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AAL-IoT

Ambient Assisted Living using Non-Intrusive Smart Sensing and IoT for Gait Rehabilitation

Joel Vieira Santos

Master's Degree in Telecommunications and Computer Engineering

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November, 2022

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TECNOLOGIAS
E ARQUITETURA

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Acknowledgements

First of all, I want to thank my supervisor, Professor Octavian Postolache, and co-supervisor, Professor Diana Mendes, for all the guidance and advice provided. I am also especially grateful to Mariana Jacob, since even though she wasn't directly related with this dissertation, her advice and help were truly useful.

To my family, for keeping me up in track, and for guiding me through the right path at all times.

To my friends and girlfriend, for constantly supporting and helping me when I most needed.

To all volunteers that helped testing the developed prototype and record the results for future analysis and discussion.

To my colleagues working with me at SPMS and Capgemini Engineering, for providing me with valuable skills and information, truly useful in the context of this dissertation.

To Instituto de Telecomunicações (IT-IUL) and ISCTE for providing me with a great opportunity to work in such a demanding project that embraces so many different areas, from IoT to mobile development.

Without your help, this project wouldn't have been possible.

To all that I enumerate, my sincere "Thank you".

Resumo

A monitorização de saúde de pacientes em hospitais, lares, clínicas de fisioterapia ou outros centros clínicos, é uma tarefa importante e recorrente. Além disso, estas instituições requerem um sistema estruturado e organizado, com acesso ao historial médico de todos os utilizadores. O desenvolvimento de um sistema com a capacidade de medir a características de saúde físicas dos utilizadores pode ser também aplicado à área de fisioterapia. Neste contexto, o trabalho de investigação de mestrado apresenta uma solução de um sistema não-intrusivo caracterizado por sensores inteligentes, como parte de um ecossistema de IoT, que visa resolver todas as questões enunciadas.

O sistema IoT utiliza uma carpete inteligente, SensFloor, para medir vários indicadores físicos, como a posição dos utilizadores e as características da marcha considerando jogos sérios que foram implementadas para aumentar a motivação de utilizadores nos planos de reabilitação de marcha. Os dados produzidos pelo sistema são armazenados em tempo-real numa base de dados em nuvem, pelo que tanto os fisioterapeutas como os pacientes têm acesso a estes dados. Além disso, a apresentação de resultados é realizada utilizando gráficos que são produzidos tempo-real, permitindo análises adicionais acerca da marcha dos utilizadores – Considerando a informação obtida os fisioterapeutas podem tomar medidas para melhorar o plano de treino com exercícios mais personalizados.

Palavras-chave: IoT, AAL, mHealth, eHealth, carpete inteligente, marcha, monitorização, análise de dados, jogos sérios

Abstract

Health monitoring of users in medical centers, nursing homes, physiotherapy clinics or other healthcare centers, is an important and recurring task. In addition, these facilities require a structured, organized system with access to all users' medical history. The design of a system that can measure individuals' physiological health characteristics (PHC) may also be applied to physical rehabilitation. In this context, this Master's research work presents a solution of a non-intrusive system characterized by smart sensing as part of an IoT ecosystem, that aims to solve all the issues stated.

The IoT system uses a smart carpet, SensFloor, to measure several physical indicators, such as users' position and gait characteristics, considering serious games that were implemented to increase the motivation of users in gait rehabilitation plans. The produced data by the system is stored in a real-time cloud database, thus physical therapists and patients are able to access it. Also, the presentation of results is achieved using several dashboards that are produced in real-time, to provide further analysis on users' gait and PHCs – Considering the obtained information, physiotherapists may take measures to improve the training plan with personalized exercises.

Keywords: IoT, AAL, mHealth, eHealth, smart carpet, gait, monitoring, data analysis, serious games

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List of Abbreviations:

IT, Information Technology

eHealth, electronic Health

mHealth, mobile Health

IoT, Internet of Things

IoMT, Internet of Medical Things

AAL, Ambient Assisted Living

EHR, Electronic Health Record

DSR, Design Science Research

LAN, Local Area Network

PHC, Physiological health characteristics

FBG, Fiber Bragg Grating Networks

VGRF, Vertical Ground Reaction Forces

VR, Virtual Reality

MR, Mixed Reality

AR, Augmented Reality

MLS, Motion and location sensors

RTPTS, Real-time position tracking systems

RFID, Radio Frequency Identification

SNS, Serviço Nacional de Saúde

SPMS, Serviços Partilhados do Ministério da Saúde

PEM, Prescrição Eletrónica Médica

API, Application Programming Interface

CPU, Central Processing Unit

RAM, Random-Access Memory

HTML, HyperText Markup Language

CSS, Cascading Style Sheets

JSON, JavaScript Object Notation

AWS, Amazon Web Services

CRUD, Create, Read, Update, Delete

UI, User Interface

NCU, Número de Cartão de Utente

RMSE, Root Mean Square Error

GDPR, General Data Protection Regulation

Chapter 1. Introduction

The purpose of this chapter is to further explain the context of this dissertation, mainly its primary objectives and the methodology used to achieve such results.

1.1 Motivation and context

With the increment of global average life expectancy, the number of people who require constant health monitoring also increases. In this context, fast, reliable access to full medical records of patients should be a priority in healthcare facilities. The design of systems able to store and transmit medical data in real-time, while simultaneously implementing security policies, is a challenge [1], partly considering that some medical facilities do not have a sufficient budget to accommodate the implementation of such systems. In Portugal, the adoption of eHealth[1] solutions in the public sector is mainly influenced by the following internal factors: *(i)* the size of the hospital/medical facility, *(ii)* the orientation towards quality in the provision of health services, and, more recently, *(iii)* the decentralization of management and *(iv)* the preparation of professionals to use the new solutions [2]. As a result, in small-sized, low-budget medical institutions, health professionals have limited capabilities for patients rehabilitation monitoring, and patient rehabilitation outcomes.

A survey revealed that, in Portugal, private hospitals and healthcare institutions have higher technical capabilities by comparison with Public Healthcare (SNS). The key factors that distinguish both have focus on waiting time, that is, the queueing time for appointments and waiting time for the subsequent consultations/examinations [3]. In addition, private facilities usually have access to more sophisticated IT systems that reduce these waiting times and allow users themselves to appoint consultations and exams. This results in an organized, distributed system, that keeps record of the user's medical history, and allows health professionals to assess the best methods based on previous data.

In nursing homes, in addition to their current health status and medical records, healthcare givers must also keep track of the elderly people's position in real-time, so they can act in the moment they need assistance. In more advanced ages, emotional health is also a very important factor that needs to be considered, as there are studies that show depression levels tend to increment in elderly people and are aggravated in nursing homes [4][5]. Consequently, one main challenge healthcare givers seem to face is the ability to recognize these situations, and act upon them. Physical exercise in nursing homes can prove effective in reducing the pain intensity, improving mobility, and psychological well-being of elderly people [6], and must be adapted according to each individual user. This may also be applied to physiotherapy clinics and gyms, where physical activity is essential, and keeping the user motivated is a must. In these facilities, it is crucial to assess what the best exercises are for each person, according to their needs.

IoT ecosystems include networks characterized by a variety of objects (including sensors and actuators). The IoT may be applied to healthcare systems, used to remotely monitor patients and measure their health characteristics, so that action can be taken accordingly. Internet of Medical Things (IoMT) brings the concept of IoT applied to medical infrastructures, by making

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[1] ***eHealth*** (Electronic Health) – stands for the digitalization of health services. Likewise, *mHealth* (Mobile Health) is the use of mobile devices to accomplish healthcare solutions.

use of clinical sensors, actuators, and frameworks [7]. IoMT revolutionized the healthcare field, as it is possible to gather physiological information of patients to detect, predict, treat, or maintain potential disabilities, and monitoring patients in real-time. IoMT may also reduce the contact among patients and healthcare professionals, which may prove crucial in the midst of a pandemic (such as COVID-19).

IoT-based systems may also be applied to physical rehabilitation [8], and may take advantage of intelligent prediction algorithms to assess the best options. These systems may be classified in two complementary definitions, according to the measurement type: *(i)* intrusive and *(ii)* non-intrusive measurement. Whereas *(i)* means the measurement procedures have impact on the user's mobility or comfort (*e.g.*, wearable devices), *(ii)* produces minimal to null physical impact. Studies indicate that intrusive systems have a significant impact on the perceived usefulness and ease of use of the smart system [9], and some intrusive smart systems may not be applied directly to real circumstances, since *"no users will walk around continuously connected to a number of sensors so as to have an application that can monitor their state during the day"* [10].

To provide continuous assistance to the users under physical rehabilitation, Ambient Assisted Living solutions may be considered. Thus, AAL emerges as a non-intrusive IoT system used to monitor users' vital signs and support them on a daily basis. The system administrator may then establish security policies for the gathered data, making it only available to health professionals (such as caregiver, physicians, etc.) or even the user's relatives.

In this regard, SensFloor®, by Future Shape, represents a promising solution that was chosen considering that it can measures multiple users' position, speed, step length, and many other physical characteristics in non-intrusive manner. This distributed sensing system may also be used to send fall alerts in real-time. Considering all issues stated previously, this dissertation presents an AAL-IoT system based on the usage of SensFloor as a hardware component.

1.2 Research questions

To conduct this dissertation, the following research questions were formulated:

- Are non-intrusive IoT systems a valid way to measure individuals' physical position accurately?
- How can AAL using IoT help health professionals monitoring patients?
- In what way can AAL be adapted according to the users' needs, in order to keep them motivated?
- How can AAL enhance the current health-applied IoT solutions?

1.3 Objectives

The main objective of this dissertation is to develop an AAL-IoT system that performs user monitoring during gait rehabilitation sessions. Using a completely non-intrusive sensor, SensFloor, the developed system gathers the users' position and other relevant characteristics, and stores these in a real-time database, so that health professionals can monitor patients in real-time, especially in a gait physical rehabilitation context. The user tasks are associated with developed serious games that are increasing the user motivation during physical rehabilitation.

The system was developed with particular focus on nursing homes, physiotherapy clinics and gyms, as these are places that are associated with physical activity and physical rehabilitation plans. In these facilities, the access to full medical history may not always be possible, therefore, this dissertation also considers this issue and presents a basic electronic health record (EHR) implementation. Thus, the EHR stored data may be used to interconnect different clinics and also to perform the training plan optimization.

Also, it is crucial to keep the users motivated to continue exercising and to adapt the system according to the individual person's needs. To do so, the developed physical exercises are adaptable to each individual, and the concept of serious games was implemented. In addition, a mobile application with a user-friendly, intuitive interface was also designed, which provides feedback, making it possible for the user to analyze the measurements and see his/her progression and improvement. In a physiotherapy clinic, the physiotherapist must assess the physical evolution of their patients, so that the best exercises can be applied. By measuring these characteristics, the system presents visual information (in the forms of graphs and charts) so that the physiotherapist can make a more informed decision.

1.4 Research Methodology and Schedule

Design Science Research (DSR) is a methodology whose main objective is to identify the problem, develop and test solutions and evaluate the final result, as shown in **Figure 1**. DSR is used to create artifacts, that is, technological innovations, to solve specific problems, and test whether the solution is valid or not. In the context of this dissertation, this was the methodology followed, and will be further explained.

1. The first step is "*Problem identification and motivation*", where the specific problem to be solved is presented – this step corresponds to the "**Motivation and context**" section. In the context of this dissertation, and as stated in the introductory chapter, this means designing a fast, reliable, completely non-intrusive system that measures users' position and gait characteristics in real-time. The system should also keep users motivated to exercise through the use of serious games.
2. The next step is to present "*Objectives of a solution*", by proposing a new solution and explaining why it is valid and acceptable. It should also present a comparison with current state of the art solutions – this step corresponds to the "**Objectives**" and "**Chapter 2. State of the Art**" sections. The main objective with this research work is to design an accurate AAL system that makes use of a smart carpet to monitor users PHCs.
3. The third step is the "*Design and development*" of the previously proposed solution, targeting it to accomplish the desired results and solve the problem. In this step, the methodology followed is presented, as well as the corresponding technologies to achieve such results – this step corresponds to the "**Chapter 3. System Description**" section. In this chapter, all hardware, software, firmware, and database characteristics are described, as well as the designed serious games and data visualization tools.

4. After designing the artifact, the "*<u>Demonstration</u>*" of the solution is crucial, by finding a suitable context and applying it to solve the specific problem with real data – this step corresponds to the "**Chapter 4. Experimental Results and Discussions**". In this case, this chapter describes the tests that were carried out, and appraises the overall performance of each one. By doing so, it is possible to obtain a positive or negative feedback of the prototype.
5. The fifth step is to "*<u>Evaluate</u>*" the designed artifact's results, and check if all objectives were accomplished with the implementation of the new solution – this also corresponds to the "**Chapter 4. Experimental Results and Discussions**" section. By getting feedback from users and volunteers, it is possible to analyze if the system achieves the desired objectives and if it is a viable solution. Because DSR is a cyclic methodology, if the evaluation fails, the process should return to step 2 or 3, and repeat the steps.
6. Finally, after constant testing the designed solution and obtaining positive results, the "*Communication*" of the solution must be done, and the artifact must be presented to an audience. This corresponds to the presentation of this dissertation to an audience and to the publication and presentation of scientific articles.

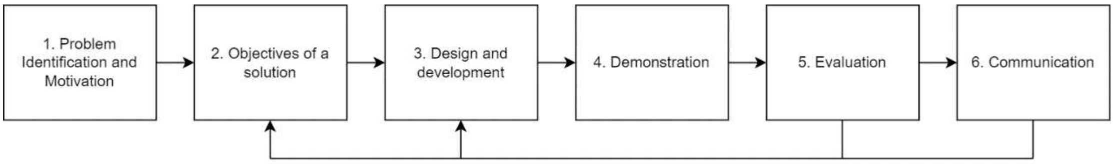
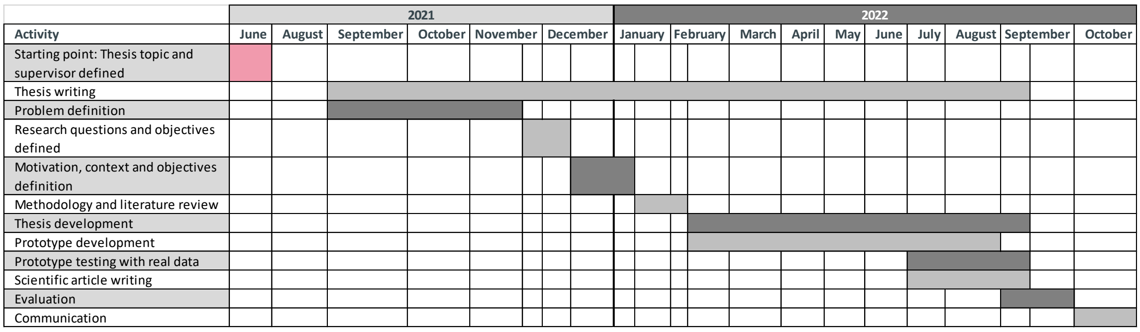


Figure 1 - Design Science Research

As a way of organizing the work developed in this thesis, a planning map was made, represented in the tables below.



