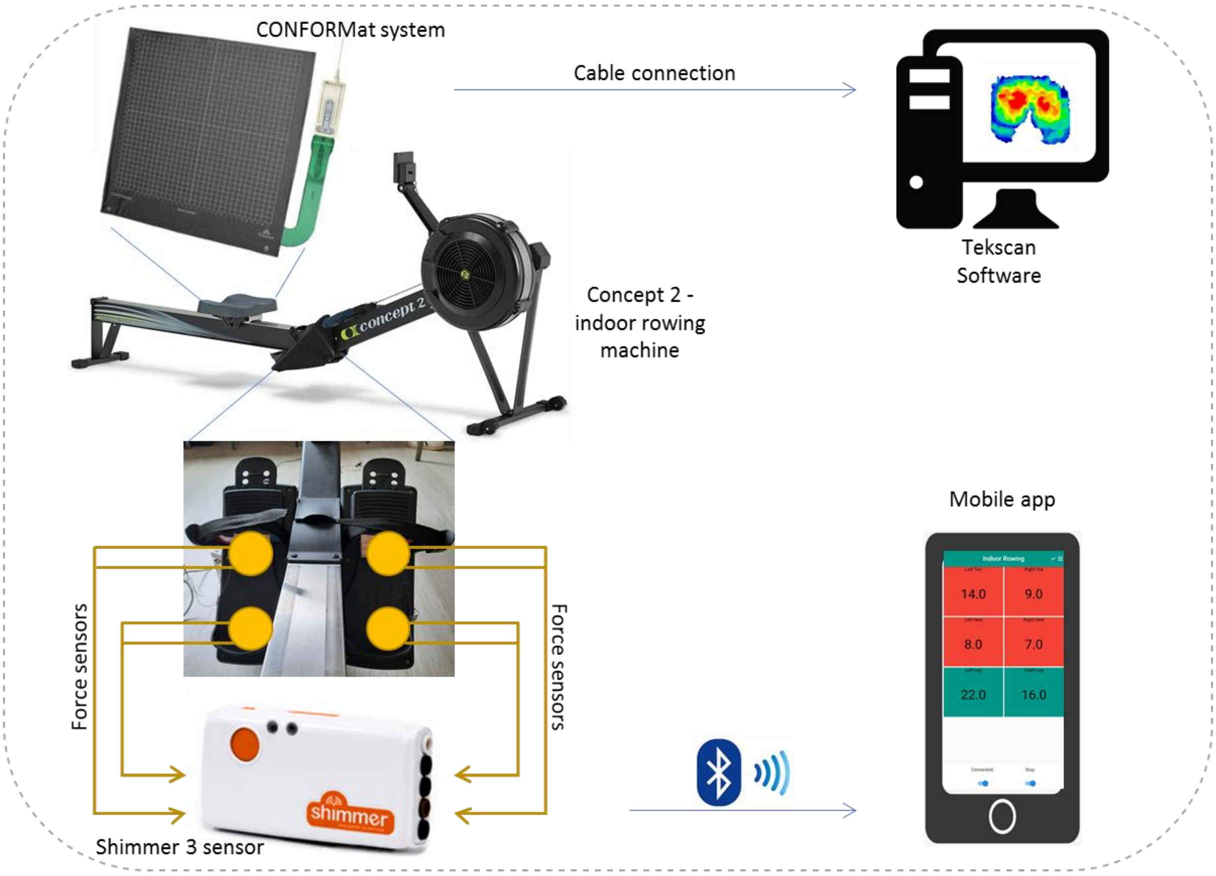

Figure 20 - Hardware system architecture

The indoor rowing machine as attached in the footplate four force sensors connected to the Shimmer3 [10] further explained in sub-chapter 3.2 Deep Dive system architecture. The Shimmer3 will send via Bluetooth the data acquired by the sensors in real time to the developed mobile app. This mobile app written in Flutter will be described in more detail in sub-chapter 4.2.

Additionally, in the machine seat is attached the CONFORMat system which will acquire the information from the user balance and force distribution of the rower seat more detailed in sub-chapter 3.2.4.

3.2. Deep Dive system architecture

This sub-chapter will describe in detail the proposed architecture components: the force sensor used in the footplate of the machine, the signal conditioning used to adapt the information from the sensors, the Shimmer3 Sensor used to transfer the data to the mobile application, and the CONFORMat System used on the seat of the machine.

3.2.1. FlexiForce Sensor

The force applied in the footplate, is measured by four FlexiForce force sensors [17]. In this project is used four force sensors two in the heels and the other two in the toes attached to the footplate. This sensor was chosen due to its adaptability to the environment, availability and affordable price.

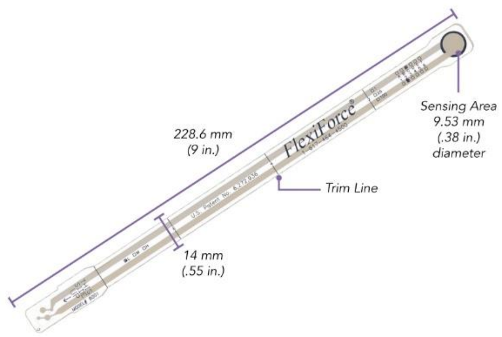

Figure 21 - FlexiForce sensor

FlexiForce sensors are resistant to most environments, thin, flexible and can measure the force between two surfaces, which will be between the athlete's foot and the footplate. These sensors work as a resistance in an electrical circuit, when a force is applied to the sensor the resistance decreases and when the sensor is discharged, that resistance increases. The sensors are terminated with a solderable male square pin, which allows them to be connected to conditioning circuit. The two outer pins are active, and the centre pin is inactive. The table below shows the characteristics of the sensors [40].

Table 5 - FlexiForce sensor typical performance

	Typical Performance	Evaluation Conditions
Linearity (Error)	< ±3% of Full Scale	Line drawn from 0 to 50% load
Repeatability	< ±2.5%	Conditioned sensor, 80% of full force applied
Hysteresis	< 4.5% of Full Scale	Conditioned sensor, 80% of full force applied
Drift	< 5% per logarithmic time	Constant load of 111N
Response Time	< 5 µsec	Impact load, output recorded on oscilloscope
Operating Temperature	-9°C - 60°C	Convection and conduction heat sources
Durability	≥ 3 million actuations	Perpendicular load, room temperature, 22N
Temperature Sensitivity	0.36%/°C	Conductive heating

The sensor consists of a polyester film bilayer, with silver deposited on each layer as the conductive material. A layer of pressure-sensitive ink defines the active sensing area which is 9.53mm in diameter. As this is smaller than the fingertip area applying the force, some of the force will bypass the sensor. Flexiforce sensor output is analogue voltage.. This analogue voltage is converted into digital by using ADC described in the sub-chapter 3.2.2. Signal condition [41].

3.2.2. Signal conditioning

As shown in **Error! Reference source not found.**, the force applied in the FlexiForce sensor will be transformed into a resistance variable. A conditioning circuit was added to the system to extract information from the force sensors, transforming the resistance variation voltage variance. Since analogue-to-digital converters (ADCs) are limited in their input voltage range for operation. [42].

Subsequently, it was used the LM324N series which consists of four independents, operational amplifiers. Each force sensor is part of a resistance divider which output is connected to an operational amplifier connected to one of the amplifiers and a resistance (R) (Figure 22) [43]. In this case, this circuit uses an inverting operational amplifier arrangement to produce an analogue bases on the sensor resistance (Rs) and a fixed reference resistance (R).

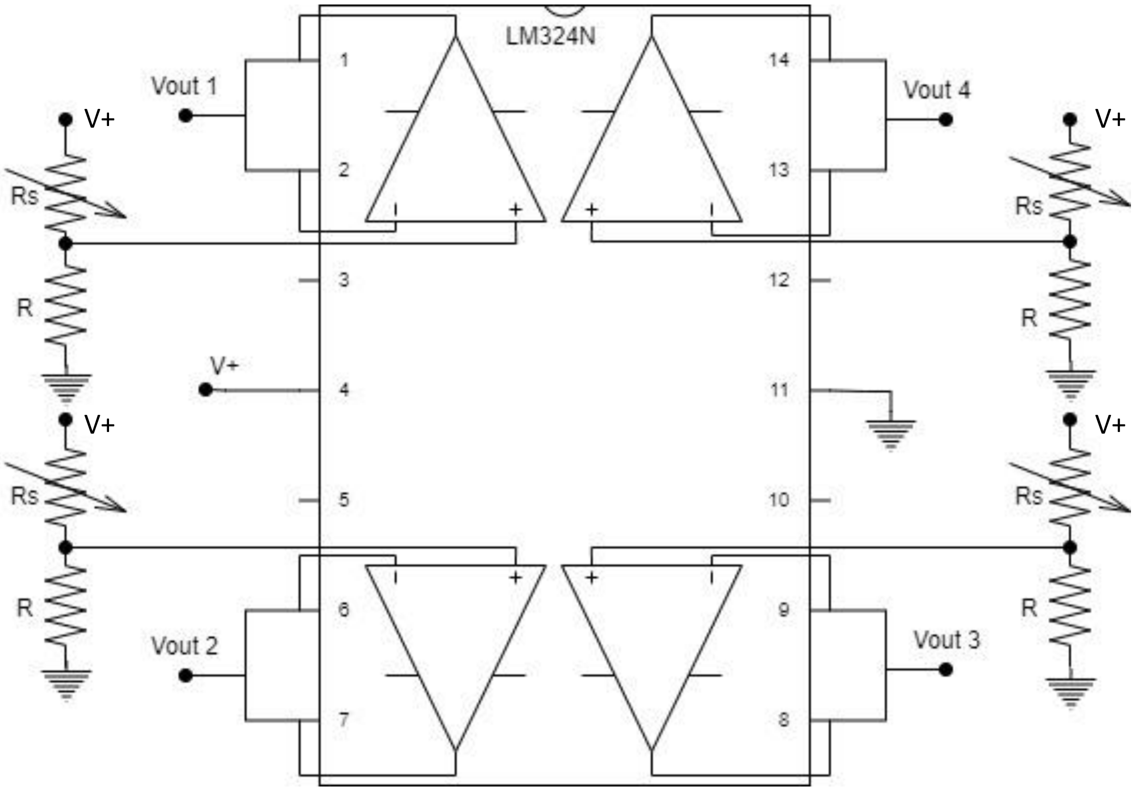

Figure 22 - LM324 amplifier and signal conditional

$$Vout = \frac{R}{Rs+R} * Vref \qquad (1.1)$$

The output voltage is obtained using the equation (1.1) the parameters are defined as follows:

- Vout: is the output voltage [V];
- Rs: is the variable resistance associated to the force sensor [Ω];
- R: is the reference resistor [Ω];
- V+: is the reference voltage [V].