	2021						2022									
Activity	June	August	September	October	November	December	January	February	March	April	May	June	July	August	September	October
Starting point: Thesis topic and supervisor defined	▨															
Thesis writing			▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	
Problem definition			▨	▨	▨											
Research questions and objectives defined					▨	▨										
Motivation, context and objectives definition						▨	▨									
Methodology and literature review							▨	▨								
Thesis development								▨	▨	▨	▨	▨	▨	▨	▨	
Prototype development								▨	▨	▨	▨	▨	▨	▨		
Prototype testing with real data													▨	▨	▨	
Scientific article writing													▨	▨	▨	
Evaluation															▨	
Communication																▨

Activity	Start	End
Starting point: Thesis topic and supervisor defined	15/07/2021	-
Thesis writing	15/09/2021	30/09/2022
Problem definition	15/09/2021	27/11/2021
Research questions and objectives defined	28/11/2021	15/12/2021
Motivation, context and objectives definition	20/12/2021	10/01/2022
Methodology and literature review	11/01/2022	05/02/2022
Thesis development	08/02/2022	10/09/2022
Prototype development	08/02/2022	25/08/2022
Prototype testing with real data	20/07/2022	08/09/2022
Scientific article writing	20/07/2022	08/09/2022
Evaluation	03/09/2022	30/09/2022
Communication	30/09/2022	-

Table 1 - Schedule

1.5 Structure and organization of dissertation

The present work is organized in five Chapters, that intend to describe the different phases until its conclusion.

The first and current Chapter introduces the subject of the investigation and contextualizes the reader. It also presents the main goals and provides a brief description of the structure of the work. This chapter also gives a general look at the activities and tasks done, in a “calendar-like” structure.

The second Chapter describes the current State of the Art, by presenting multiple developed solutions using different approaches, as a way to contextualize this dissertation’s scope.

The third Chapter is dedicated to the developed prototype, including the main hardware, software, and database characteristics and architecture, and applications in physiotherapy.

The fourth Chapter provides information about the developed metrics used to evaluate the system’s behavior, as well as a comparison and general appraisal between these metrics. It also presents simulated and real-life tests carried out, with comments and discussions about each.

The fifth and final Chapter presents the conclusions of this dissertation and the future work.

Chapter 2. State of the Art

This chapter presents current solutions within health monitoring systems, as well as real-time position tracking systems and IoT systems for exercising and rehabilitation, different ways to store health-related data in storages and finally a comparison between various smart carpets.

2.1 Literature Review Process

To begin with, articles were selected from a variety of possibilities, using article repository platforms such as **Google Scholar**, **b-on biblioteca do conhecimento online** and **IEEE Xplore**. Through the selection of these articles, the methodology followed is shown in **Figure 2**.

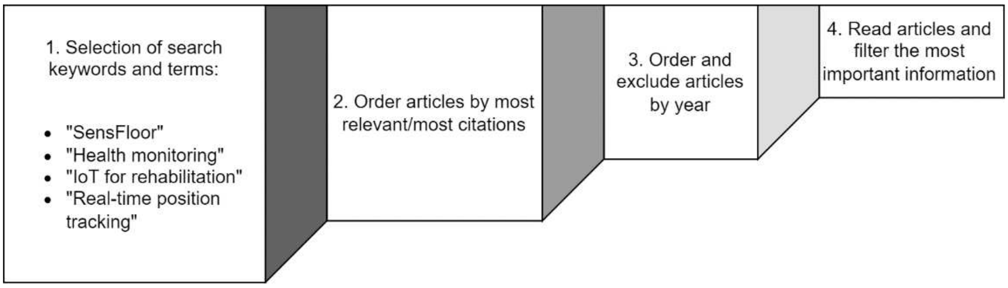


Figure 2 - Literature Review Process

2.2 Architectures of IoT health monitoring systems

The principle beneath different (health) monitoring systems is the same, to gather health data from users and process it. However, the technology to accomplish that is what usually changes. Through the use or not of wearable systems, Edge of Things (EoT) real-time computing [11] and Cloud Computing, several options are available.

An IoT system is usually decomposed in layers, as shown in **Figure 3**.

1. The first layer, in ascending order of complexity, is composed of sensors, actuators and other objects that produce data, so naturally, here is where the data is originated.
2. The second layer corresponds to the edge layer, which is composed of embedded systems, microcontrollers, and other devices with some processing power. These devices' main function is to receive and filter data from the previous layer, and in some cases process the data (edge computing).
3. The third layer, fog, consists in servers, gateways, switches, etc. that define LANs and take the processing of data closer to the network.
4. The fourth layer, cloud, is where business logic is implemented, and big data processing usually happens.

Edge computing means acquiring and processing the data near or at the network's edge, as opposed to cloud computing. Edge of Things may bring advantages and solve various issues such as latency and bandwidth consumption, because of the large area between IoT and Cloud layers [11].

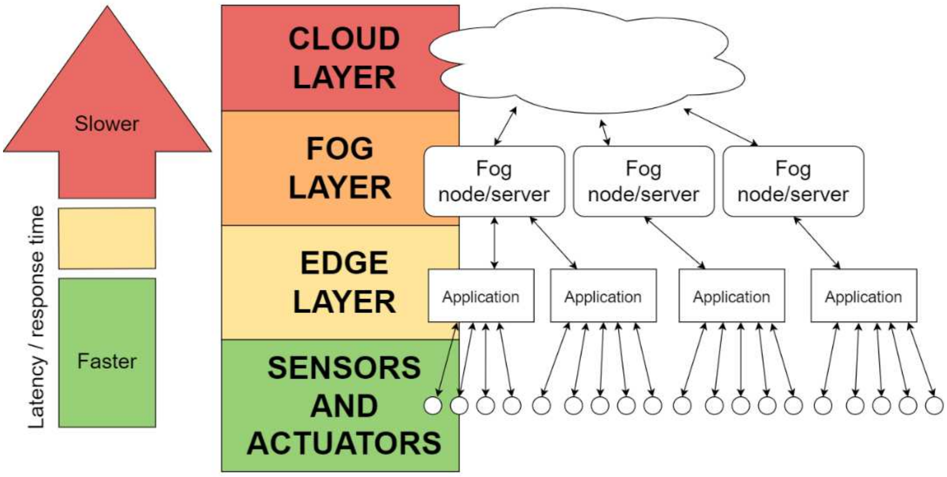


Figure 3 - IoT layers, adapted from [12]

2.3 Wearable/intrusive health monitoring systems

Wearable devices, such as smartwatches and smartbands, are evolving exponentially, in terms of processing power and functionalities available. As a consequence, the reliability, accuracy, and adaptability are improving, and their measurements can be used by health professionals to analyze.

It is important to understand what the most important vital signs to be measured are, and how can a wearable device be implemented in such way. Overall, heart rate, blood pressure, respiratory rate, blood oxygen saturation and body temperature are of a major importance to be measured [13][14], and are presented in a number of wearable devices. Other important health parameters might be considered, such as glucose level (for diabetics), electrocardiography, pain level, stroke volume, etc.

In rehabilitation procedures, posture, motion control, gait, feet pressure and other physical characteristics are crucial measurements. The study presented in [15] investigates all 123 environmental factors of wearable devices, and correlations between each. Some measured factors may be applied directly in the context of physical rehabilitation, mainly in the activity measurement section, such as the number of steps, exercise type auto-detection and exercise tracking, floors and stairs climbed, and calories burned. Some wearable devices also suggest exercise plans for users to follow, and when implemented with more complex sensors and hardware, these devices provide useful data.

Some wearable devices are designed as multipurposed and may measure accurately most of the parameters previously presented. Other devices are developed to solve specific problems and measure particular characteristics. The trend is to reduce the size of these wearable devices, minimizing discomfort, so that the device can be used both in normal daily activities and in physical exercise. That is not always possible, due to the nature of the measurements and to requirements that need to be accomplished, and the user ends up using several intrusive sensors attached that can compromise comfort and usefulness. Other wearable devices' drawbacks are the need to worry about charging and wearing and taking off the sensor. People with dementia or illness may have a limited ability to use these wearable devices, and studies show that elderly people prefer non-wearable sensors [16].

2.3.1 Gait rehabilitation

The measurement of users' physiological health characteristics (PHC) varies according to the specific characteristic measured. Most solutions offer different approaches to the same problem, but the usage of intrusive systems to achieve the desired objective is often common. The usage of smart systems may result in a benefic improvement of people's walking ability. An elderly person's walking ability shows a big difference comparing with a younger adult, as the older person may have a shorter step length, more walking instability, reduced hip range and flexion and quicker fatigue [17].

One solution to analyze users' gait is the usage of **smart insoles** with biofeedback[2] [17], as shown in **Figure 4** so that users can be encouraged to improve several parameters. Smart insoles are part of smart clothing devices – this group covers smart devices that can be worn, such as smart jackets, smart glasses, etc. One particular solution [17] concluded that the biofeedback associated with the smart insoles resulted in dramatic improvements in swing time (6.45%), stride length (4.52%) and hip flexion (14.73%); also, the cadence was significantly reduced by 5.5%.

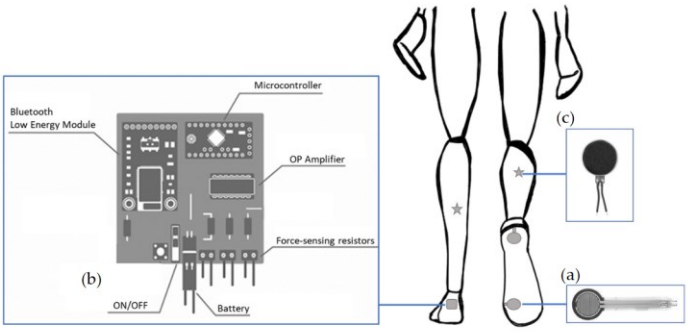


Figure 4 – Gait monitoring system using smart insoles with biofeedback, taken from [17]

In this regard, it is possible to incorporate Fiber Bragg Grating Networks (FGB) in smart insoles and use the optical fiber technology to monitor vertical ground reaction forces (VGRF) and plantar pressure [18], which are of great importance in the analysis of gait rehabilitation. In this study, it is stated that there are pathologies associated with abnormal VGRF and plantar pressure, such as diabetes, and that an accurate monitoring of these characteristics is crucial to avoid and reduce the risk of these pathologies.

Motion capture ("mocap") systems may also be used to gait analysis [19][20], and the principle behind these is quite simple: placing markers on various locations on a person's body, and by using several cameras and devices designed to follow the variation in marker position, the body's movement can be tracked. Vicon motion capture systems are often used along with GaitCore to analyze motion of all kinds, from optical to inertial and VR. These systems produce a significant amount of data, as almost any physical characteristic can be measure, from knee

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[2] ***Biofeedback*** – usage of sensors to monitor and provide feedback about characteristics of the user's body, so that the user has better control over it.

angle to muscle activity. However, as shown in **Figure 5**, these systems are very intrusive, and some users might end up losing motivation [10].

Figure 5 - Motion capture system, taken from [20]

Gait analysis is also correlated to physical rehabilitation, as the gathered data is subsequently analyzed by physiotherapists to assess patients' diagnostic. A number of physical rehabilitation IoT systems have been proposed, from **simple wearable solutions** [21] to **exoskeletons** [22] and **virtual, mixed or augmented reality (VR/MR/AR)** solutions [23][24][25][26], and have proven beneficial in upper and lower-limb motor function, balance and gait.

The need for physical rehabilitation can cause fatigue, stress and depression in patients, and studies reveal that only 44% of patients adhere to the rehabilitation program [27]. Highly intrusive rehabilitation systems may discourage the user even further, by causing discomfort and, in some cases, pain. In-home rehabilitation is also a possibility. However, homes usually lack the specific facilities to rehabilitation provided in hospitals and physiotherapy clinics – more importantly, patients' motivation is affected negatively by repetitive exercises [28]. So how can intrusive sensors and smart systems be used in a way that keeps the user motivated to continue exercising?

The concept of **gamification** and **serious games** is an approach for improving patient motivation and engagement during physical rehabilitation sessions. Traditional rehabilitation may be adapted by selecting a variety of games or ludic activities that meet treatment objectives [28]. When used simultaneously with the technologies previously presented, such as VR/MR/AR, gamification may improve even more [28][29]. Thus, by opposition with traditional rehabilitation programs, users show greater enjoyment, higher decision freedom, lower physical demand and anxiety, and less pressure, while improving their physical performance [30]. Games should provide clear feedback, text, and audio instructions, so that the patient can be informed how to achieve goals [28]. Gamification is not all about games, and may be applied to a great variety of systems. By defining objectives throughout the application, the user keeps engaged and motivated to continue.

2.4 Non-intrusive health monitoring systems

As mentioned previously, this dissertation focuses on completely non-intrusive, remote health solutions to measure accurately individual's PHCs. Non-intrusive systems consist mainly in the usage of remote sensors and devices, such as **cameras**, using wireless communication protocols, clustered in an IoT network. Cameras are classified as **vision-based systems** and may be used in a variety of solutions, from face recognition and security systems to eye tracking technology, with the advantage of monitoring several users simultaneously with good accuracy

[31]. Vision-based systems usually run different algorithm techniques (SVM, FFNN, K-Nearest Neighbors, Decision Trees, etc.) to identify and classify several elements.

PHCs can also be measured using cameras, and gait recognition is also possible. Biomedical indicators and parameters may be extracted from videos to classify the user's gait; Pedro et al. achieved this through the analysis of silhouettes, Gait Energy Image (GEI) and the Skeleton Gait Energy Image (SEI), represented in **Figure 6** and **Figure 7** [32]. By analyzing the results in convolutional neural networks, it is possible to classify users' gait and assess or predict possible physical illnesses. In this article, it is possible to predict if a person is Diplegic, Hemiplegic, Neuropathic or Parkinsonian through the usage of several cameras, including normal mobile phone cameras and more sophisticated 4K and RGB cameras.

Figure 6 - Gait sequence through a series of key silhouettes, and the resulting Gait Energy Image (GEI), taken from [32]

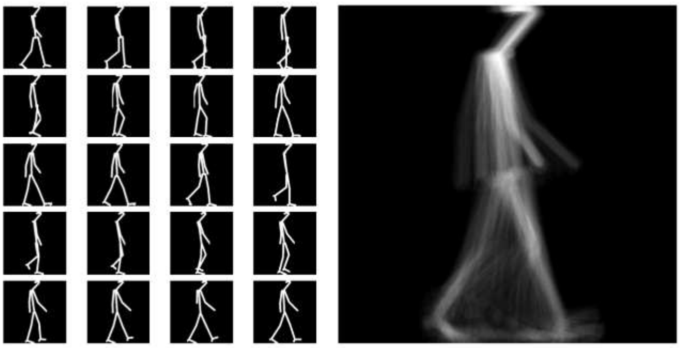


Figure 7 - Down-sampled set of skeleton frames corresponding to one complete gait cycle (left) and respective SEI (right), taken from [32]

Motion and location sensors (MLS) are also an unobtrusive way to detect the presence of people in an area. One simple application of these sensors is automatic lighting in public spaces. MLSs may also be used to measure physical parameters, such as the position and speed of users [33]. Nowadays smartphones include a variety of sensors, including MLSs – it is possible to detect feet movement and calculate user's steps using only the sensors in a smartphone. Using the embedded smartphone's gyroscopes, angular velocity can be calculated and used in algorithms to measure if the user is moving and calculated the corresponding number of steps [34]. Tahir, M. N., Rashid, U. developed an algorithm tested in real time environments for walking, running, climbing up and down stairs, that showed promising results with almost 99% accuracy [34]. Patil, A.K. et al.'s paper describes a complex IoT system using multiple LIDARs and inertial sensors for real-time pose tracking of human motion and reveals precise and realistic results (**Figure 8**)[35].

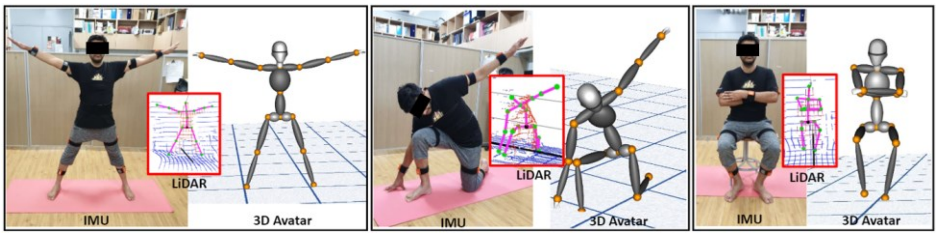


Figure 8 - Real-time pose tracking of human motion for reconstruction on a three-dimensional modelusing multiple lidars and inertial measurement units (IMUs), adapted from [35]

The concept of gamification may also be applied to unobtrusive health solutions. **Microsoft Kinect**, shown in **Figure 9**, designed originally for Xbox, is a hands-free MLS, that uses RGB cameras, infrared projectors, depth sensors and microphones, thus being classified as a vision-based system. Beshara, P. et al. have written about the reliability of Microsoft Kinect and other inertial sensors, smartphone applications and digital inclinometers/goniometers to measure shoulder Range of Motion (ROM) [36]. Overall, Kinect demonstrated moderate-good levels of reliability in these measures, being a low-cost device.

Figure 9 - Microsoft Kinect sensor v2 for Xbox One

This particular system shows promising results incorporating the concepts of gamification and serious games to several rehabilitation and healthcare areas [37], [38], from using hand gestures for elderly care [39] to post-stroke rehabilitation [40]. Gamification has proven useful and benefic in intrusive systems, and unobtrusive systems, such as Microsoft Kinect, also benefit from it [32][33]. Other non-hands-free similar devices, such as Nintendo Wii, showed several injuries related to overuse or incorrect use of handheld controller, amongst them, tendinopathy, and hand lacerations [41].

2.5 Real-time position tracking systems

Tracking human movement in real-time is a need in certain cases, in particular in healthcare facilities, physiotherapy clinics, fitness training and rehabilitation. **Real-time position tracking systems (RTPTS)** may be implemented through the usage of different devices, from simple motion sensors to more complex IoT networks that connect several devices, such as cameras, infrared and ultrasonic sensors. Wearable systems may also be used in such way, and smartphone embedded GPS tracking system is often used on a daily basis.

RTPTS can be accomplished using different principles, such as, but not exclusively, **satellite communications** (*e.g.*, GPS), **electromagnetic tracking systems (EMTSs)** or **echo location**. Echo location means the distance to an object is measured using ultrasonic waves emitted, by measuring the time between the emission of ultrasonic pulses and their reception (**Figure 10**). These pulses may be ultrasonic sound waves (*e.g.*, ultrasonic sensor HC-SR04), light/laser (*e.g.*, LIDAR), radio frequencies (*e.g.*, Radar), etc.

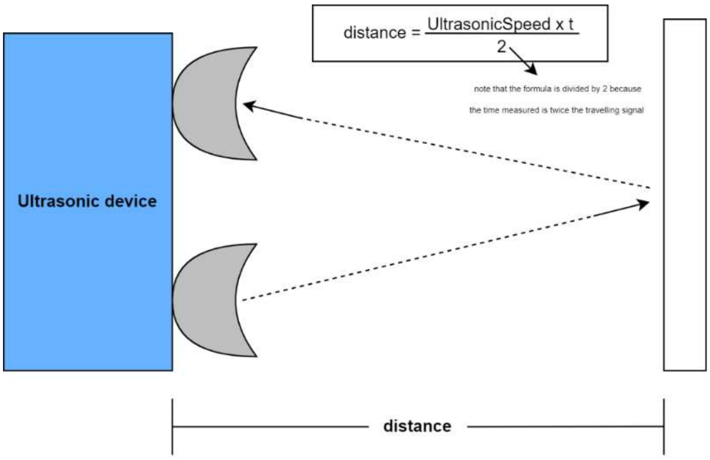


Figure 10 - Ultrasonic sensor

Articles from various sources have been written using several of the above-mentioned technologies. By merging LIDAR and inertial sensors together in an IoT network, Patil, A.K. et al. accomplished the measurement of several PHCs in real-time, such as human detection, estimation of height, skeletal parameters, position, and orientation [42]. Wireless communication protocols, such as Bluetooth, ZigBee, or RFID[3] can also be used in this context. A comparative study between Bluetooth Low Energy (BLE) and RFID on identification of a neurodegenerative disease concluded that BLE presents the best position sensing ability [43]. RTPTSs are not only designed to track a human person's position and may be suited to track other things as well, *e.g.*, using low-cost RFID tags for object tracking with high accuracy [44].

These technologies, however, may present some indoor location tracking issues, as they often have relatively close measurement distances, and physical obstacles (such as walls) may be outliers in the system. In order to achieve high accuracy, complex networks of RTPTS devices need to be implemented, keeping blind spots and obstacles into consideration.

2.6 Smart carpets

Smart carpets are sensitive walkways, placed on the floor, that measure users' PHCs, providing gait identification. Smart carpets are non-intrusive systems, as they can be placed in a discreet way and do not cause discomfort to users. As these are sensors that measure the forces applied to them, it is possible to develop several functionalities useful for physiotherapy that are not possible in other non-intrusive sensors, like feet pressure and accurate fall alarms. Smart carpets can also locate the user accurately, acting like a real-time position tracking system, and may prove more accurate while tracking users indoor, since obstacles don't have a high impact. Smart carpets may be installed to cover all the necessary area, without complex IoT networks, and it should be possible to define home plans and home divisions, as a way to record and/or track users' movements with precision.

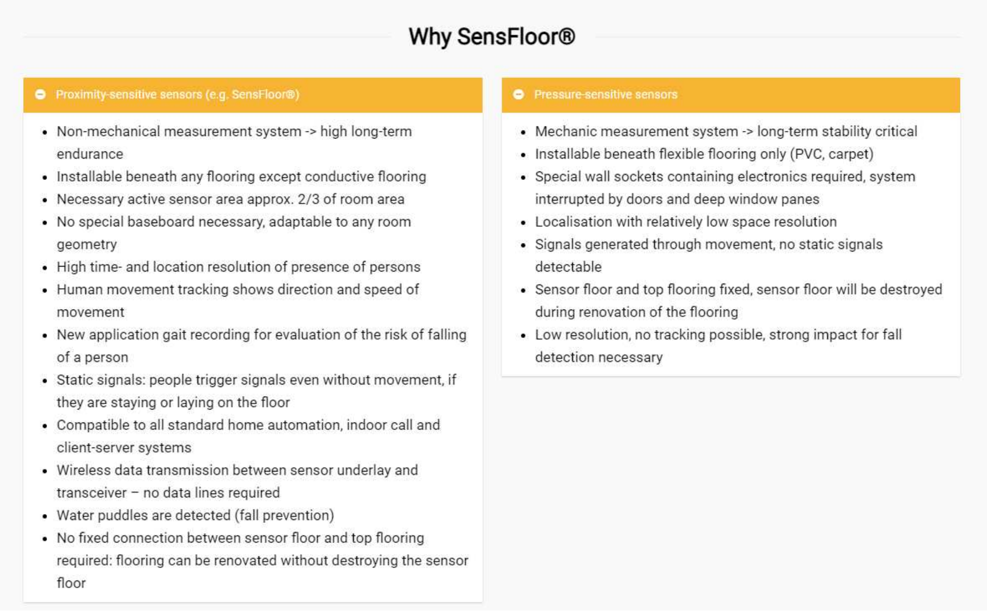
---

[3] **RFID (Radio Frequency Identification)** – wireless system with a transceiver and a transponder, acting as a "reader" and a "writer" to identify or authenticate entities in a given system

2.6.1 SensFloor® characteristics and projects

SensFloor®, by FutureShape, is a large area sensor floor, that can be installed beneath all kinds of flooring, making it invisible (**Figure 11**). Being a smart carpet, SensFloor can detect users standing on it, which offers a variety of advantages when comparing to traditional sensing techniques, as seen in **Figure 12**.

Figure 11 - SensFloor, by FutureShape



Why SensFloor®

Proximity-sensitive sensors (e.g. SensFloor®)

- Non-mechanical measurement system -> high long-term endurance
- Installable beneath any flooring except conductive flooring
- Necessary active sensor area approx. 2/3 of room area
- No special baseboard necessary, adaptable to any room geometry
- High time- and location resolution of presence of persons
- Human movement tracking shows direction and speed of movement
- New application gait recording for evaluation of the risk of falling of a person
- Static signals: people trigger signals even without movement, if they are staying or laying on the floor
- Compatible to all standard home automation, indoor call and client-server systems
- Wireless data transmission between sensor underlay and transceiver – no data lines required
- Water puddles are detected (fall prevention)
- No fixed connection between sensor floor and top flooring required: flooring can be renovated without destroying the sensor floor

Pressure-sensitive sensors

- Mechanic measurement system -> long-term stability critical
- Installable beneath flexible flooring only (PVC, carpet)
- Special wall sockets containing electronics required, system interrupted by doors and deep window panes
- Localisation with relatively low space resolution
- Signals generated through movement, no static signals detectable
- Sensor floor and top flooring fixed, sensor floor will be destroyed during renovation of the flooring
- Low resolution, no tracking possible, strong impact for fall detection necessary

Figure 12 - SensFloor advantages

SensFloor was developed by FutureShape starting in 2005 and was first installed in a large project – a nursing home with 70 rooms, including bathrooms – in 2012 in France. At that time the fall detection and the switching of orientation alerts were the main functions of the system. Since then, the emphasis in the development was placed on sophisticated software algorithms to detect many more events in the domain of care, such as inactivity, wandering, leaving the bed or the room at night. SensFloor care systems have been installed in more than 50 nursing homes, senior residences, and hospitals. More than 40 living labs at universities and private institutes in Europe (including ISCTE-IUL) have been equipped with SensFloor, providing an interesting base for research and development [45].

In combination with intrusion alarms, the SensFloor system is able to trace the movement and presence of intruders and make it accessible over an internet browser or a mobile app. It is also possible to display the activity remotely and send alarms through a secure channel over the internet such that the current health status of persons can be checked by relatives or care providers. Usually, it takes one hour to install up to 2-4 square meters, depending on intended floor construction. The cost of the SensFloor installation is less than 4% of the overall costs of an apartment. SensFloor transceiver can also be based on a microcontroller (such as a Raspberry Pi, BeagleBone, etc.); through the SensFloor API, information is available to be used in the individual application or to be forwarded to other systems.

SensFloor is equipped with gait recording, making it possible to record users' movements in a given period of time, providing useful data for health status assessments in Neurology, Geriatrics and Rehab. As seen in **Figure 13**, by analyzing the record of users' past positions and the corresponding gait pattern, the health expert is able to evaluate the effect of physical training and medication and detect patterns in several diseases. Especially for patients with a higher risk of falling, early diagnosis and treatment are essential. It is possible to measure speed, average step length and width, etc. and analyze the data, which can prove helpful in recognizing asymmetric and instable gait patterns. The data is structured and saved for medical record. SensFloor is also suitable for rollators and other walking aids[46].

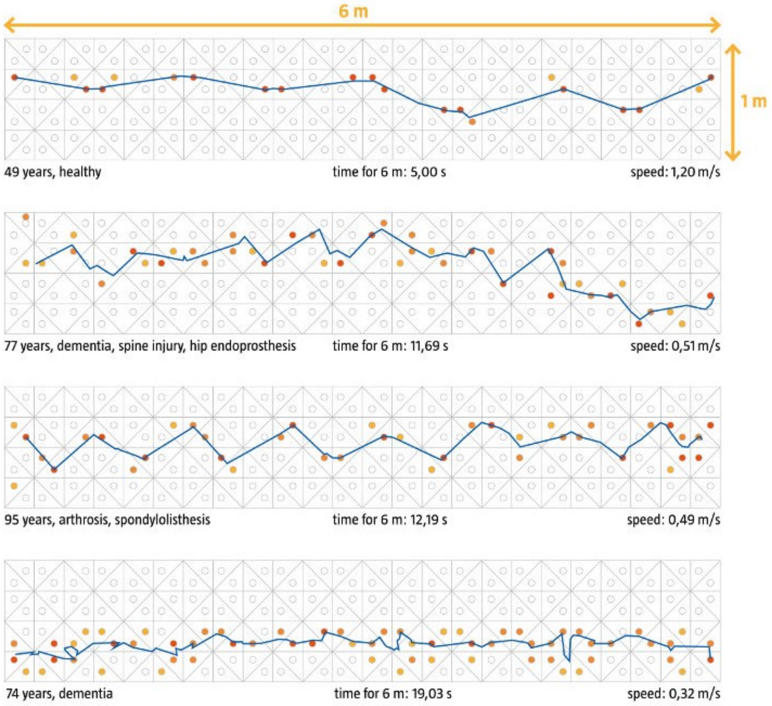


Figure 13 - SensFloor Gait Recording and analysis [46]

In Charlotte, North Carolina-based Maxwell Group, a management company that operates 15 senior care communities with approximately 3.000 units across six states, chose to install Sole with SensFloor Technology. In their opinion, the smart floor technology is an alternative to wearables or cameras providing privacy and independence for residents, increasing opportunity for smart personal engagement and monitoring while maintaining resident dignity and privacy. "*For me, one of the big things is the safety and the comfort that I feel like this* [technology] *gives to families*", said Gina Gaines, director of design for Maxwell Group. Allison Wolff, director of Healthcare and Senior Living at Shaw, noted that hourly rounds can result in 17% engagement during a 24-hour period, while Sole with SensFloor can discreetly monitor for the other 83% of time [47].

Gamification is also a possibility with SensFloor. Thus, various other projects were done using SensFloor, including casual and serious games. In 2017, the company Migros has toured across a number of Swiss shopping malls with its "Reaction wall" (**Figure 14**). With the help of SensFloor sensors located under the flooring, visitors were able to operate the game and test their reactivity at the same time. There was also the concept of a "Wheel of fortune" and "Type generator".

Figure 14 - "Reaction wall" game using SensFloor

Presence detection with SensFloor is possible without cameras and the sensor floor can also issue an alter in the event of vandalism. SensFloor can be combined with wearable devices to a more accurate human tracking and identification [48].

NaviFloor®, also developed by FutureShape, is also worth mentioning. NaviFloor, however, is more suited for robotics applications such as robot navigation, as it provides landmarks on a floor using RFID tags; using robots with RFID readers, it is possible to determine robots' exact position.

2.6.2 GAITRite® characteristics and projects

GAITRite® is a portable pressure sensitive walkway that measures spatial and temporal gait characteristics, providing easy identification of gait anomalies. GAITRite's proprietary software analyzes multiple gait cycles and offers reporting automatically, and data can be easily exported. It is currently used worldwide in 54 different countries (including Portugal), with statistics stating that "*every hour of every working day, there is a subject walking on a GAITRite*". Also, a recent Google Scholar search for "GAITRite" returned 4519 results across a multitude of diseases and conditions, meaning that plenty articles and papers have been published in this thematic. GAITRite is suited almost exclusively for physical rehabilitation, as it measures 100+ gait related parameters, including step time, cycle time, step length, toe in/out, etc. It can also be integrated with EMG, Motion Capture, and other systems, either by receiving a sync to time zero or sending it. These walkways come in a variety of options, such as:

- GAITRite Basic – suited for small clinics; one direction walkway, as shown in **Figure 15**.
- GAITRite CIRFACE – allows U-Turns, Left and Right turns, Sit to Stand, Start and Stop and Stepping up and down functionalities, with curbs and ditches, stairs, platforms, etc.
- GAITRite SAFARI – allows a whole new level of portability, with a portable solar based power system.