The V+ used was 3.3 V which comes from the Shimmer3 sensor (more detail in the sub-chapter 283.2.3 Shimmer3 Sensor) and the reference resistance is 470K Ω.

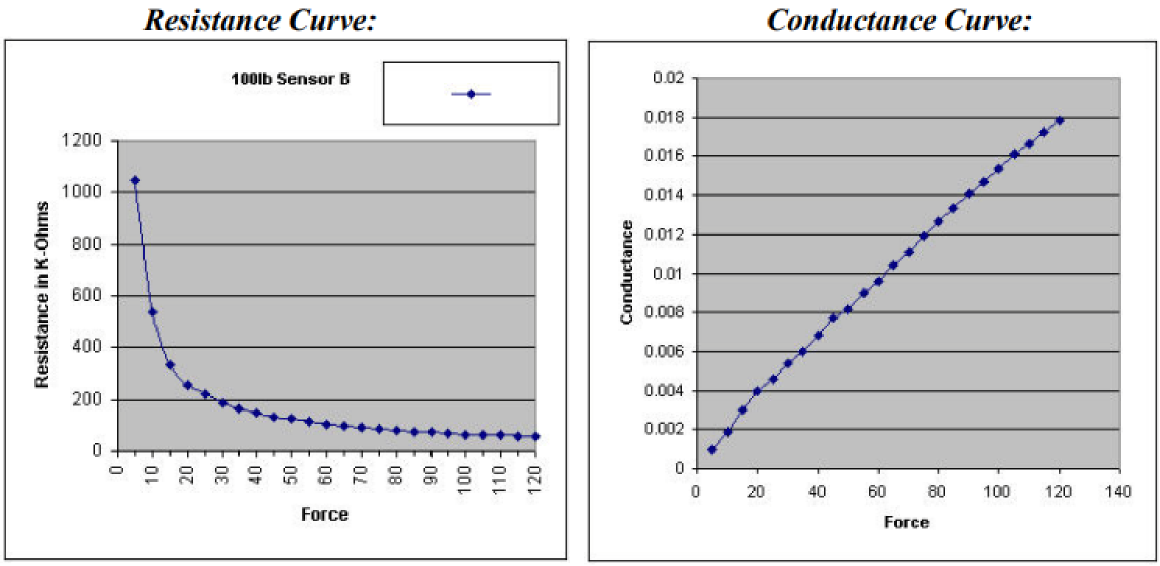

Figure 23 –Flexiforce Sensor Characteristics [44]

The RS, variable resistance associated to the force sensor [Ω], will behave as the curves seen in Figure 22.

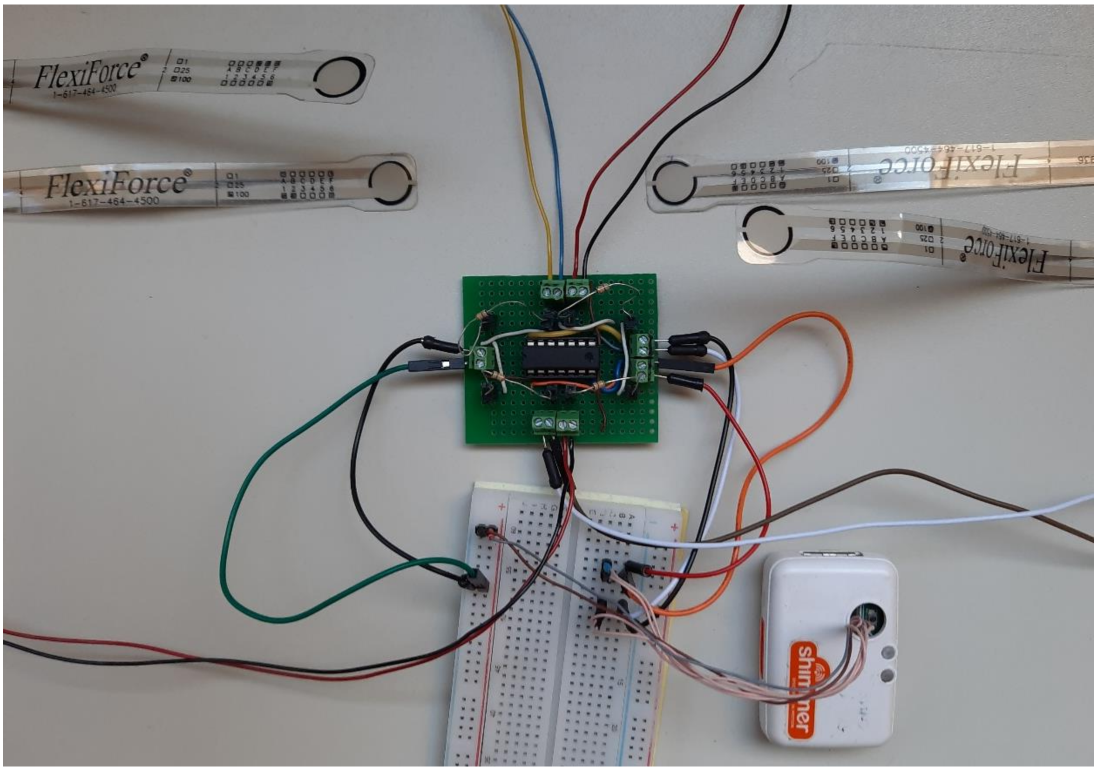

Figure 24 -System setup: Force sensors, conditioning circuit and Shimmer3 circuit characterized by 4 analogue channels

In Figure 24, is possible to see the FlexiForce sensors connections to the signal condition and after the Shimmer3 sensor (explained in the next sub-chapter 3.2.3).

3.2.3. Shimmer3 Sensor

Shimmer3 is a wireless smart sensor which includes accelerometer, gyroscope, and a magnetometer in lightweight, low-power, wirelessly platform. Furthermore, the sensor includes a processor for on-board 3D orientation estimation. Five coloured LEDs indicate device status and operating mode, as well as indicating Bluetooth streaming functionality [10].

The computation core of Shimmer3 is the low-power MSP430 microcontroller. Besides, configures and controls various integrated peripherals through I/O pins, available on the internal/external-expansion connectors, with the 16 channels 12-bit analogue-to-digital converter (ADC) [45]. . The Shimmer3 platform includes the PROTO3 Mini expansion board (Figure 25), connected via the internal expansion connectors. The PROTO3 typically can be used to connect an analogue output sensor, connect a digital sensor using I2C interface, connect a digital sensor using the SPI interface, connect a serial UART, or connect a parallel Bus interface.

Using Bluetooth, the maximum value of the converter will be 4096 ADC. Considering 1,6 V resister divider and taking into account the 3,3 V of power supply the real value will be 2048 ADC.. Thus, it is ensured the power supply of 3V and GND connections to the relevant points on the force sensors. The conditioning circuit outputs associated with force sensors are connected to the A1, A12, A13 or A14 of the Proto3 board. The acquired signals are transmitted through Bluetooth to the created mobile application (Explained in the sub-chapter 4.2 Mobile Application) Connections to the ADC channels can be made directly to the PROTO3 Mini Expansion Board through-hole connections. [46].

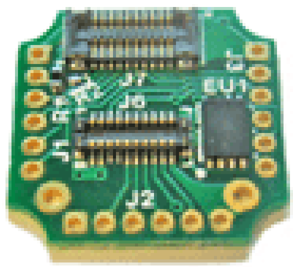

Figure 25 - PROTO3 Mini Expansion Board

3.2.4. CONFORMat System

The CONFORMat system provides accurate, real-time information on pressure distribution and Centre of Force (CoF) trajectory that helps providers develop an optimal seating and positioning system for each user . The system specifications can be found in the table 6 presented below. [38].

In this MSc thesis work the Tekscan system is installed in the ergometer seat to measure the seat pressure distribution during all phases of the rowing stroke as well as the CoF. The system is wired connected (Figure 27 - CONFORMat wired connection) with the computer via USB port. The software that is used for CONFORMat control and data visualization is a specific Tekscan software.