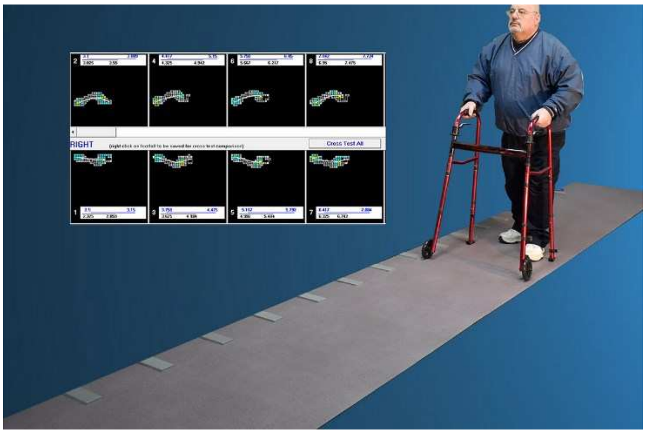


Figure 15 - GAITRite system

Studies have investigated the reliability and validity of the GAITRite system and reported it to be highly valid in measuring both temporal and spatial characteristics [49]. Among the projects already carried out using GAITRite, most focus on the area of physical rehabilitation, gait analysis, fall prediction and interoperability with other devices (such as Kinect and smart insoles). This reveals that GAITRite may not be suited for home automation and security implementations. **Table 2** compares GAITRite with SensFloor in terms of capabilities and functionalities.

	SensFloor®	**GAITRite®**
Sensors type	Capacitive, similar to the touch screen of a mobile phone	Pressure, triggered when mechanical pressure is applied, with 8 levels of relative pressure
Interfaces	HDMI, Ethernet, WLAN, USB, Bluetooth, floating relay or Cloud	USB, AC Power Input
Portable	No	Yes
Assembling time	1 hour per 2-4 square meters	75 seconds
Suited for gait analysis and rehabilitation	Yes	Yes
Suited for home automation	Yes	No
Suited for security, access controls	Yes	No
Possibility to replay previous measures	Yes	Yes
Processing unit	Microprocessor with a transceiver, such as a Raspberry Pi or Beagle Bone	Computer-like device
Cost	4% of the overall costs of an apartment	Low-cost
Measurements and Functionalities	• Counting of persons, identify their direction and speed • Record users' gait, speed, position, number of steps. • Distinction between walking and lying persons • Heatmaps for presence and distribution analysis • Presence-controlled light and air conditioning • Fall and activity alarm, localization of intruders	• 100+ gait related parameters, including step time, cycle time, step length, toe in/out, etc. • GAITRite CIRFACE allows U-Turns, Left and Right turns, Sit to Stand, Start and Stop and Stepping up and down functionalities, with curbs and ditches, stairs, platforms, etc. • Can be integrated with EMG, Motion Capture and other systems

Table 2 - SensFloor vs GAITRite

2.6.3 CatWalk XT

Another smart carpet worth mentioning is the CatWalk XT, a complete gait analysis system for quantitative assessment of footfalls and locomotion in rats and mice. Although this device is not suitable for human beings, it is possible to analyze gait and footprints of moving animals and predict several (neurological) disorders and lesions. Examples include spinal cord injury and other nerve injuries, neuropathic pain, arthritis, stroke, Parkinson’s, Cerebellar ataxia, traumatic brain injury, peripheral nerve damage, and several articles have been published in this sense (**Figure 16**). As long as the animal is able to traverse the CatWalk runway, the system can evaluate its gait.

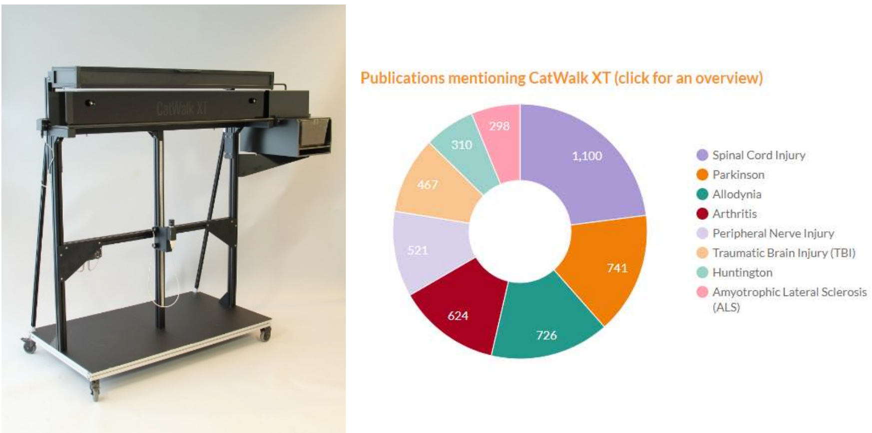


Figure 16 – CatWalk XT (left) and publications mentioning it (right)

The system consists of a corridor that directs the free movement of the animal in a straight line, a hardened glass walkway that enables CatWalk XT's Illuminated Footprints technology, a high speed color camera for extremely accurate spatial and temporal resolution and the CatWalk XT software for the recording and automated analysis of the locomotor ability of the rodents. Similarly to GAITRite, CatWalk provides over 100 gait-related parameters for qualitative and quantitative analysis.

2.6.4 Non-commercial smart carpets

It is possible to design own smart carpet systems using arrays of sensors. Muheidat, F. et al. developed a smart carpet system using sensors with a conductive material to pick up 60Hz signals, valuable to detect humans’ presence and falls [16]. The sensor array, shown in **Figure 17**, is installed under carpets, and the 60Hz signals are then processed (amplified and digital-converted) using several processing boards, each board connection to a 32 sensors array. The data is sent and received between the boards using I^2C communication protocol. **Figure 18** shows the system overview and architecture.

Figure 17 - Foil sensors (left) and one single sensor (right), taken from [16]

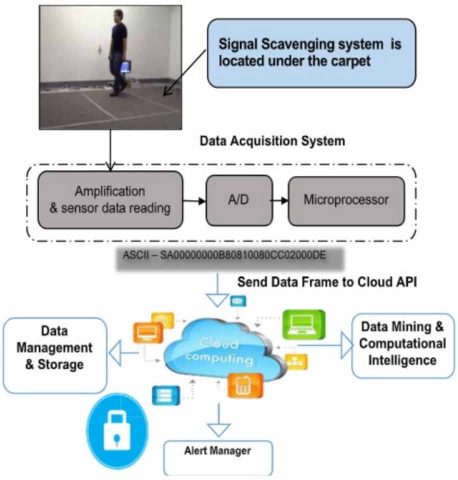


Figure 18 - System overview: floor-based sensors, data acquisition, analysis, and reporting, taken from [16]

This particular solution showed 95% sensitivity and 85% specificity in detecting falls. The results of the developed system were then compared to a system using GAITRite, resulting in a mean percentage error difference to GAITRite in 1.43% in walking speed. This means the developed system achieved an excellent agreement with the GAITRite system. The performance of this system was compared to two other systems using Kinect, web cameras and motion-capture Vicon (all these systems use GAITRite as validation basis); the results were the following (mean percentage difference): 1.34% using a smart carpet, 2.9% using Kinect and 0.18% using a web camera.

2.7 Health storage systems

Health information is very sensitive and personal, therefore it must be stored in a secured way, by ensuring that only certain people have access to it. According to [13, 14 and 15] of the General Data Protection Regulation (GDPR), users must have the right to be informed about who has access to their data, and the right to request a copy of any of their personal data. In most health monitoring systems, it would be useful that, besides health professionals, the user's relatives have access to the health status. The user, or someone representing the user, should be able to define which people have access to his/her data, so that in cases of urgency there are no inconveniences.

Another desirable feature in health monitoring systems is the ability to send automatic alerts in real-time in the event of unusual health measurements or if the user falls.

2.7.1 Global health information storage standards

International standards for representing and transferring health-related data between health information systems (such as hospitals and medical clinics) have been developed. These standards are necessary as different medical facilities must have access to the patients' medical history, so that the users don't have to repeat the same exams or medication (as represented in the scenario proposed in **Figure 19**). Some challenges health institutions face regarding this issue include:

1. Impact on security, efficiency, and healthcare costs for not having the right information when needed.
2. Clinical information present in IT systems may not be correct.
3. Costs associated with paper records in a digital era.

By following the same health information managing standards and allowing data sharing between different medical institutions, interoperability is achieved, and these issues can be surpassed. Interoperability in this case is not only about moving data from one system to another, but also making sure both systems understand the information the same way.

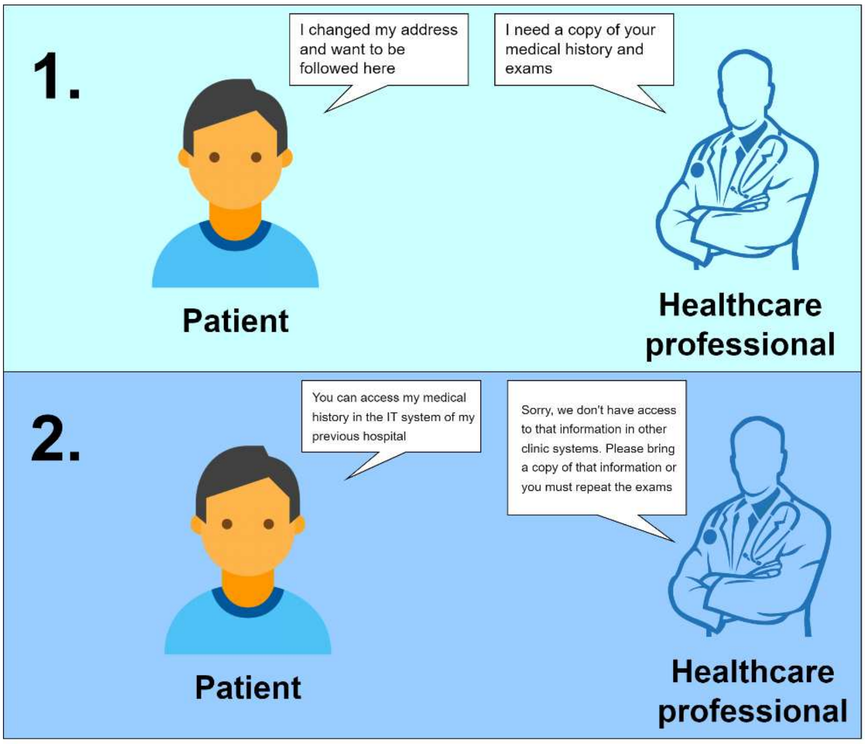


Figure 19 - Problem in a medical facility with no health information storage standards

Health Level 7 (HL7), founded in 1987, defines standards for gathering, exchanging, and sharing health information, and supports managing and evaluation of healthcare services. Level 7 refers to the application layer in the OSI model, which is "layer 7". Several HL7 versions and standards have been implemented, such as CDA, v2, v3 and FHIR.

CDA (Clinical Document Architecture) is based on HL7 v3 and is an exchange model for clinical documents. It contains XML-formatted data, and also supports documents encoded in

.pdf, .doc, .rtf or image formats like JPEG and PNG. A CDA may contain any clinical record, *e.g.*, imaging report, discharge summary, pathology report, etc. CDA ensures multiple characteristics [50]:

- Persistence – data remains intact for long periods of time.
- Stewardship – trusted source of information.
- Potential for authentication – certificate that clinical information is correct and accurate.
- Context – information about the document, *e.g.*, patient identity or who created the document.
- Wholeness – access to the full document.
- Human Readability – the document can be easily interpreted by a human person.

HL7 v2.x, also known as Pipehat, is the most widely implemented standard in the world for health and medical transactions between systems. It is updated regularly and supported in more than 35 countries, and by 95% of US healthcare organizations [51]. It aims to support hospital workflows and may be applied to unified or distributed systems. As it is the most used standard, it supports the most commonly used interfaces in the health industry, thus reducing implementation costs; new versions are usually backward compatible.

HL7 v3 is a new approach that allows implementers to work with a set of messages and tags needed to build complete information about reports. It is not compatible with v2, even though it is based in XML. It focuses on semantic interoperability by specifying that information should be displayed in a clinical context that ensures that both systems (sender and receiver) share the same meaning (semantics). Some case studies and implementation of HL7 v3 systems include countries like The Netherlands (that has v3 messages at the core of its health infrastructure), Canada, Germany, Croatia, and Mexico [52].

Fast Healthcare Interoperability Resources (FHIR), pronounced "fire", combines the best characteristics of previous HL7 protocols, such as v2, v3 and CDA. However, it is easier to implement has it uses an HTTP RESTful protocol, and data representation has multiple formats (XML, JSON, HTTP, RDF, etc.). It describes elements, known as "resources", that can be manipulated directly through their URL and using HTTP calls. As shown in **Figure 20**, in addition to the document elements, resources may contain narratives, which are human-readable information of the resource's content and additional extensions.

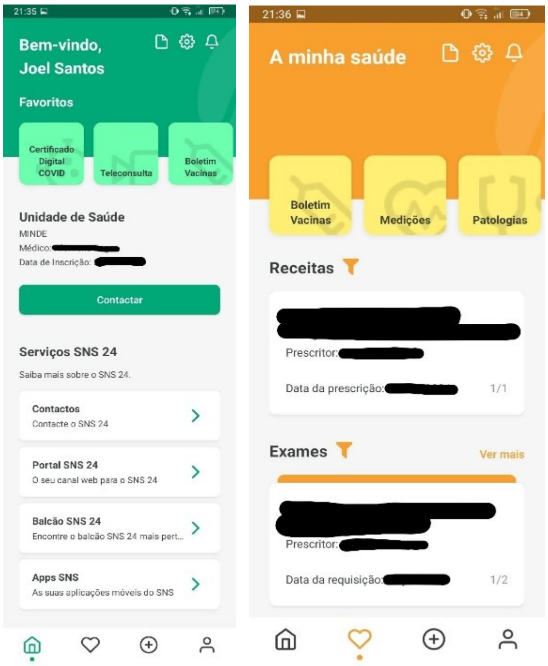
Figure 20 - HL7 FHIR architecture

2.7.2 Health storage systems in Portugal

SNS (Serviço Nacional de Saúde), created in 1979, is Portugal's medical infrastructure, providing the right to healthcare to all citizens. SPMS (Serviços Partilhados do Ministério da Saúde, E.P.E.) provides shared services to establishments and services of SNS – these services include the areas of logistics, financial services, human resources and IT and communication systems.

In Portugal, HL7 standards for health data storage and sharing are not yet implemented across the country, although it is being analyzed by SPMS [53], and several training courses on HL7 protocols have been implemented, namely using FHIR protocol. Fernando Miranda, a team leader in the management unit working for SPMS, refers that "*several health organizations use HL7, including SPMS's interoperability team*". The estimated time until these protocols are implemented countrywide is unknown, but professionals are leaning towards that, in order to be prepared for the implementation to happen. Private physiotherapy clinics don't usually have access to other clinics' information, and users need to store their information themselves. With a system that connects these private institutions, by giving them access to the same data, interoperability can be achieved.

SNS24 reunites users' health information in a mobile application, including the user's identification, vaccination report, exams and medication history, allergies, etc. (**Figure 21**). In this app, the user may also register health specific measurements, such as glycaemia, blood pressure and body mass index (BMI). Teleconsultations are also implemented in this application, and direct contacts to medics and SNS24, or Linha Saúde 24, Portugal's health cellphone line that provides 24-hour services, and gives triage, counselling, and referral in situations of illness. In SNS24's web portal, users may authorize who can access their data and under what circumstances, as well as keep track of who has accessed their information, as shown in **Figure 22**.



Bem-vindo, Joel Santos

Unidade de Saúde
MINDE
Médico: [redacted]
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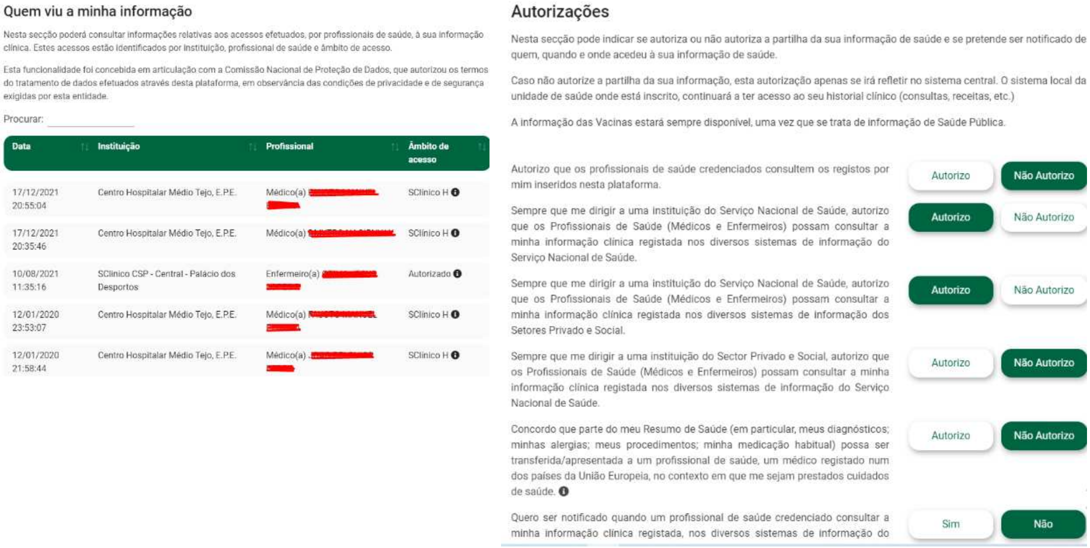
A minha saúde

Receitas
[redacted]
Prescritor: [redacted]
Data da prescrição: [redacted] 1/1

Exames
[redacted]
Prescritor: [redacted]
Data da requisição: [redacted] 1/2

Figure 21 - SNS24 app interface



Quem viu a minha informação

Nesta secção poderá consultar informações relativas aos acessos efetuados, por profissionais de saúde, à sua informação clínica. Estes acessos estão identificados por instituição, profissional de saúde e âmbito de acesso.

Esta funcionalidade foi concebida em articulação com a Comissão Nacional de Proteção de Dados, que autorizou os termos do tratamento de dados efetuados através desta plataforma, em observância das condições de privacidade e de segurança exigidas por esta entidade.

Procurar:

Data	Instituição	Profissional	Âmbito de acesso
17/12/2021 20:55:04	Centro Hospitalar Médio Tejo, E.P.E.	Médico(a) [redacted]	SClinico H
17/12/2021 20:35:46	Centro Hospitalar Médio Tejo, E.P.E.	Médico(a) [redacted]	SClinico H
10/08/2021 11:35:16	SClinico CSP - Central - Palácio dos Desportos	Enfermeiro(a) [redacted]	Autorizado
12/01/2020 23:53:07	Centro Hospitalar Médio Tejo, E.P.E.	Médico(a) [redacted]	SClinico H
12/01/2020 21:58:44	Centro Hospitalar Médio Tejo, E.P.E.	Médico(a) [redacted]	SClinico H

Autorizações

Nesta secção pode indicar se autoriza ou não autoriza a partilha da sua informação de saúde e se pretende ser notificado de quem, quando e onde acedeu à sua informação de saúde.

Caso não autorize a partilha da sua informação, esta autorização apenas se irá refletir no sistema central. O sistema local da unidade de saúde onde está inscrito, continuará a ter acesso ao seu historial clínico (consultas, receitas, etc.)

A informação das Vacinas estará sempre disponível, uma vez que se trata de informação de Saúde Pública.

Autorizo que os profissionais de saúde credenciados consultem os registos por mim inseridos nesta plataforma. Autorizo [✓ Não Autorizo]

Sempre que me dirigir a uma instituição do Serviço Nacional de Saúde, autorizo que os Profissionais de Saúde (Médicos e Enfermeiros) possam consultar a minha informação clínica registada nos diversos sistemas de informação do Serviço Nacional de Saúde. [✓ Autorizo] Não Autorizo

Sempre que me dirigir a uma instituição do Serviço Nacional de Saúde, autorizo que os Profissionais de Saúde (Médicos e Enfermeiros) possam consultar a minha informação clínica registada nos diversos sistemas de informação dos Setores Privado e Social. [✓ Autorizo] Não Autorizo

Sempre que me dirigir a uma instituição do Sector Privado e Social, autorizo que os Profissionais de Saúde (Médicos e Enfermeiros) possam consultar a minha informação clínica registada nos diversos sistemas de informação do Serviço Nacional de Saúde. Autorizo [✓ Não Autorizo]

Concordo que parte do meu Resumo de Saúde (em particular, meus diagnósticos; minhas alergias; meus procedimentos; minha medicação habitual) possa ser transferida/apresentada a um profissional de saúde, um médico registado num dos países da União Europeia, no contexto em que me sejam prestados cuidados de saúde. Autorizo [✓ Não Autorizo]

Quero ser notificado quando um profissional de saúde credenciado consultar a minha informação clínica registada, nos diversos sistemas de informação do Sim [✓ Não]

Figure 22 - SNS24's history of data accesses (left) and health-related authorizations (right)

SNS24 app's medical history feature is compatible with hospitals that use PEM (Prescrição Eletrónica Médica), which is the electronic implementation of medication prescriptions. Nowadays, PEM is responsible for more than 70% of total registered prescriptions daily in Portugal, that is around 250.000 prescriptions generated every day [54]. The implementation of this service means that by using the app, users have access to their full medical history, all that is needed to access this application is a personal SNS user number. As mentioned previously, free access to updated health information is crucial in every health-related facility, so that health professionals may take past-based decisions. Currently, it is not yet possible to schedule appointments and exams online in most public health facilities, thus incrementing waiting times.

Some private medical facilities, clinics and gyms have their own mHealth applications, that allow users to, in addition to see their health history, schedule appointments and exams, and automatically see the results and medication prescribed. Hospital da Luz, for example, is a network of private hospitals and clinics spread throughout the country and it is possible to create an account and access the functionalities described. In this dissertation's "**Motivation and context**", it is referenced that "*The key factors that distinguish* [public and private medical facilities] *have focus on waiting time, that is, the queueing time for appointments and waiting time for the subsequent consultations/examinations* [3]. *In addition, private facilities usually have access to more sophisticated IT systems that reduce these waiting times and allow users themselves to appoint consultations and exams*", such as MY LUZ (**Figure 23**).

Figure 23 - MY LUZ app interface

Chapter 3. System Description

This chapter describes the developed solution in detail, more specifically the main hardware and software components, used technologies and general system functionalities. The system hereby presented is divided in the following components: *(i)* the hardware, consisting of a sensing array and specific signal conditioning circuits, and a computation platform expressed by a Raspberry Pi, *(ii)* the developed healthcare professional web application and *(iii)* the developed patient mobile application.

Hardware *(i)*, the web application *(ii)* and the mobile application *(iii)* require software and database components to perform the required functionalities, which will be described in further chapters. Considering that one key issue with the implementation of eHealth systems is the ability to keep an organized medical history record of patients, by storing and transmitting this data to be displayed in real-time, this functionality was also considered in this work and will be later presented in detail.

3.1 Hardware Characteristics and Embedded Platform Application

As stated previously, the proposed solution makes use of a smart carpet, SensFloor, which will now be explained in more technical detail. This smart sensing system is made of a 3 mm thick underlay with capacitive sensor arrays that can detect persons and conductive materials. This smart carpet makes use of a transceiver, **SensFloor Transceiver SE10**, which is an extension board for the Raspberry Pi embedded platform. This transceiver is used for the reception of wireless messages from SensFloor, and is plugged in directly into Raspberry Pi, as shown in **Figure 24**. These received messages are sent wirelessly at 868 MHz using a proprietary protocol between SensFloor components, and include information about steps, presence detection, direction, velocity, counting users and persons lying on the floor. This particular solution makes use of a SensFloor smart carpet with 2:1 ratio dimensions, with a total of 4 meters horizontally and 2 meters vertically.

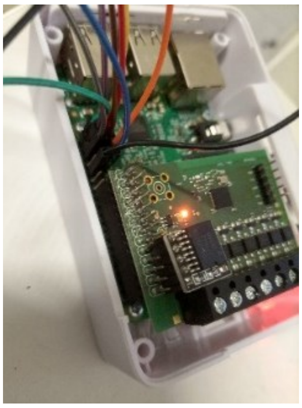


Figure 24 - Raspberry Pi with SensFloor shield

Through the SensFloor API, information is available to be used in the individual application or to be forwarded to other systems. The embedded platform gathers this data, filters it, and may then store it in a cloud database, so that it is accessible by other systems, as shown in **Figure 25**.

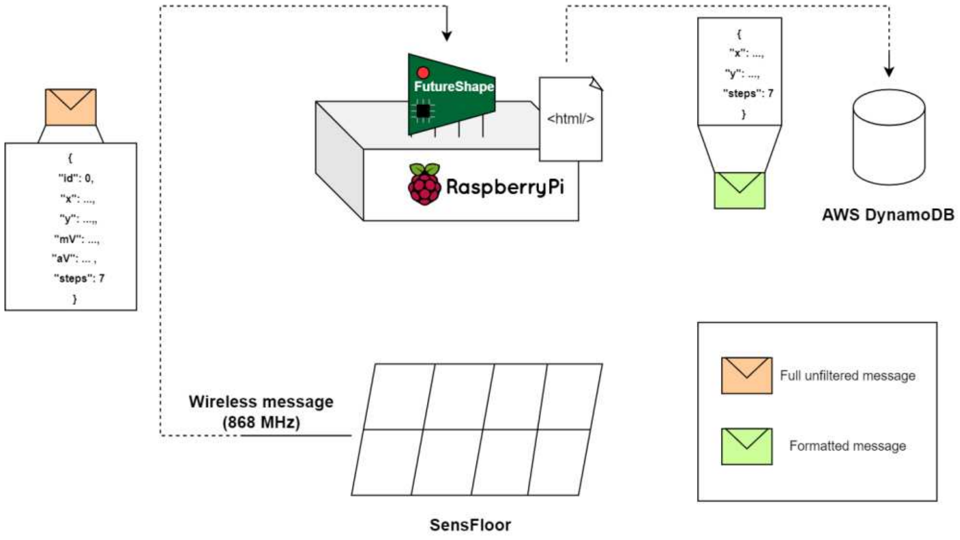


Figure 25 - Hardware Diagram

Raspberry Pi 3 is the chosen embedded platform for SensFloor system, more specifically Raspberry Pi 3 Model B V1.2 2015. This particular model comes with the following hardware specifications:

- CPU Quad Core 1.2 GHz Broadcom BCM2837 64 bit
- RAM: 1 GB
- Wi-Fi: Wireless BCM43438
- Bluetooth: Low Energy (BLE) on board
- Internet: 10/100 Mbps
- GPIO: 40-pin extended GPIO
- Ports: 4 USB 2.0 ports
- Output: 4 pole stereo output and composite video port
- Full size HDMI
- CSI camera port for connecting a Raspberry Pi camera
- DSI display port for connecting a Raspberry Pi touchscreen display
- Micro SD port for loading your operating system and storing data
- Upgraded switched Micro USB power source up to 2.5A

The embedded platform application is associated with the smart carpet, which means that it runs where the carpet is installed (in the rehabilitation clinics). The Raspberry Pi developed application is based on SensFloor API, which is written in JavaScript. In this context, a plain HTML[4] file was created, with additional CSS[5] styles, to be run directly from the microcontroller.

The embedded platform hosts a static IP Address, which is used by the SensFloor API to connect directly to the raw data sent from the smart carpet. According to **Figure 25** and **Figure 26**, the script first checks the connection with the static IP Address, using the API's method **on('connect')**, and then proceeds to actually receive the data whenever it updates, using the

---

[4] **HTML** (HyperText Markup Language) – standard language used broadly in all web applications

[5] **CSS** (Cascading Style Sheets) – used to change the visual appearance of markup languages, such as HTML documents

method **on('objects-update')**. This method returns an array of objects, corresponding to the unfiltered SensFloor data, and all fields may be accessed directly. By doing so, it is possible to gather only the relevant fields and filter the data according to the required functionalities. However, this filtered data is only visible in the embedded platform application and cannot be accessed just yet by the other applications, therefore, this data is then uploaded to a real-time cloud database, in this case, **Amazon DynamoDB**.

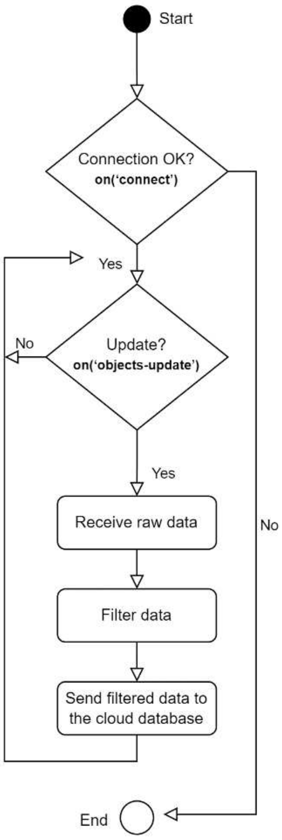


Figure 26 - Block diagram of the embedded platform application

The unfiltered, raw data is sent in a JSON[6] format, as shown in **Appendix A**. Each field may contain valuable information about the user's gait characteristics, for instance:

- "id" is a unique identifier.
- "birthX" and "birthY" is the initial user's position, using (x,y) coordinates in meters.
- "x" and "y" represent the current user's position, using (x,y) coordinates (in meters).
- "size" is the step size (in meters).
- "isStatic" validates if the user is standing still.
- "mV" is the average user's speed.
- "locationHistory" contains an array of all past user's positions, using (x,y) coordinates (in meters).
- "velocityHistory" contains an array of all past user's velocities.
- "steps" represents the average number of steps the user as taken so far.

---

[6] **JSON** (JavaScript Object Notation) – standard format for simple data exchanges between systems

Through these values, it is possible to calculate other physical indicators, for instance, using "mV", it is possible to calculate the maximum speed of the user during the gait rehabilitation exercise. It is also possible to count how many people are standing on the smart carpet by counting the number of objects that are sent in each update. Through deep analysis of location and velocity history, it is possible to predict patterns and deduce potential physical disabilities. However, for the purpose of this project, the filtered data will only contain the **(x,y) position**, and a **timestamp** in milliseconds, that will be useful later on.

This system's SensFloor dimensions are 4 meters horizontally and 2 meters vertically, which means that the (x,y) coordinates must lie between these two values, respectively, as represented in **Equation 1**.

$$x \in [0,4] \quad ; \quad y \in [0,2]$$

Equation 1 - (x,y) values interval

In an early stage, the idea was to run a Node.js[7] instance in background, hosting a plain JavaScript file to perform all the tasks, without the need to create a HTML file. However, because Raspberry Pi 3 has memory limitations (as shown in the "**Hardware Characteristics and Embedded Platform Application**" section), it could be problematic to keep this file running on background, sending all data with each update in real-time. According to the diagram in **Figure 26**, every time an update occurs, the Raspberry Pi has to process the received data, filter it, and send it to a real-time cloud database, and it wouldn't be viable to keep this whole process running by itself. As an attempt to solve this issue, a simple button was implemented in the HTML file as a way to start the process (shown in **Figure 27**). By clicking this button, the system starts to filter and send data, which is made available almost instantly throughout the other applications.