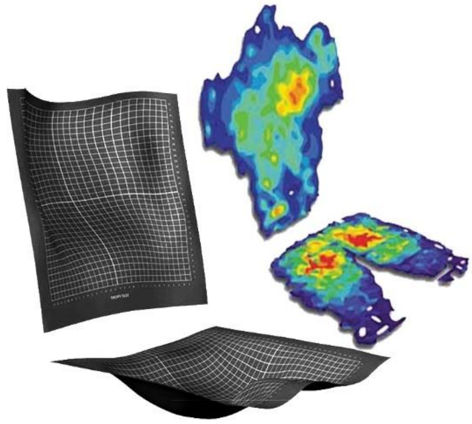

Figure 26 - CONFORMat system

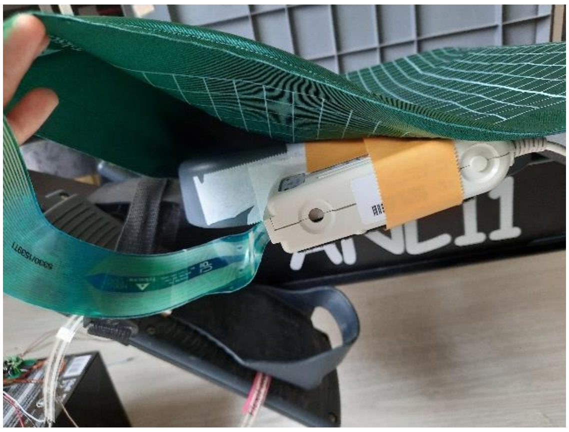

Figure 27 - CONFORMat wired connection

Table 6 - CONFORMat System specifications

	CONFORMat 5330
Sensor Technology	Resistive
Resolution	0.5 sensels per cm2 (3 sensels™ per in2)
Number of sensels	1,024
Active Sensing Area Dimensions	47.14 x 47.14 cm (18.56 x 18.56 in)
Pressure Range	5 psi/ 35 kPa
Electronics included	Evolution® or VersaTek
Max Scanning Rates	Up to 100 Hz
Max Distance from PC	4.5 M/15 ft (Evolution) 9.1 M/15 ft (VersaTek) (Up to 30.5 M/100 ft available)
Connection	USB
Power	Host computers USB BUS

CHAPTER 4

System software

In this chapter is described not only the developed software for this project but also the usage by the CONFORMat Clinical 7.60 software developed by Tekscan.

4.1. CONFORMatClinical software

The CONFORMat Clinical 7.60 software work with Windows based operating system and presents the following features:

- Pressure on the individual Sensels™ can be assessed numerically (box inset), easing identification of high pressure areas
- Display 2D and 3D real-time and recorded data
- Display contact area, average and peak pressures, and Centre of Pressure and its trajectory
- View data frame by frame
- Side-by-side comparisons of pre- and post-treatment conditions
- Measure distance between two points (anatomical landmarks or sites)
- Isolate and analyse specific regions
- Import and export subject movie files

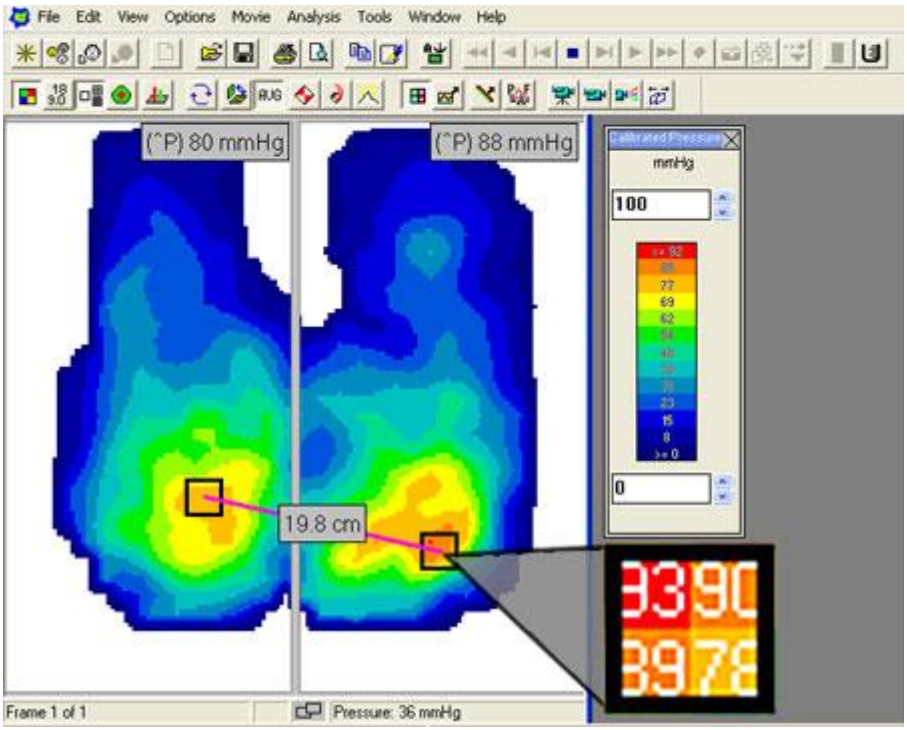

Figure 28 – Captation from the CONFORMatClinical software

4.2. Mobile Application

The mobile application of this system, developed for Android, aims to help the coach and athletes during the training session to manage the results after the training. Thus, the historical record can be considered to find the athlete performance through past workouts.

It was used flutter from Google a free and open source user interface for applications for mobile, web, desktop, and embedded devices from a single codebase [47]. Although flutter is similar to native applications, this tool was chosen because it uses Dart which is easy to implement.

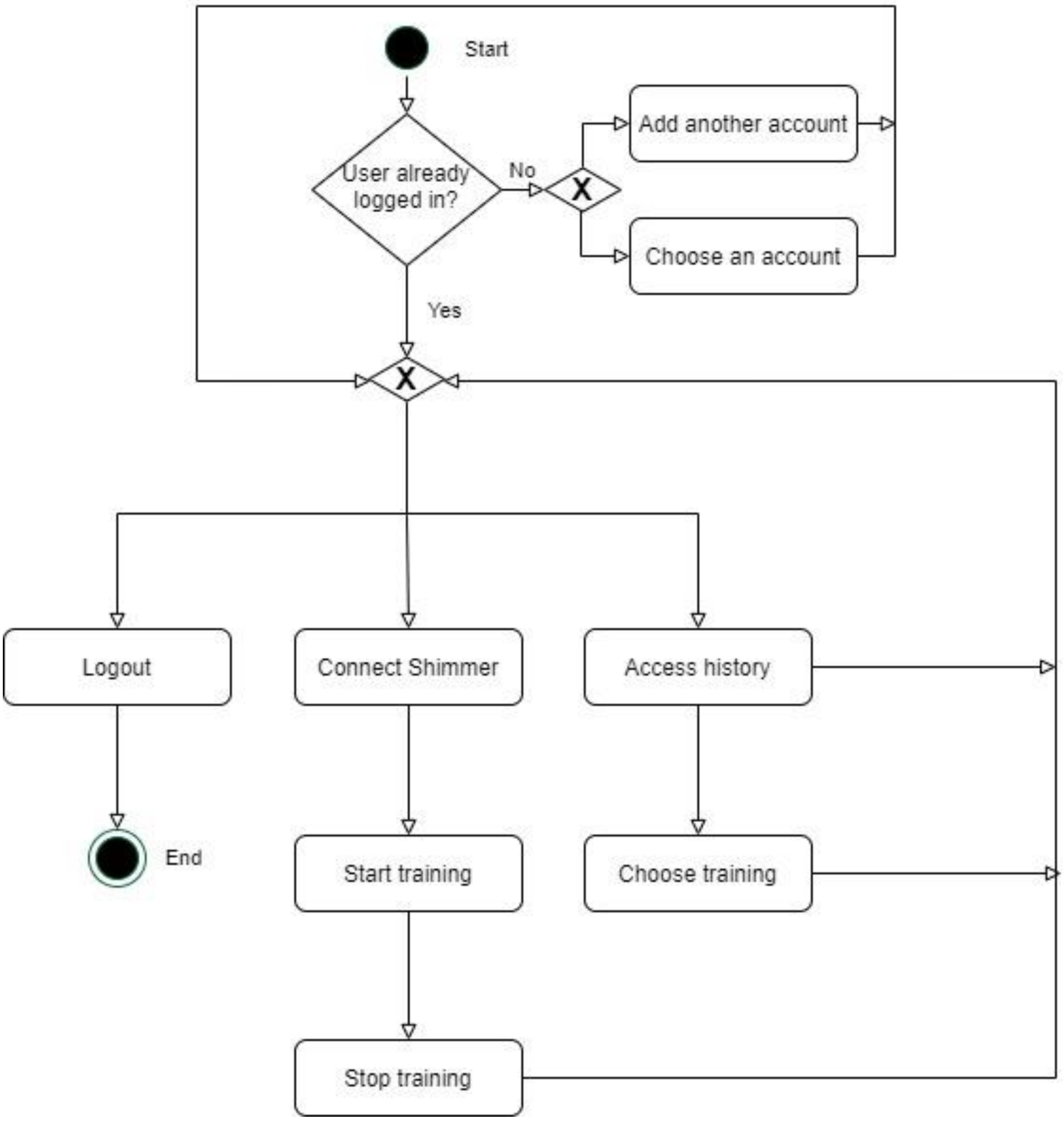

Figure 29 - Mobile application activity diagram

4.2.1. Rower log-in

As soon as the application is installed and opened, the user can log in with a Google account. The user may pick one from the showed list or add another account (Figure 30). In case he has already log-in before and did not log out, the application will automatically skip this step.

Figure 31 shows how the code handles the login. There could be two options. One detects when the user is already signed, and the other is the re-authentication when the application is reopened. For this code it was used the plugins available on FlutterFire [48]. The user email will be saved in Firebase Database (Figure 32) [49].

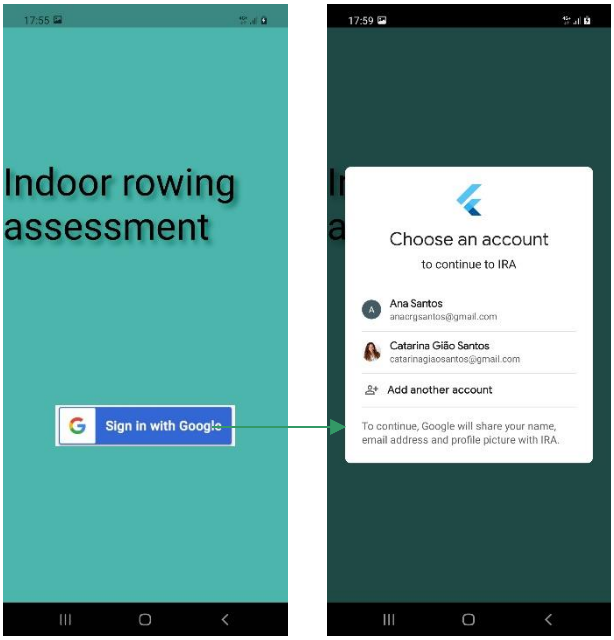

Figure 30 - Choosing or adding an account

```
// Detects when user signed in
googleSignIn.onCurrentUserChanged.listen(
    (GoogleSignInAccount googleSignInAccount) {
  handleSignIn(googleSignInAccount);
}, onError: (error) {
  print("Error signing in: $error");
});

// Reauthenticate user when app is opened
googleSignIn
    .signInSilently(suppressErrors: false)
    .then((GoogleSignInAccount googleSignInAccount) {
  handleSignIn(googleSignInAccount);
}).catchError((error) {
  print("Error signing in: $error");
});
```

Figure 31 - Log-in with a Google account

```
createUserInFirestore(GoogleSignInAccount googleSignInAccount) async {
  //storage.ref(googleSignInAccount.id).ge

  final DatabaseReference databaseRef = database.reference();
  final DatabaseReference childRef =
      databaseRef.child(googleSignInAccount.id);
  final Query query = childRef.equalTo('id', key: googleSignInAccount.id);
  final DataSnapshot dataSnapshot = await query.once();
```

Figure 32 - Insert user in the database

4.2.2. Main application page

The main application page (Figure 32) will display a board with six cards. Once the application is connected with the Shimmer3 device, each card displays the value obtained from the force sensors. This page will be responsible for giving real-time feedback to the rower. The three possible colours will change accordingly to the force applied in the force sensor. The developed application will detect if the force from one of the legs is substantially more significant than the other and if the rower is not applying the force correctly in the footplate. From this main page, the user may decide to Logout, Connect Shimmer or Access history (described in detail in the sub-chapters below).

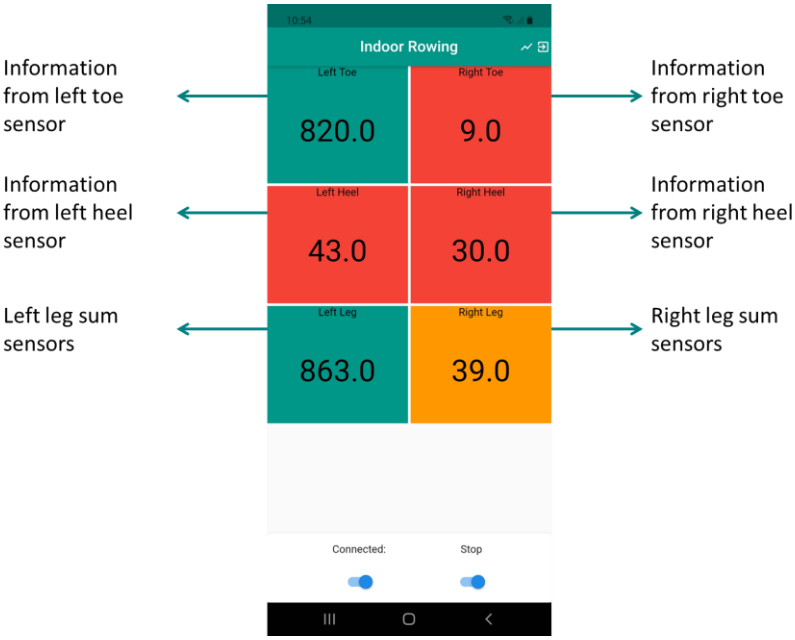

Figure 33 – Main application page during training

During the training, the application can show three different colours: teal, red or orange.

- **Teal colour** will reflect that the force applied in the sensor is above than established value for each sensor. In case of the toes sensor above 100 and the heels above 300.

- **Red colour** will reflect that the force applied in the sensor is below the established value for each sensor. In case of the toes sensor below 100 and the heels below 300.
- **Orange colour** can only appear in the leg sum, reflecting that the leg sum in orange is 1.5 times less than the other leg sum.

If the colour turns red, the rower should apply more force to that part of the feet. Besides, if the colour turns orange, the rower should pay attention to the force applied with both sensors from that side of the leg. In Figure 32, it is possible to see an example where the rower needs to apply more force in the left heel and the right leg.

4.2.3. Shimmer3 connection

To collect data from the force sensors first, the user must connect the Shimmer3 via Bluetooth by clicking the "Connect" button triggering the method in Figure 34 responsible for this association. This code uses the Shimmer3 APIs, which are libraries for software developers that allow rapid integration of the Shimmer3 platform into software applications [50].

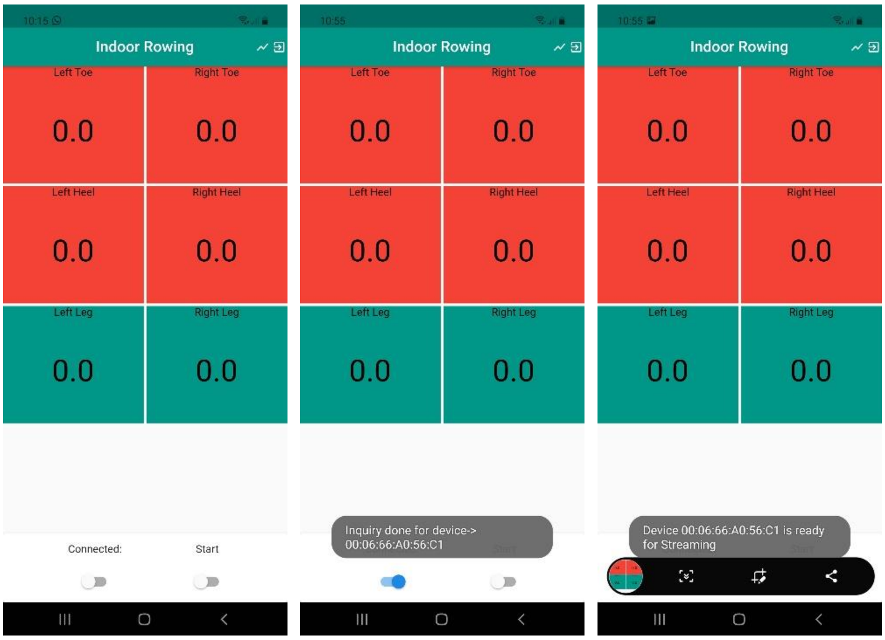

Figure 34 - Connecting to Shimmer3

```java
public void connectDevice() {
    Log.i(LOG_TAG, "method connectDevice called");
    Intent intent = new Intent(getApplicationContext(), ShimmerBluetoothDialog.class);
    startActivityForResult(intent, ShimmerBluetoothDialog.REQUEST_CONNECT_SHIMMER);
}
```

Figure 35 - Connect Shimmer3 to the device code

4.2.4. Start training

When the athlete is ready to start the training, it must press the start button to start recording the information from the sensors. The information collected from the sensors will be presented in real-time in the six cards described in sub-chapter 4.2.2. To stop the training, the user has to tap the stop button, and automatically the training is saved and ready to be seen in the history tab described in the sub-chapter below.

4.2.5. Historical data

To access the historical data, the user must tap the chart figure on top of the main page. A new page will be opened, the historical page, is where the athlete or coach can access all the pieces of training from the logged user. To see the train in detail, the user must tap the arrow to visualise the three charts and the table. The top chart contains the toes information, the middle the heels and the bottom the leg sum. In blue is presented the information from the left toe, heel, and leg opposite to the green that refers to the right toe, heel, and leg. Additionally, is it possible to see a table with several data divided by every 30 seconds of training, such as average force, maximum force, average left leg, average right leg, average left toe, average right toe, average left heel, and average right heel.

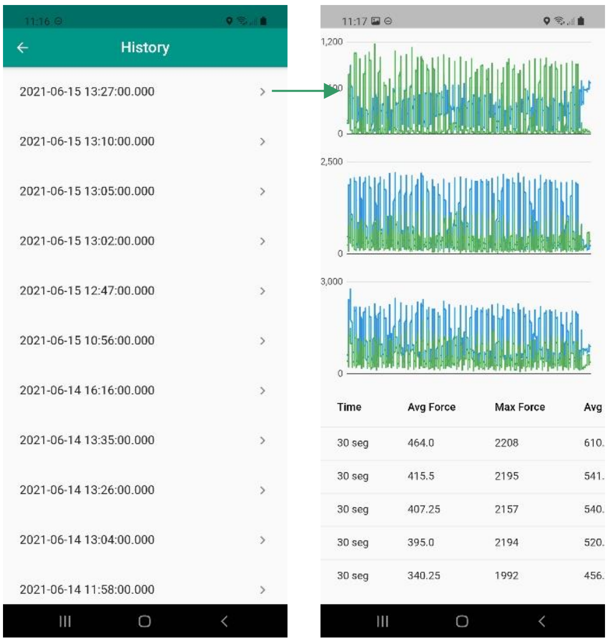

Figure 36 – Mobile APP historical data

In Figure 35 by analysing the charts is possible to conclude that the athlete used more the left heel contrary to the use of the toes which the right toe was the most used. Overall, by looking over the third chart, with the sum of both sensors the athlete used more his left leg.

4.2.6. Log out

In case the user desires to log out it can press the log out button at the top of the main page that will direct to the initial page to log in.