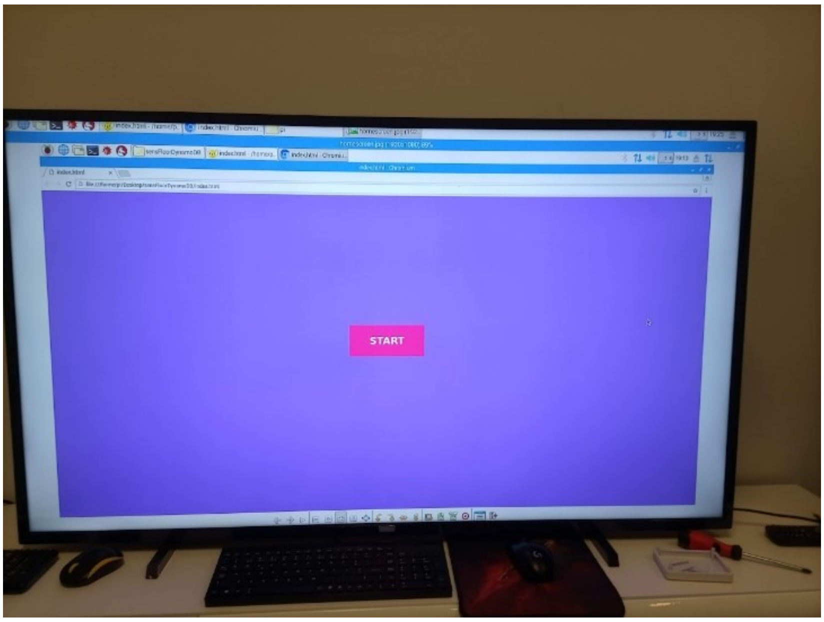


Figure 27 - Embedded platform application interface

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[7] **Node.js** – allows the execution of JavaScript code outside a web browser

3.2 Software Description

By looking at the previous chapters, it is possible to conclude that the developed system uses three different applications: an **embedded platform application** that receives data directly from the SensFloor, a **web application** to be used by healthcare professionals and physiotherapists and a **mobile application** that the patient may (or may not) use as well. **Table 3** enumerates the different technologies used by each of the developed applications.

This chapter describes all the developed applications in detail, as well as the technologies associated with each one.

Application	Hardware	Base Programming Languages	Other	Associated Databases
Embedded Platform	SensFloor	HTML + CSS	SensFloor API	Amazon DynamoDB
	SensFloor Transceiver SE10	JavaScript		
Web	-	HTML + CSS	PHP	Amazon DynamoDB
		JavaScript	Chart.js	AWS RDS + MySQL
		Bootstrap	Microsoft Power BI	Google's Firebase
Mobile	-	Google's Flutter	External Flutter packages	Google's Firebase

Table 3 - Developed applications and corresponding technologies used

Amazon DynamoDB

As previously explained, the embedded platform application makes use of a real-time cloud database to store the data as it updates, Amazon DynamoDB. This database is a NoSQL database, which means the data is not stored in a structured manner. NoSQL databases generally provide faster access to the stored data [55], while being easily adapted to different project scales – Amazon DynamoDB ensures a performance below 10 milliseconds for any scale, meaning the data is stored almost immediately.

To set a database instance up, AWS[12] generates an access key (and a corresponding access key ID), which is used directly in the application. To do so, an Identity and Access Management (IAM) User has to be created in the AWS portal, so that the access key and ID are bound to this user. Then, using the generated key, it is possible to create an Amazon DynamoDB instance, and edit the desired settings. Being cloud-hosted, the created database instance may be accessed outside the embedded platform application environment using this key-ID pair.

In the free tier, Amazon DynamoDB offers 25GB of free storage, which is enough to accommodate 200 million requests per month. It is worth noting that AWS runs on a pay-as-you-

---

[12] **AWS (Amazon Web Services)** – cloud computing platform that offers a variety of services

go model, meaning that if the user exceeds the limits defined in the free tier, fees are applied. Amazon DynamoDB also offers statistics on each table created, like the read/write usage and requests, the throttled requests, and throttled events.

Amazon DynamoDB is **Key-Value oriented**, which means that each object is accessed with a unique key. In this regard, it would be unwise to keep storing all measurements, each one with a different unique key. To solve this, only one measurement is stored at a time in the database instance, with a unique static key – every time an update occurs, the previously saved measurement is replaced with the new one. Because DynamoDB is Key-Value oriented, only one object may be associated with its unique key, and therefore if a new object is added with an existing key, it replaces previously saved objects. As the unique measurement key is static, it is possible to read the stored measurement in other applications, by keeping an active reading of the database in these applications.

The embedded platform uses the SensFloor API to retrieve and filter the SensFloor raw data and stores it in the DynamoDB instance. Amazon DynamoDB was implemented in this system so that the smart carpet data is accessible by other systems outside the Raspberry Pi's environment. The web application then retrieves the data from this same instance and displays it in the corresponding interface. Whenever a new measurement is stored in the DynamoDB instance, that is, whenever an update occurs, these steps are repeated. This process is shown in **Figure 28**, and is constantly repetitive.

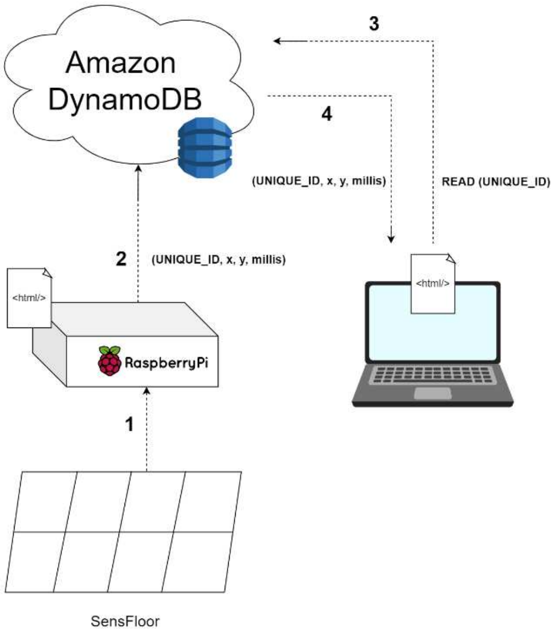


Figure 28 - Writing and reading data from DynamoDB

3.2.1 Web Application

The web application was developed in order to connect the whole system, *i.e.*, all three applications, and only the healthcare professional can access it. This application was developed using HTML and CSS as the base language, with Bootstrap framework to improve responsiveness.

Bootstrap is a web framework with prebuilt grid system and components, allowing a faster and more structured development. This grid system allows web pages to be displayed properly in different screen sizes, like computer monitors and mobile phones, thus becoming responsive pages. JavaScript was also used throughout the application, not only for visual front-end components (such as modals and dropdown lists) but also to communicate with databases and handle the data received.

This application's functionalities are summarized below and will be further described:

- Healthcare professional/physiotherapist registration/login forms, and the possibility to edit personal medical information (such as email and area of medical specialization).
- Obtain a list of all patients registered in the mobile application (and their data).
- Mechanism to prescribe new exams/medication to registered patients and obtain their medical history documents.
- Analyze graphs and charts with the measurements manually entered by registered users in their mobile application (such as height and weight).
- Obtain the smart carpet data and display the current position in real-time in an interface grid, with the possibility of extracting all data into a static file.
- Start new physical rehabilitation exercises with different input parameters according to each patient and display resulting graphs, as well as details about previous exercises.

Authentication

When starting the web application, the interface shows a login/register form, as shown in **Figure 29**. This mechanism uses a real-time cloud database, **Google's Firebase**, to authenticate users and retrieve, save, and update personal data.

Currently, the registration process for healthcare professionals is made using a simple mechanism consisting in email, password and login provided, without restrictions. However, in an ideal scenario, the healthcare professional would register in the application through his/her information in "**Ordem dos Médicos**", which is a unique identifier for all healthcare professionals registered in Portugal. Another option would be to create an administrator user that accepts or rejects new registrations in the system.

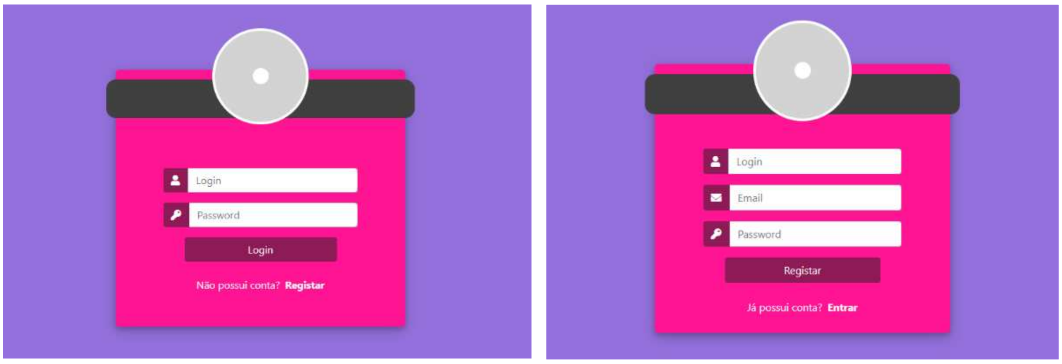


Figure 29 - Web application's login/register form for healthcare professionals

Google's Firebase

Firebase provides several services, as shown in **Figure 30**. In the context of this dissertation, **Firebase Auth**, **Cloud Firestore** and **Storage** were used.

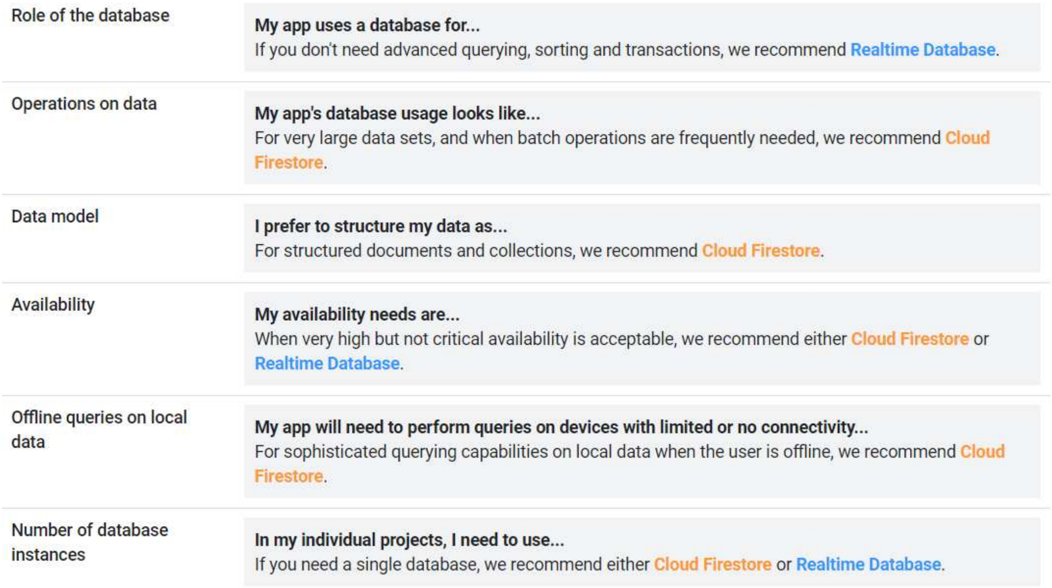
Figure 30 - Google's Firebase available services

Firebase Authentication (Auth, for short) provides backend services and prebuilt UI libraries for users to authenticate in the developed application. It supports multiple authentication mechanisms, using passwords, phone numbers, guest sign in, and other federated identity providers like Google, Facebook, Twitter, Microsoft, and more. It also allows an easy integration with custom backend services, using standards like OAuth 2.0 and OpenID Connect.

Much like Amazon DynamoDB, Firebase Cloud Firestore is also a cloud-hosted, NoSQL database, which means that when a CRUD operation occurs (Create, Read, Update, Delete), all devices connected to the Firebase instance are updated in real-time – for example, when the healthcare professional prescribes a new exam, it is available in the patient's mobile application immediately. Firebase Cloud Firestore is **Document-Oriented**, which means that the data is stored in documents, which in turn are stored in collections. These documents hold data and have their own unique identifier (Document ID), and their structure is similar to a JSON object, meaning that documents may contain their own fields and/or other collections and subsequent documents within.

Firebase as another database service, Firebase Realtime Database, which is Firebase's original database. Both Cloud Firestore and Realtime Database are free solutions that offer real-time updates, so how to choose which one is more suited for this specific project?

To answer this question, Google provides a form "*Choose a database: Cloud Firestore or Realtime Database*" (https://firebase.google.com/docs/firestore/rtdb-vs-firestore), with the key considerations before developing the project, such as the main role of the database (advanced querying or synchronizing data), the data model (complex documents or a simple JSON tree), database availability, offline queries, etc. As shown in **Figure 31**, after choosing the preferred configurations, Cloud Firestore is mainly recommended. The main differences between both databases are shown in **Appendix B**.



Role of the database	**My app uses a database for...** If you don't need advanced querying, sorting and transactions, we recommend Realtime Database.
Operations on data	**My app's database usage looks like...** For very large data sets, and when batch operations are frequently needed, we recommend Cloud Firestore.
Data model	**I prefer to structure my data as...** For structured documents and collections, we recommend Cloud Firestore.
Availability	**My availability needs are...** When very high but not critical availability is acceptable, we recommend either Cloud Firestore or Realtime Database.
Offline queries on local data	**My app will need to perform queries on devices with limited or no connectivity...** For sophisticated querying capabilities on local data when the user is offline, we recommend Cloud Firestore.
Number of database instances	**In my individual projects, I need to use...** If you need a single database, we recommend either Cloud Firestore or Realtime Database.

Figure 31 - *"Choose a database: Cloud Firestore or Realtime Database"* form

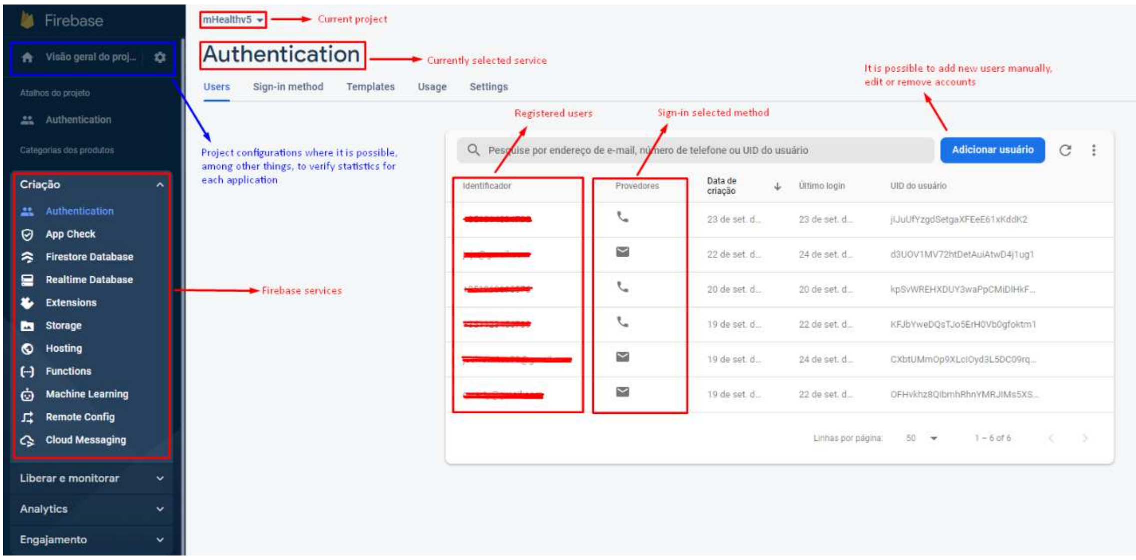
Appendix C shows an example of collections and documents using Cloud Firestore, applied directly in the context of this dissertation, where collections are represented in green, documents in red and document's fields in blue. In this particularly developed solution, Cloud Firestore is directly integrated with Firebase Auth as so:

1. Cloud Firestore has two main collections, according to each type of user, "Admin_data" for healthcare professionals and "Users_data" for patients and regular users. When a new user registers in the mobile or web application, a new document is created within the respective collection, and the corresponding login data is stored in Firebase Auth.
2. If a user (be it a healthcare professional or regular user) updates his/her personal information, the respective document fields are updated in real-time, as well as all Firebase-connected instances.
3. Every time a user logs in/out of their account in the mobile application, the field "**status**" is updated in the Cloud Firestore. By doing so, it is possible to track if the user is online or offline.