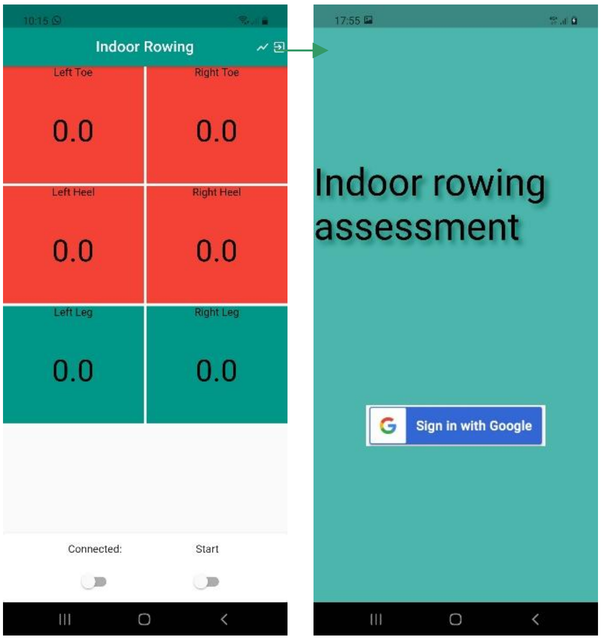

Figure 37 - Log out

The application ca be used during the training to see the real-time feedback. After the training the athlete and the coach can analyse the training and compare with the older ones. This can be useful to improve the rower's technique and performance.

CHAPTER 5

Results and Discussion

This chapter describes the results obtained from the developed system. A set of six volunteers were considered, and a comparative analysis was performed throughout the results. The training protocol was expressed by a sensors' calibration followed by sensors colocations and finally the test phase .

5.1. Experimental protocol

5.1.1. Ergometer explained

The footplates of the ergometer are made of two separate pieces of durable plastic. Nowadays, the footplate does not relay any data to the user and is used only as an area to keep the feet strapped in to allow the athlete to drive backwards through the rowing stroke. The shoes' toe in the footplate is prohibited from motion, while the heels rise and fall during the rowing cycle. The footplate is attached to the ergometer, and it does not move. On the opposite side, the rower's seat is constantly moving on a trail during the rowing stroke (explained below).

5.1.2. The rowing stroke explained

The rowing motion is a continuous, repetitive movement, divided by four main phases. At the **Catch** (Figure 37), the oars have just been placed into the water with the Hips and Knees fully flexed. After this compressed position, there is the **Drive** (Figure 38) phase of the stroke. Where first the legs strait followed by the trunk and arms, driving the body back toward the bow of the boat. The Drive phase ends at the **Finish** (Figure 39) with the legs fully extended and the arms closed to the body. The **Recovery** (Figure 40) phase begins with movement of the arms away from the body followed by forward flexion at the hip and the forward movement of the spine resulting in the movement towards the Catch position again. This same cycle is repeated for the length of the race or practice.

Figure 38 – Rowing stroke Catch phase

Figure 39 - Rowing stroke Drive phase

Figure 40 - Rowing stroke Finish phase

Figure 41 - Rowing stroke Recovery phase

5.2. Sensor's location

The sensors used to perform the tests were placed in strategic positions of the footplate and seat. Thus, in figure 41 is presented the setup and the names considered for the sensors placed in the footplate moreover in figure 42 the CONFORMat systems placed in the seat of the machine.

Figure 42 - Footplate sensors location

Figure 43 – CONFORMat System in the seat

5.2.1. Sensor's calibration

Before starting the testing phase, the sensors on the footplate went through a rigorous calibration to ensure that all of them behaved in the same way when the force is applied.

To calibrate the sensors, first, they were submitted to different weights. In table below we can see the different weights used as well as how the sensors reacted to the weight oscillations. The acquired values obtained by the a12, a13 and a14 Proto3 analogue input channels were very similar unlike the sensor a1 that behaved differently.

Table 7 - How sensors behave when submitted different weights before calibration

Weight (g) / Acquisition channel	a1	a12	a13	a14
200	700	280	200	400
1200	2250	1600	1700	1900
1320	2400	1800	1800	2000
1700	2400	2200	2100	2400

To ensure that all sensors reacted equally, it was necessary to create a trend line for the a1 sensor to get all the multipliers needed. It was concluded that just one trend line would not be enough, therefore two multipliers were considered one between the values 0 to 1350 and the other one for the values greater than 1350. The equations retreive from the trends lines (Figure 43 and 44) where used in the code (Figure 45) to calibrate the sensor a1. To create this trends lines to calibrate the sensor 1, an avarege from the other three sensors were created. Using the values from this avarege and the a1 sensor was possible to create the trend line.

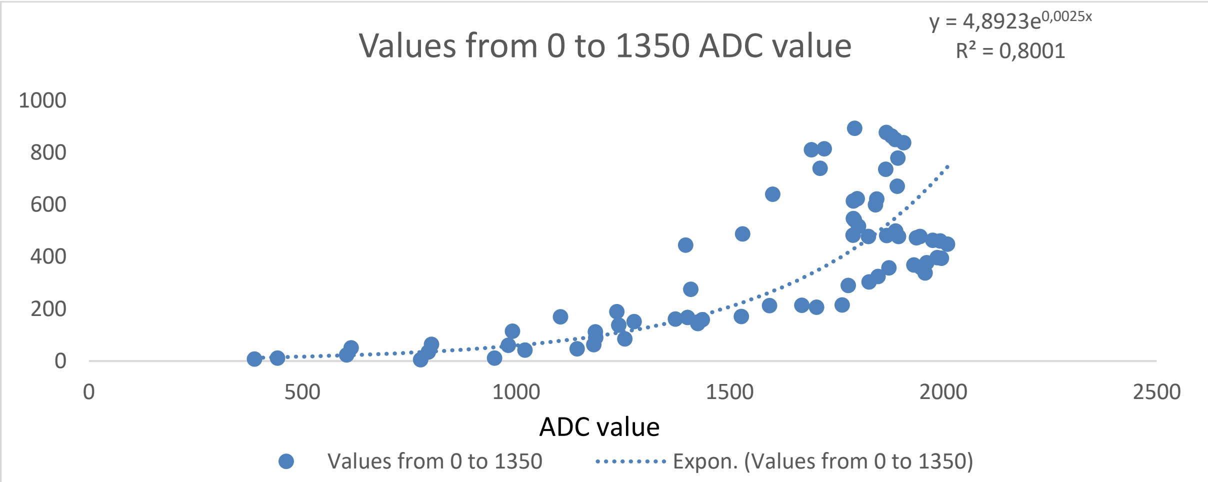

Figure 44 - Obtained trend line for values between 0 and 1350

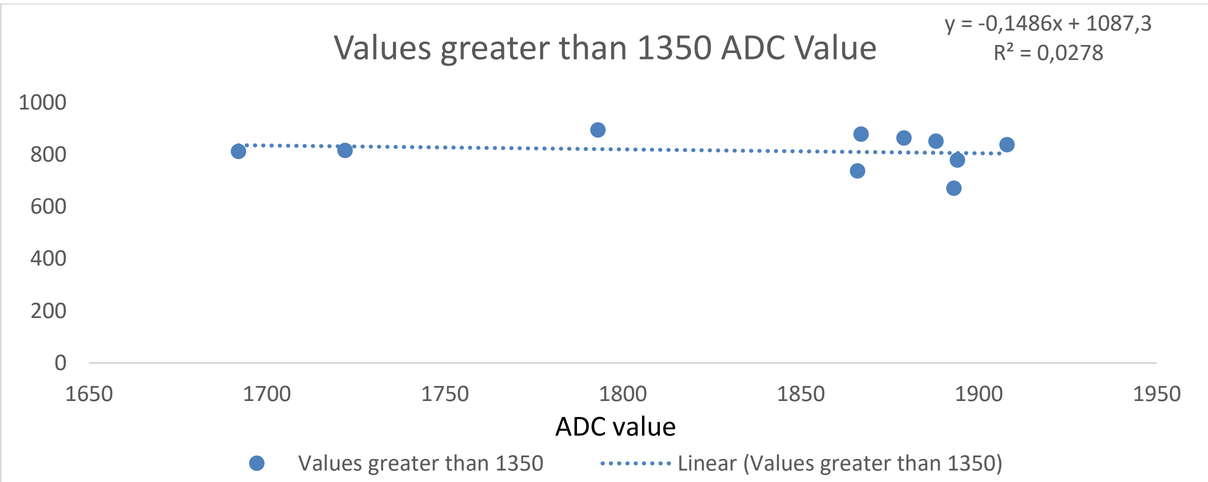

Figure 45 - Obtained trend line for values greater than 1350

```
int a1Calibrado = 0;
if (a1 < 1350) {
  a1Calibrado = (4.8923 * exp(0.0025 * a1)).toInt();
} else {
  a1Calibrado = (-0.1486 * a1 + 1087.3).toInt().abs();
}
```

Figure 46 - a1 sensor calibration

Table 8 - How sensors behave when submitted different weights after calibration

Weight (g) / Acquisition channel	a1	a12	a13	a14
200	270	280	200	400
1200	1700	1600	1700	1900
1320	1800	1800	1800	2000
1700	2000	2200	2100	2400

As it possible to see in Table 8, sensor a1 when the weight was applied after the calibration it behaved similar to the other sensors. Although the force applied in the sensors can be much higher thar 1700 grams it was notice that the behaviour of the sensor did not change with the higher values. For that reason, it was only considered low weights during the calibration.

5.3. Tests in rowers' volunteers

The test rowers' phase was performed with 6 healthy rowers volunteers. Two females and four males. Age average around 22.3 years old and shoe size average around 42.83 cm.

Table 9 - Volunteer's description

	Age	Male/Female	Shoe size (cm)	Weight (Kg)
Volunteer 1	25	Female	40	52
Volunteer 2	19	Male	45	85
Volunteer 3	21	Male	43	75
Volunteer 4	23	Male	44.5	78
Volunteer 5	20	Male	46.5	85
Volunteer 6	26	Female	38	69

The test consisted in rowing 150 seconds in the ergometer with the four force sensor in the footplate, connected to the Shimmer sending real-time information to the mobile application, and the CONFORMat System in the seat retrieving values simultaneously. In the following sections it is possible to see the results obtained from the tests for each six volunteers.

5.3.1. Results - volunteer 1

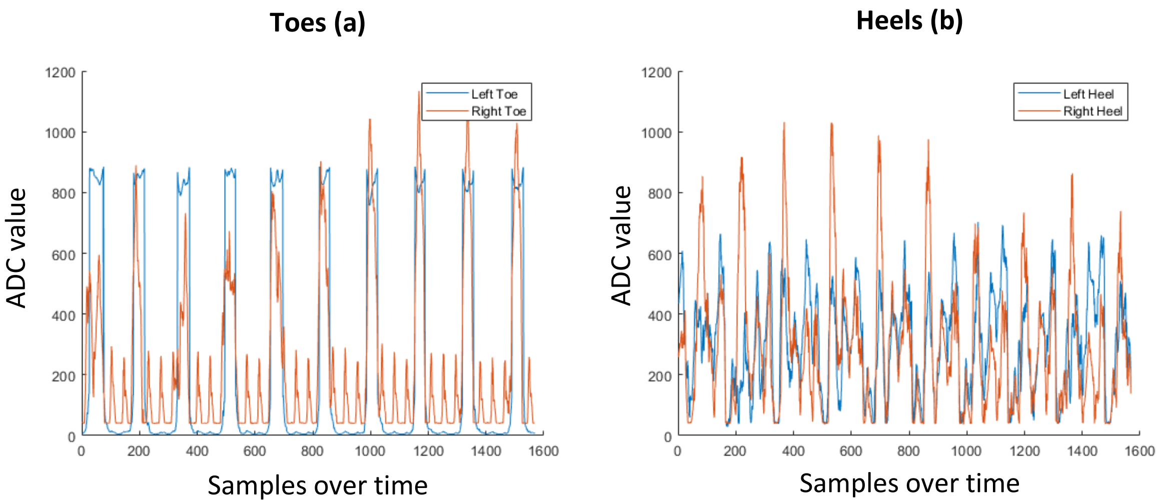

Figure 47 - Results from footplate Toes (a) Heels (b)

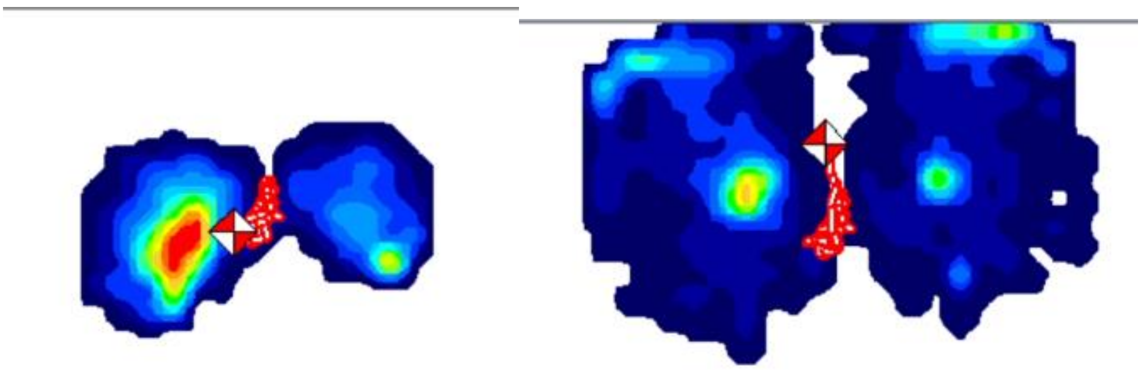

Figure 48 - Results from COMFORMat

It is possible to verify, comparing figures 46 and 47, that the athlete applies more force in the right heel sensor however, in the seat, the athlete tends to lean to the right and apply more force in the left buttock. To improve the athlete's performance he should focus on the seat posture by not leaning to the right side.

5.3.2. Results – volunteer2

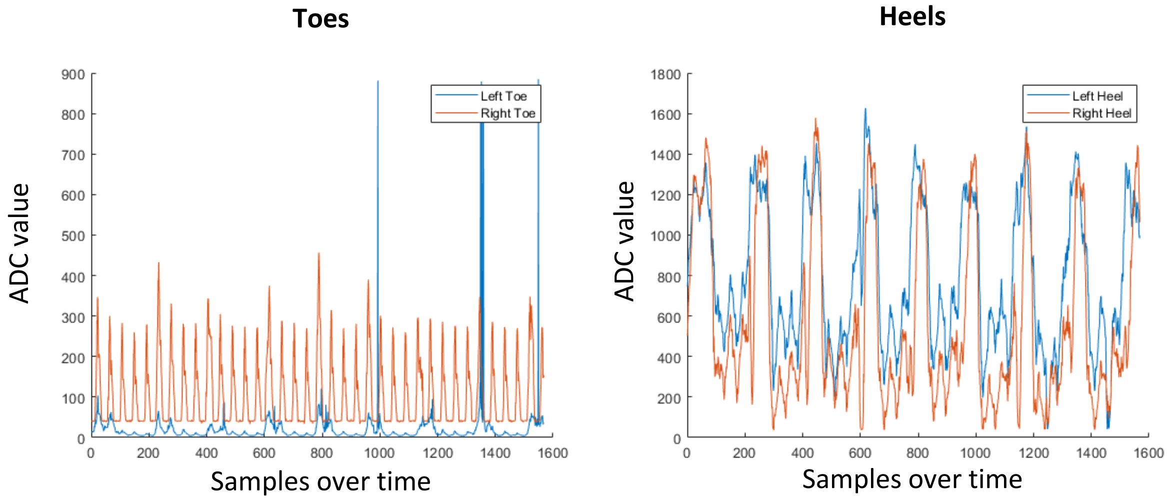

Figure 49 - Results from footplate Toes (a) Heels (b)

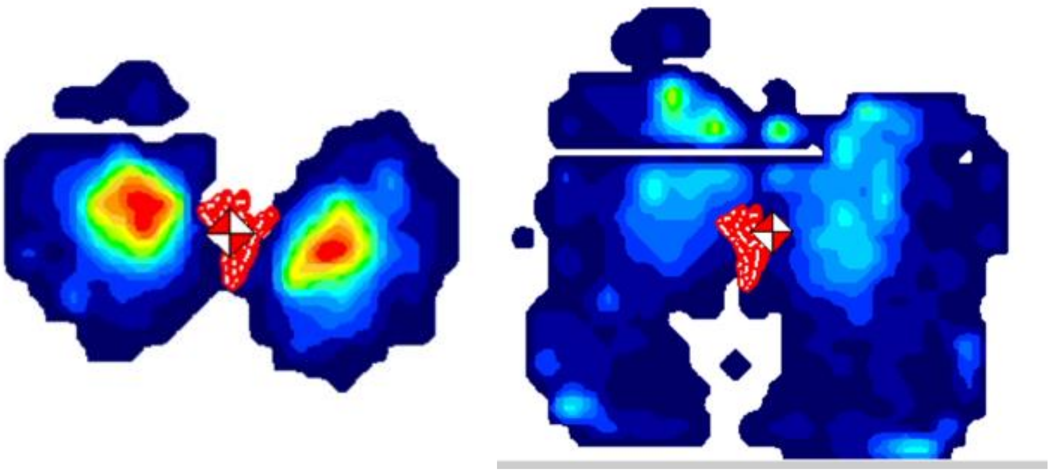

Figure 50 - Results from CONFORMat System

It is possible to verify in figure 48 (a) that volunteer 2 had an issue in the reading of the left foot sensor due to the sensor's resistance being out of place. Nevertheless, the force applied with both heels was identical (figure 48 (b)). As it possible to see in Figure 49 although the volunteer has a the CoF concentrated in the middle during the catch phase of the stroke he leans to the right side to improve his performance the volunteer should pay more attention during the catch phase.