Firebase Cloud Firestore is dynamic, meaning that when a new document is added to a missing collection (*e.g.*, when a patient has no exams and a new one is added), the collection is automatically created.

Finally, Firebase Storage is a storage API that allows users to store and share files in cloud. If the network connection is broken during file uploading/downloading, it is paused and will be resumed when connection resets. Firebase Storage stores files such as images, videos, and audio as well as other user-generated content.

In **Figure** *32* it is possible to analyze the main features of Firebase Console, and in **Appendix D**, the differences between free and pay-as-you-go plans are shown. In this project, the Spark Plan (free plan) was used.



Identificador	Provedores	Data de criação	Último login	UID do usuário
[redacted]	☎	23 de set. d...	23 de set. d...	jIJuUfYzgdSetgaXFEeE61xKddK2
[redacted]	✉	22 de set. d...	24 de set. d...	d3UOV1MV72htDetAuiAtwD4j1ug1
[redacted]	☎	20 de set. d...	20 de set. d...	kpSvWREHXDUY3waPpCMiDlHkF...
[redacted]	☎	19 de set. d...	22 de set. d...	KFJbYweDQsTJo5ErH0Vb0gfoktm1
[redacted]	✉	19 de set. d...	24 de set. d...	CXbtUMmOp9XLciOyd3L5DC09rq...
[redacted]	✉	19 de set. d...	22 de set. d...	OFHvkhz8QlbmhRhnYMRJIMs5XS...

Figure 32 - Firebase Console (Auth service)

To setup Firebase services, the developer must login into the Firebase Console and add a new project. Inside this project, the developer may add several different applications (web, mobile or desktop applications), and all of them will be connected through the same cloud reference. After adding a web application, a JavaScript reference is created, in the format shown in **Figure 33**. By adding this reference to the web application, as well as all the links provided by Firebase for each of the services used, Firebase is set and ready to be used in the application.

```
var firebaseConfig = {
  apiKey: "api-key",
  authDomain: "project-id.firebaseapp.com",
  databaseURL: "https://project-id.firebaseio.com",
  projectId: "project-id",
  storageBucket: "project-id.appspot.com",
  messagingSenderId: "sender-id",
  appID: "app-id",
};
```

Figure 33 - Firebase reference format

After adding a web application, Firebase asks if the user wants to activate the **Firebase Hosting** functionality, which allows a quick and safe web application hosting on a public domain. This domain will look something like **projectName.web.app** or **projectName.firebaseapp.com**, although it is possible to purchase customized domains. In this specific project, Firebase Hosting was not used, and **XAMPP**[13] was used instead, mainly as a local server, hosting the web application, partly because PHP was used as a backend language to connect to a MySQL database instance (as will be further explained in the "**AWS RDS + MySQL Database**" section), and Firebase Hosting does not currently support backend files hosting.

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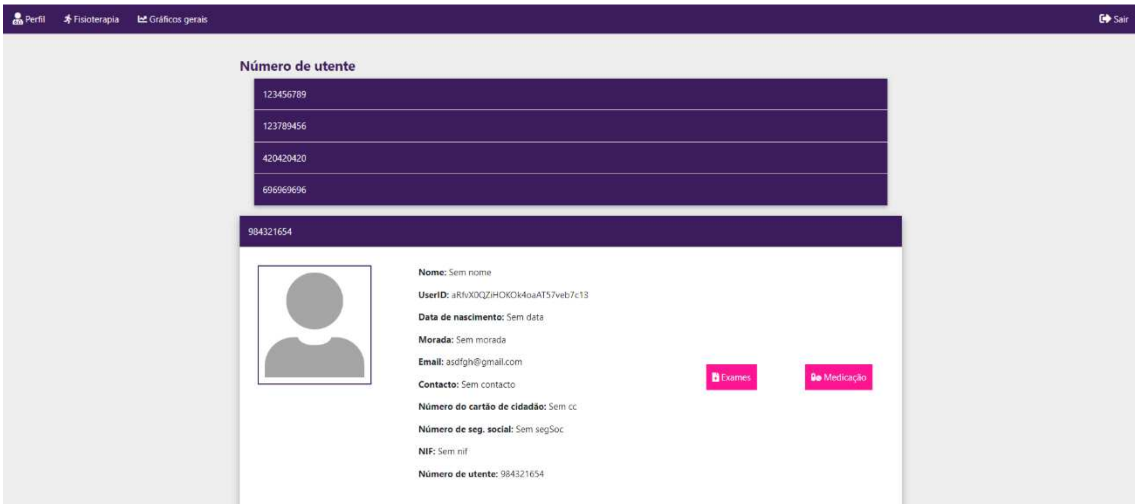
[13] **XAMPP** – abbreviation for cross-platform, Apache, MySQL, PHP and Perl, that allows to build na offline web application, on a local web server

Home and Profile tabs

After a successful login, the web application displays the interface shown in **Figure 34**. This contains a collapsible, “accordion-like” list with all the users that are registered in the mobile application. Therefore, when navigating to the home tab, the application starts by connecting to Firebase services (in this case Firebase Cloud Firestore) and retrieves an updated list of all the patients. When users change their personal information through their mobile application, this data is updated immediately in the healthcare professional’s web application.

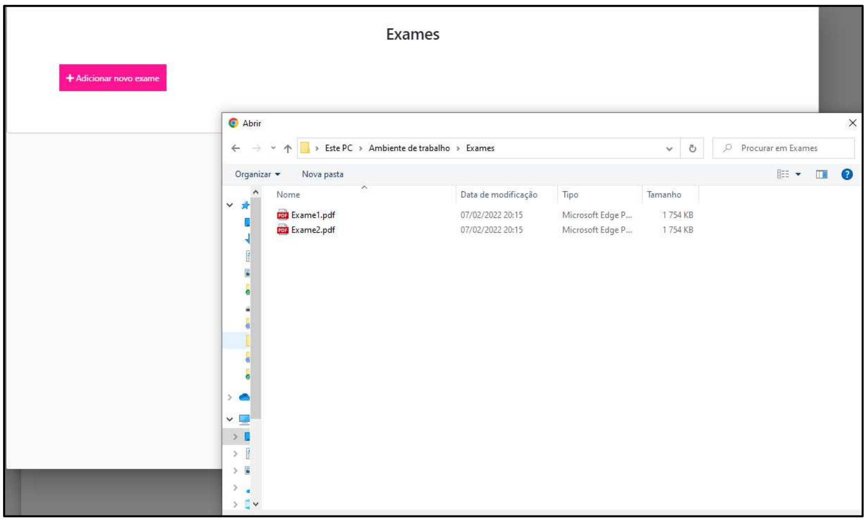


Nome: Sem nome
UserID: aRfvX0QZiHOKOk4oaAT57veb7c13
Data de nascimento: Sem data
Morada: Sem morada
Email: asdfgh@gmail.com
Contacto: Sem contacto
Número do cartão de cidadão: Sem cc
Número de seg. social: Sem segSoc
NIF: Sem nif
Número de utente: 984321654

Figure 34 - Home tab interface

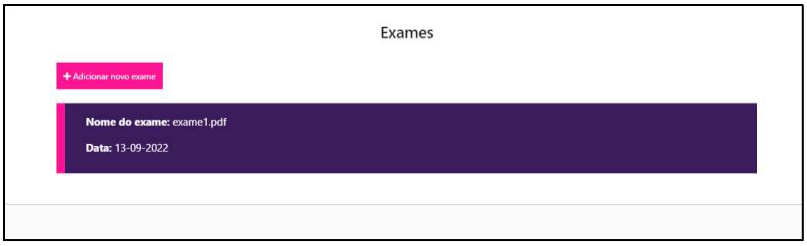
Each registered patient as an “Exams” button and a “Medication” button. By clicking in them, the healthcare professional may prescribe new exams/medication and see the medical history of the corresponding user, as shown in **Figure 35** and **Figure 36**.

After prescribing new exams/medication, a new reference is created in the Firebase Cloud Firestore for the corresponding patient, and the uploaded file is stored in the Firebase Storage. By doing so, these files may be accessed through all applications connected to this Firebase instance, and the patient has access to the files through his/her mobile application almost immediately.



Nome	Data de modificação	Tipo	Tamanho
Exame1.pdf	07/02/2022 20:15	Microsoft Edge P...	1 754 KB
Exame2.pdf	07/02/2022 20:15	Microsoft Edge P...	1 754 KB

Figure 35 - Prescribing new exams

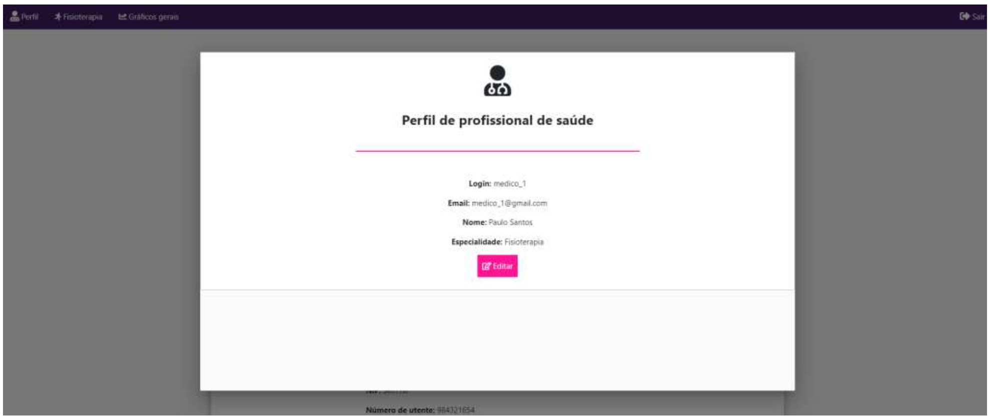


Nome do exame: exame1.pdf

Data: 13-09-2022

Figure 36 - Exams history

The files prescribed to the patients contain information about the healthcare professional who prescribed them. However, this information may be edited, by clicking in the profile tab, as seen in **Figure 37**. This link button shows a Bootstrap Modal[14] whenever it is clicked and allows the user to update his/her personal information, *e.g.*, the login information, email, name, and area of medical specialization. When this information is changed, all exams/medication that have information about this particular healthcare professional are also updated in real-time.



Login: medico_1

Email: medico_1@gmail.com

Nome: Paulo Santos

Especialidade: Fisioterapia

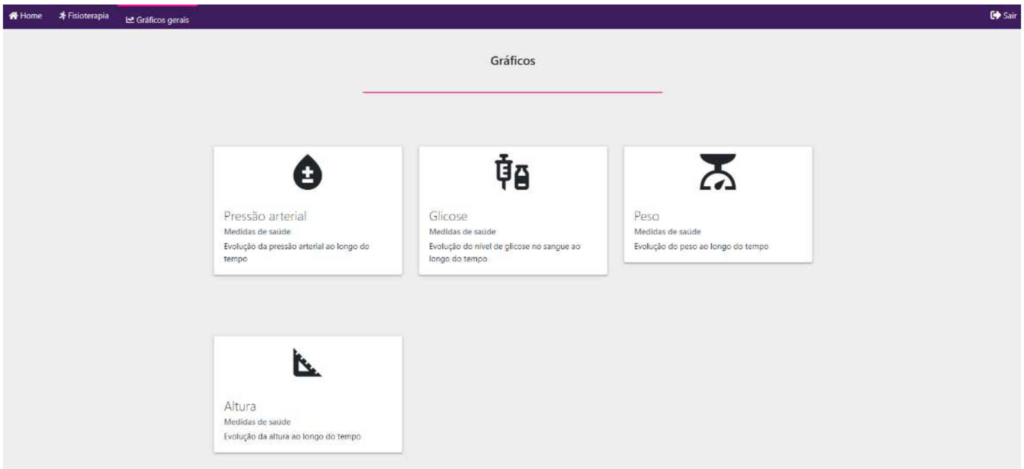
Figure 37 - Healthcare professional's profile tab

Graphs tab

As previously enunciated, patients may register some measurements through their mobile application, by manually entering their **height**, **weight**, **blood pressure** and **glucose level**. By navigating to the graphs tab, the healthcare professional may choose which type of graphs he/she wants to analyze, as shown in **Figure 38**.

---

[14] **Bootstrap Modal** – dialog/popup window that shows/hides on top of the current page. This mechanism is prebuilt using Bootstrap, and allows different options and animations



Gráficos

Pressão arterial
Medidas de saúde
Evolução da pressão arterial ao longo do tempo

Glicose
Medidas de saúde
Evolução do nível de glicose no sangue ao longo do tempo

Peso
Medidas de saúde
Evolução do peso ao longo do tempo

Altura
Medidas de saúde
Evolução da altura ao longo do tempo

Figure 38 - Graphs tab

These graphs and charts were made using **Microsoft Power BI**, which is a data visualization and analysis software. With Power BI Desktop, it is possible to connect to data from many different sources, including Excel Workbook, Text/CSV, XML, JSON, PDF, SQL Server, Oracle Database, MySQL Database, PostgreSQL Database, Azure, etc. and to create visuals to display that data in. In this specific project, Power BI connects to a **MySQL Database instance** to retrieve the data, as will be explained in the "**AWS RDS + MySQL Database**" section.

This software was chosen since there is no need to display and refresh these types of dashboards in real-time. The measures introduced by the users are of a more static nature, and therefore do not tend to change much on a daily basis. Using Power BI, these dashboards store previous measurements as well, so it is possible to analyze the patients' history.

Power BI's reports are stored in a workspace, and each report consists of a dataset (which is the collection of data that is imported or connected to) and a dashboard (which is the customized visual representation of the dataset). However, using Power BI's free version, there are some limitations, the most impactful (in this case) being that if the developer wants to publish a dashboard in a web application, this dashboard must be public, which may not be very secure, in particular if it handles users' personal data. The difference with the paid version is that each dashboard has an embed link, that may be used directly in the web application, but in order to actually view it, the user must have been granted access to the workspace. Another key difference is that using the paid version, it is possible to schedule automatic daily data refreshes, which is useful as there is no need to schedule data manually. This is even more impactful with large volumes of data, as the data takes longer to refresh, and with automatic refreshes the developer may choose the most appropriate time of the day. **Appendix E** displays the main differences between free and paid plans, the paid license being used in the context of this dissertation.

After accessing and opening the Power BI dashboards, shown in **Figure 39**, the healthcare professional may filter which patient to analyze, and filter the desired dates interval.