5.3.3. Results - volunteer 3

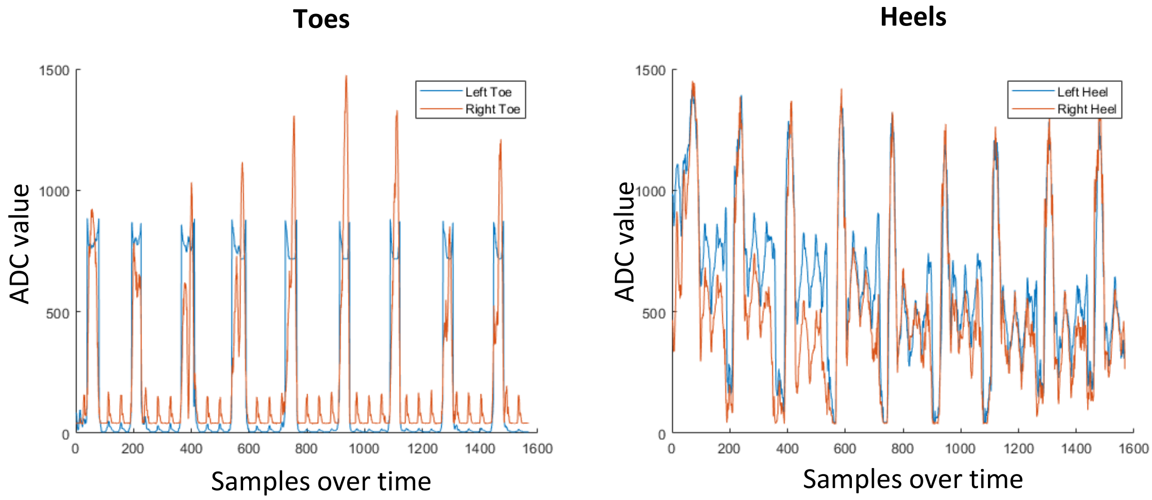

Figure 51 - Results from footplate Toes (a) Heels (b)

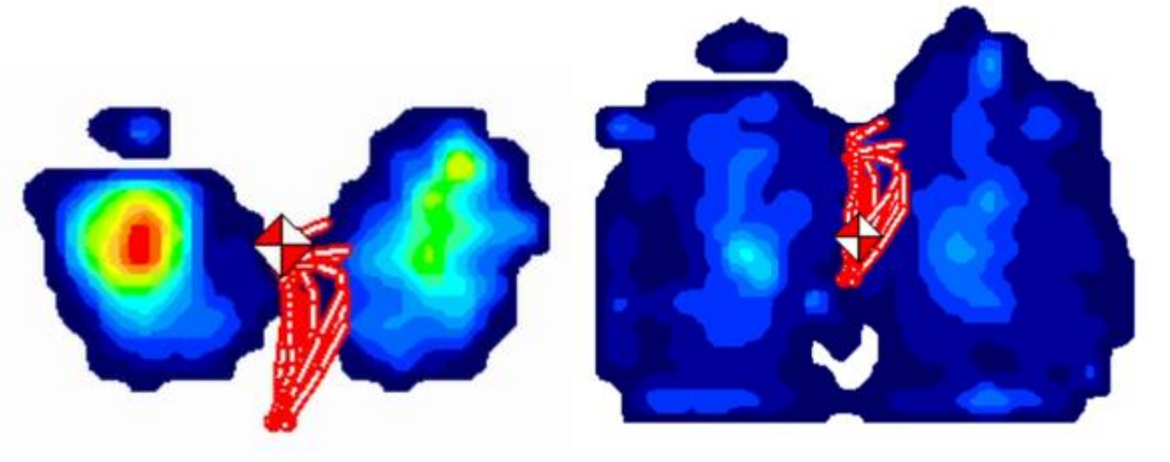

Figure 52 - Results from CONFORMat System

Although the results obtained from the footplate sensors are similar comparing both toes and heels, this athlete balance tends to lean to the left side in every stroke and apply more force with the right buttock having a triangle made by the CoF created by the CONFORMat system. This athlete should work on the way he moves on the seat while rowing to improve his posture.

5.3.4. Results - volunteer 4

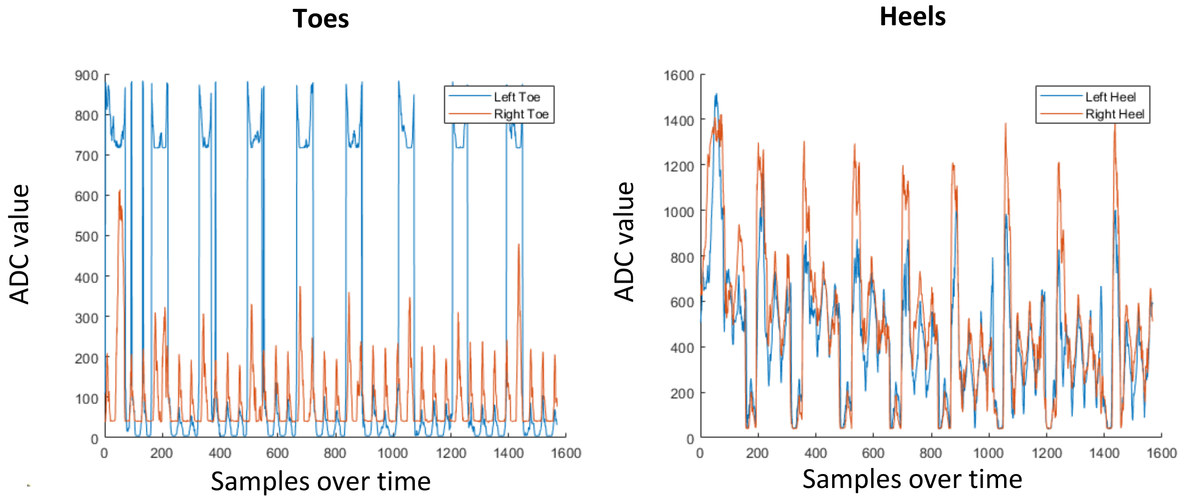

Figure 53 - Results from footplate Toes (a) Heels (b)

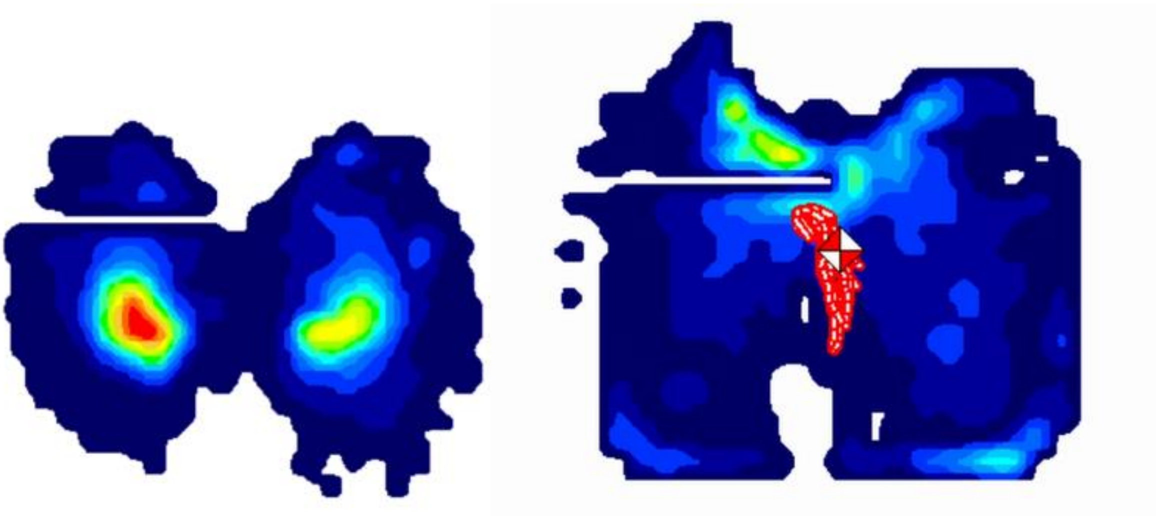

Figure 54 - Results from CONFORMat System

The force generated by the left toe of volunteer 4 was much higher than the force from the right toe (Figure 52 (a)) is it possible to compare with the volunteer 3 what was expected. This difference could be explained since the athlete has a slightly shorter right foot. Looking at the results obtained from the CONFORMat System, the centre of force is in the middle nevertheless this volunteer can improve his stroke during the catch phase when he leans to the right side.

5.3.5. Results - volunteer 5

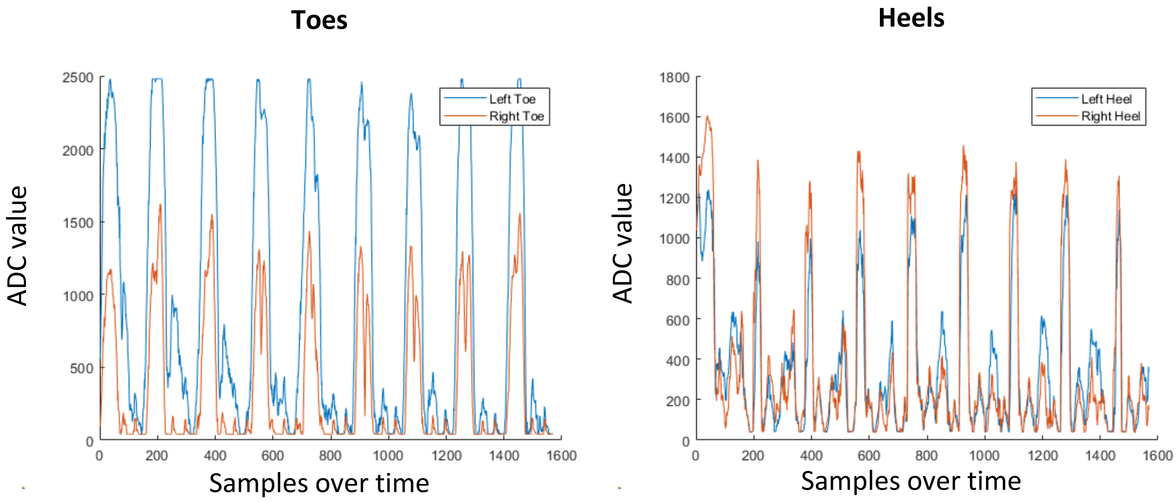

Figure 55 - Results from footplate Toes (a) Heels (b)

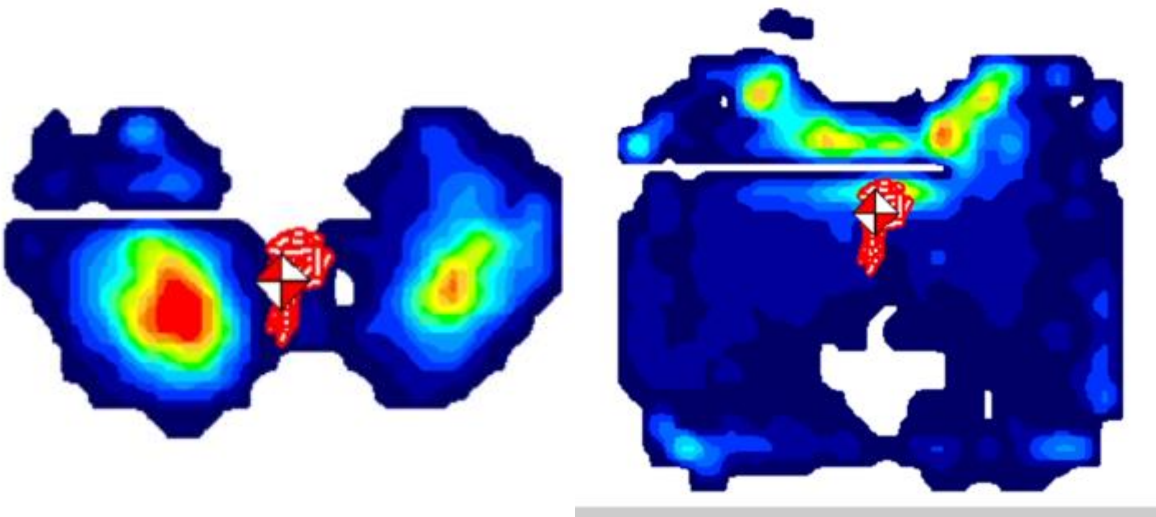

Figure 56 – Results from CONFORMat System

It is possible to notice in figure 54 (a) that the force applied with the left toe is relatively higher than the right toe. However, in figure 54 (b), the right heel force is slightly higher than the left heel. This athlete tends to apply more force with the right buttock and during the finish phase of the rowing stroke, it tends to bend to the left side. Regarding the COF during the catch phase the athlete severely leans to the left side opposite to the finish phase where the athlete leans to the right side.

5.3.6. Results - volunteer 6

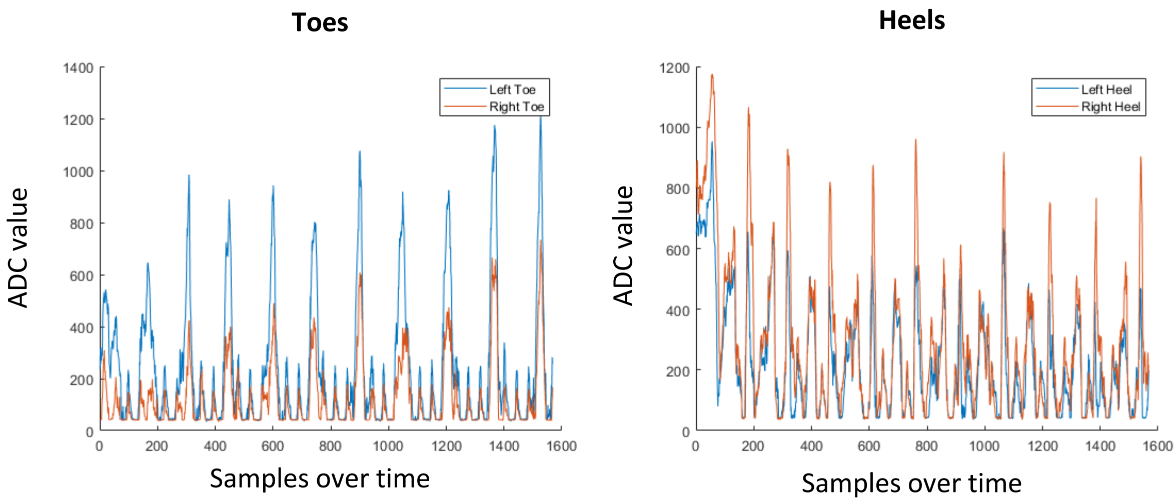

Figure 57 - Results from footplate Toes (a) Heels (b)

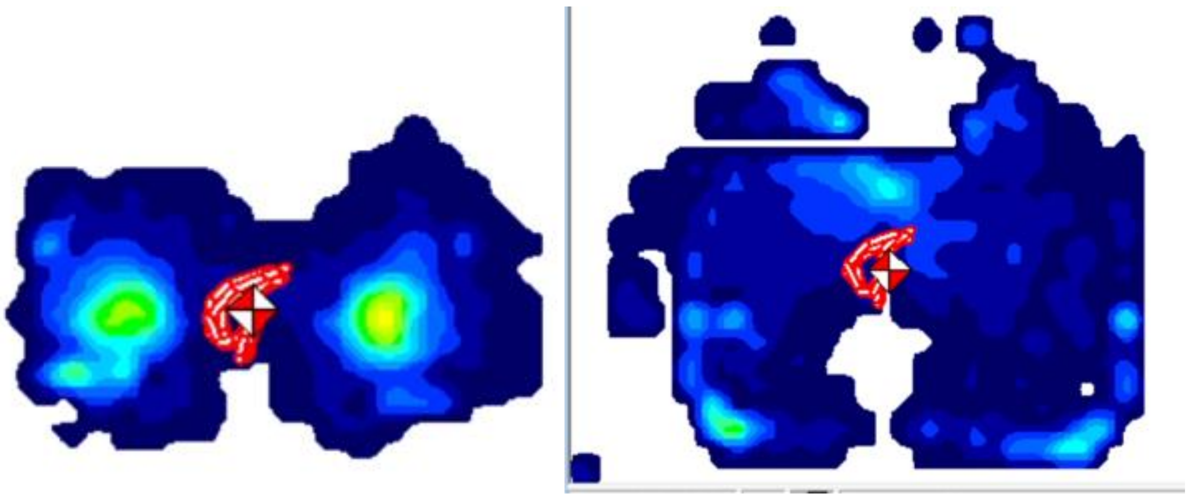

Figure 58 - Results from CONFORMat System

It is possible to notice in figure 56 (a) that the force applied with the left toe is relatively higher than the right toe. However, in figure 56 (b), the right heel force is slightly higher than the left heel. This athlete has an equal force applied with both buttocks in the CONFORMat system even though the centre of force tends to be side-tracked to the right side.

Comparing the charts from all the volunteers it was possible to determine the different phases of the rowing stroke for each one of them the Catch, the Drive, the Finish and the Recovery phase as well as identifying wish part of the feet is mostly used (Figure 58). Although the toes were constantly used more in the catch phase, the force applied into the heel's sensor is higher, closer to the finish phase.

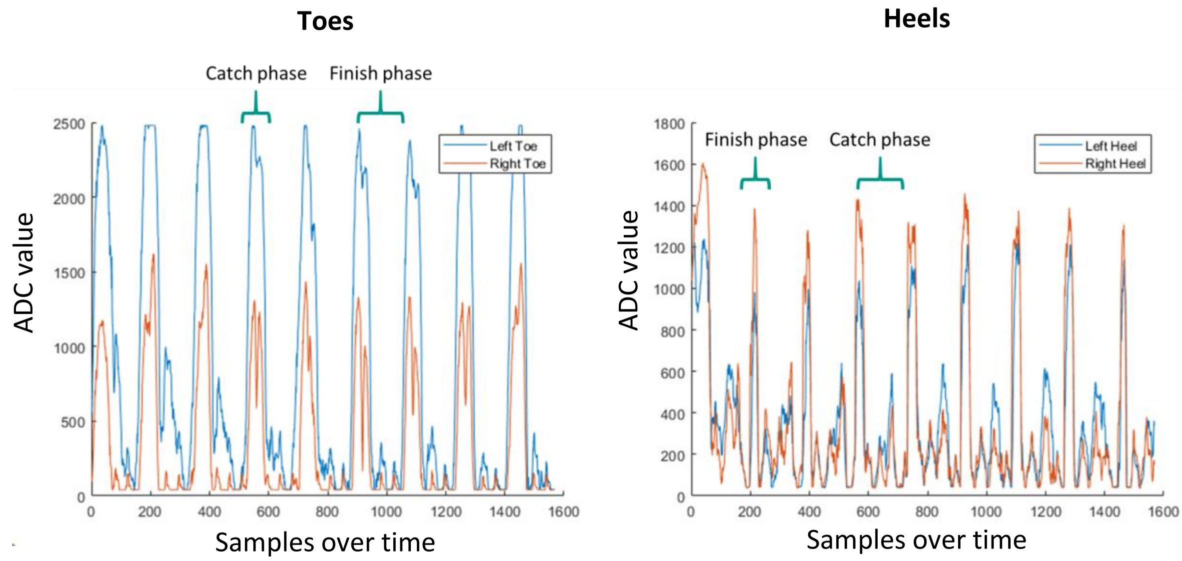

Figure 59 - Different phases of the rowing stroke

CHAPTER 6

Conclusions and future work

Bad technique in rowing can lead to several injuries or unsatisfactory results. A system for tracking the rower technique was built and implemented.

The system was able to measure and provide the rower the force applied in both heels and toes with FlexiForce sensors in real-time and show the balance and force applied in the seat of the ergometer with the CONFORMat System. In the end, the information was saved able to be reviewed after the training, allowing the athlete and coach to see the evolution in each training. This information retrieved from the force sensors helped the rower during the training by providing him feedback on the force produced in the heels, toas, and difference between legs. The information collected from the CONFORMat System was helpful because enable the rower to see the centre of force to correct the posture.

By analysing the graphs and tables provided by the developed mobile application, the rower could see where to apply more force to improve his technique. Additionally, with the centre of force, the athlete understood how the pressure on the seat was distributed in all phases in the rowing stroke. The joining of the results from the footplate and CONFORMat system gives the athelete many useful information such as: How it can correlate the centre of force with the force applied by each part of the feet and How to correlate the force applied with the legs comparing to the force applied in the mat.

The objective of this dissertation was reached, however there could be some future steps to improve it:

- It could be developed a system to be used in rowing boats.
- More metrics provided from the concept2 monitor could be used to correlate the data.

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