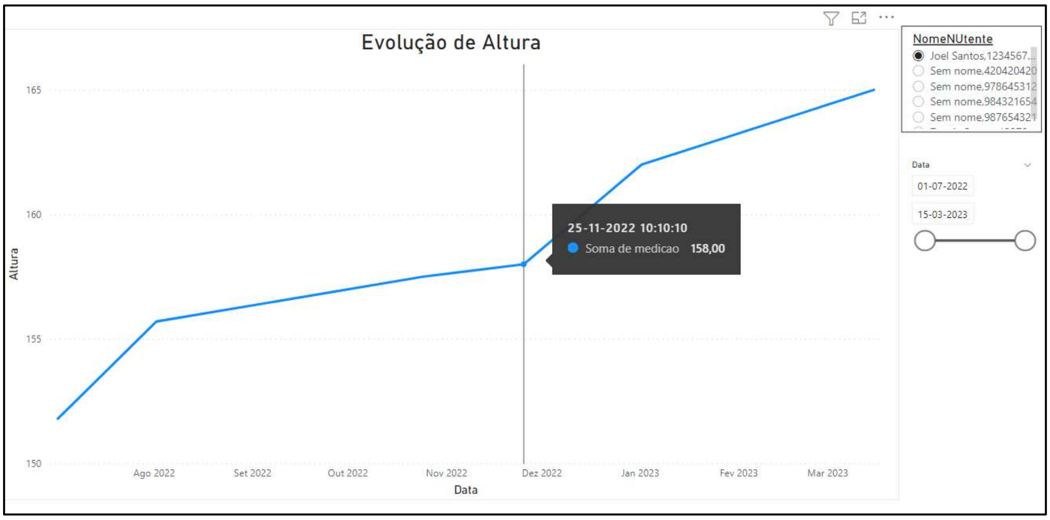


Figure 39 - Power BI height evolution dashboard

Physiotherapy tab

The developed physiotherapy tab offers two options, as shown in **Figure 40**.

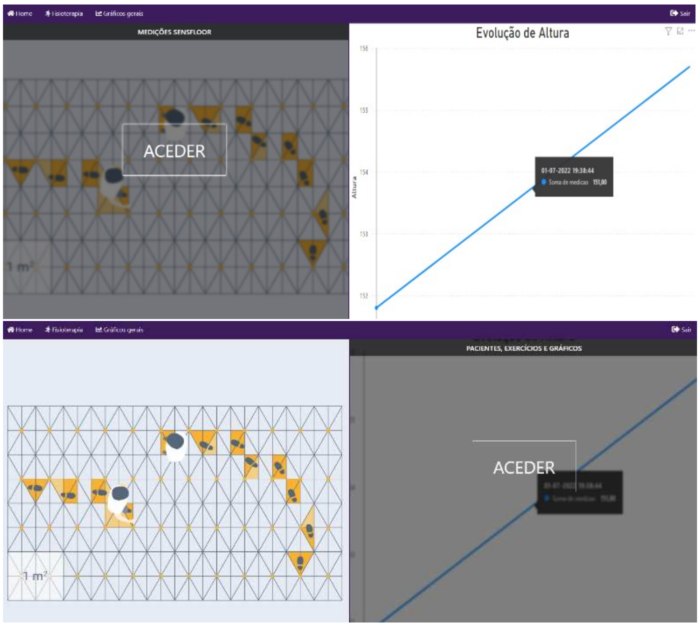
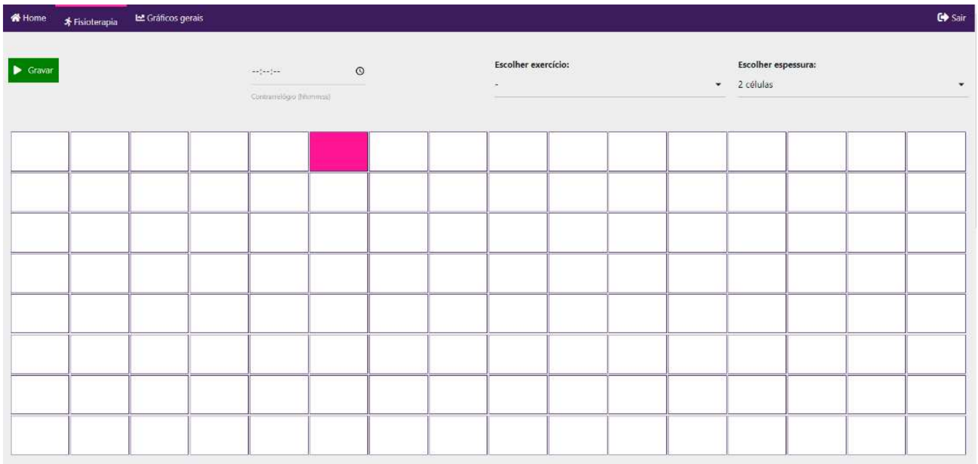


Figure 40 - Physiotherapy tab options

The difference between clicking on the left or right side is that the right side allows the healthcare professional to choose patients that are registered in the mobile application and prescribe them new physical rehabilitation exercises. On the left side, it is also possible to perform exercises, but since a patient is not selected, the exercise results will not be bound to any user. However, this is useful if the patient is not yet registered in the mobile application, acting as a guest user.

By clicking on the left side, the web application displays the interface shown in **Figure 41**, with the current user position updated in real-time. The web application accesses Amazon DynamoDB and retrieves the values sent by the embedded platform controller, by using

JavaScript code. As previously explained, when creating an Amazon DynamoDB instance, an access key and corresponding ID are generated, and by using them in different applications, they all become connected through the same DynamoDB instance, and therefore it is possible to have access to the same data. By recording this data, the physiotherapist is then able to analyze the numeric results and corresponding graphs.



--:--:--
Contrarrelógio (hh:mm:ss)

Escolher exercício: -

Escolher espessura: 2 células

Figure 41 - SensFloor implemented web interface (pink cell corresponds to the user's current position)

These coordinates, however, are not in a correct format according to the standard cartesian coordinates system. **Figure 42** shows this issue, and in order to obtain the results shown in **Figure 41**, the raw coordinates had to be mapped. In this specific case, coordinate (0,0), for instance, corresponds to the bottom right corner of the carpet.

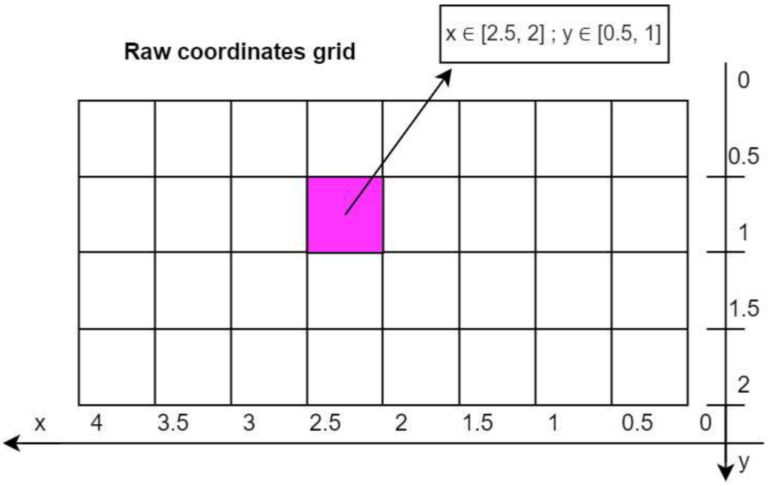


Figure 42 - Smart carpet's coordinates mapping

By clicking on the right side, the same list of registered patients is shown, but with different functionalities. To begin with, it is possible to see what patients are online in their mobile application – this is possible due to the field "**status**" in the Cloud Firestore. Users are online whenever they are logged into the mobile application, and offline whenever they logout.

Since the main scope of this project is aimed towards physical gait rehabilitation, the health professional may then prescribe new physical rehabilitation exercises to the selected users, by clicking "New Exercise". After that, it is possible to start a free exercise or choose from different preset exercises. By choosing "Free exercise", the displayed interface is similar with the one in **Figure 41** and with the functionality previously explained, but with an associated patient, which means that the data subsequently acquired and recorded will be bound to that selected patient.

Free exercise means the patient is able to walk normally and freely inside the smart carpet area, as shown in **Figure 43**.

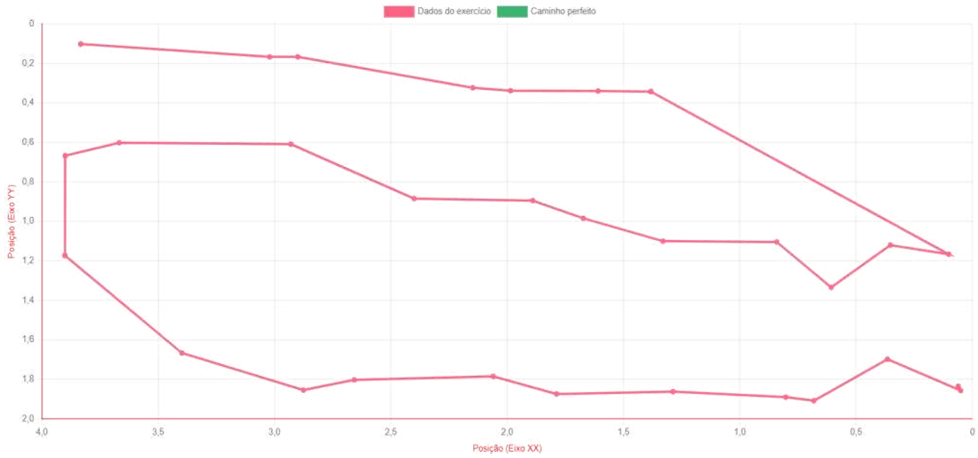


Figure 43 - Free exercise of gait rehabilitation (X and Y axis units in meters)

By choosing "Preset exercises", three default exercises are available, as shown in **Figure 44**. Using the developed system, including hardware and software, it is possible to define several virtual paths with positions the user needs to follow, and coordinate intervals to evaluate if the user stays in the correct path.

In this developed prototype, the three designed exercises consist of a **straight line** path, **circle** path, and **zig-zag** path. These path types were implemented to provide distinguished difficulties related to balance and gait training. The main difference between paths is that straight line path provides analysis of the usual gait users take, whereas circle and zig-zag paths have 90º turns. Circle path, however, implements only left 90º turns, whereas zig-zag paths applies both left and right turns.

These exercises implement the logic of serious games, in a way that they are easily adapted to each user, and past results may be analyzed so that users can keep track of their progress and evolution, as will be explained later. The virtual path and current user position are displayed in a TV screen for the user to visualize, although it would be desirable to display it directly on the floor (by means of lights or a LED projector placed above the user).

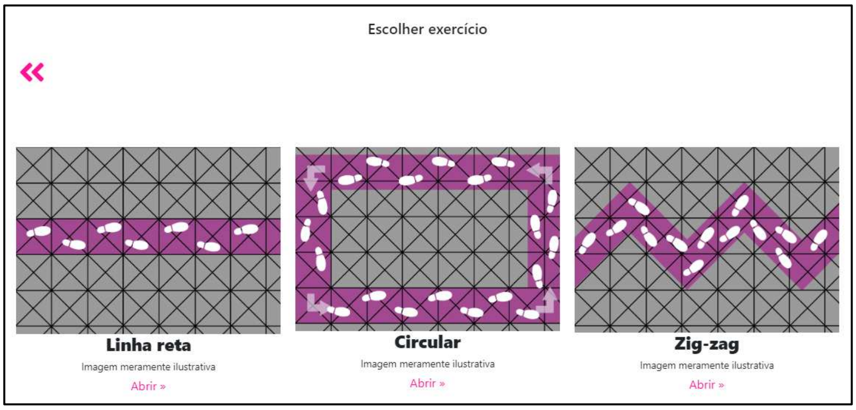


Figure 44 - Preset exercises

The physiotherapist is then able to click the "Record" button and save all subsequent measurements. By clicking "Stop", numerical results and corresponding charts are displayed. The application then gives feedback to the user about the patient's deviations and evaluate the gait, calculating a final score. This process, shown in **Figure 45**, is following described. Thus, the healthcare professionals access their web application and start the training, through which it is possible to alter the difficulty of the path, by incrementing/decrementing its **thickness** (that is, the coordinate interval) and by altering the smart carpet's **resolution** (number of interface cells). It is also possible to implement a time limit for patients to finish the exercise, by entering the values directly in the web platform ("**Time-trial mode**"). When the exercise comes to an end, the interface shows the time difference between the total exercise time and the time limit set by the clinician and appraises if the patient managed to finish the exercise in the limit time or not.

The web interface grid is always drawn in a 2:1 format, similar to the physical measurements of the carpet, and accepts any number of cells in x and y axis, as long as they match this ratio (*e.g.*, (x,y) = (2,4); (4,8); (6;12); etc.). When the patient ends the exercise, the healthcare professional clicks "Stop" and the application appraises the patient's gait, by comparing their coordinates with the virtual path, and calculates the corresponding deviations.

Finally, the application provides feedback to both the physical therapist and the patient, through the calculated general score. This feedback is provided through text and audio-based messages. It is also possible to generate a graph with the path the user has taken and compare with the correct/"perfect" path, as seen in **Figure 46**. It is worth noting that the SensFloor system has a gait recording functionality as well, as shown previously in **Figure 13**, but is not editable and customizable.

All the information that is available about the exercise, mainly the user's deviations, final score, and corresponding visual charts, are available to the healthcare clinicians through their web application and to the patient in his/her mobile application.

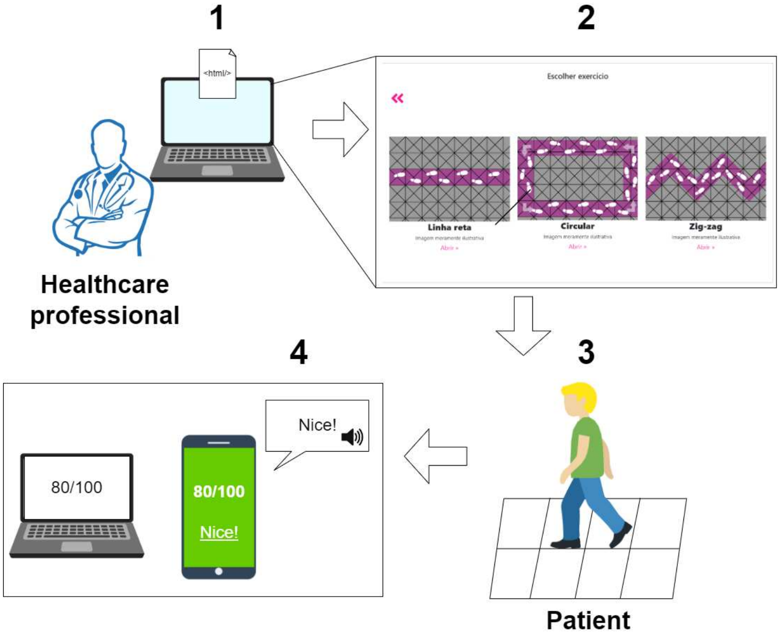


Figure 45 - The architecture of developed system applied to gait rehabilitation exercises (illustrative image only)

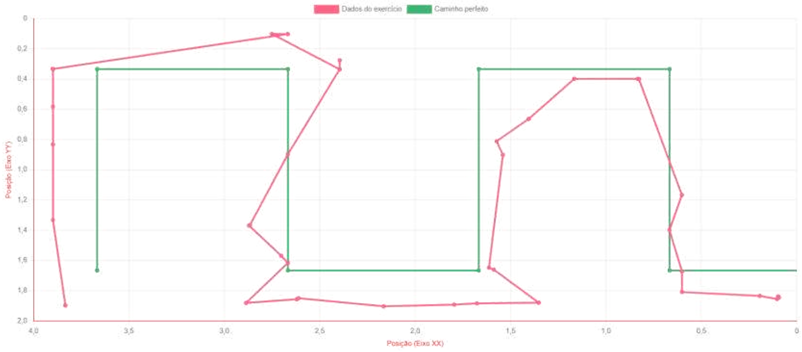


Figure 46 - User's path (pink) vs "theoretical (perfect)" path (green)

Figure 47 shows concepts of different paths, with distinguished difficulties. In the scope of this project, three different virtual paths were developed: **straight line** path, **circle** path and **zig-zag** path. When incrementing **resolution**, the web application offers more possibilities based on an extended number of cells for the user to step. By incrementing/decrementing the virtual path **thickness** (which corresponds to the coordinate intervals the users need to follow in order to successfully complete the exercise), the virtual path's bounds change, and the coordinate intervals adjust making it possible for the healthcare clinician to adapt the exercise according to the specific user.

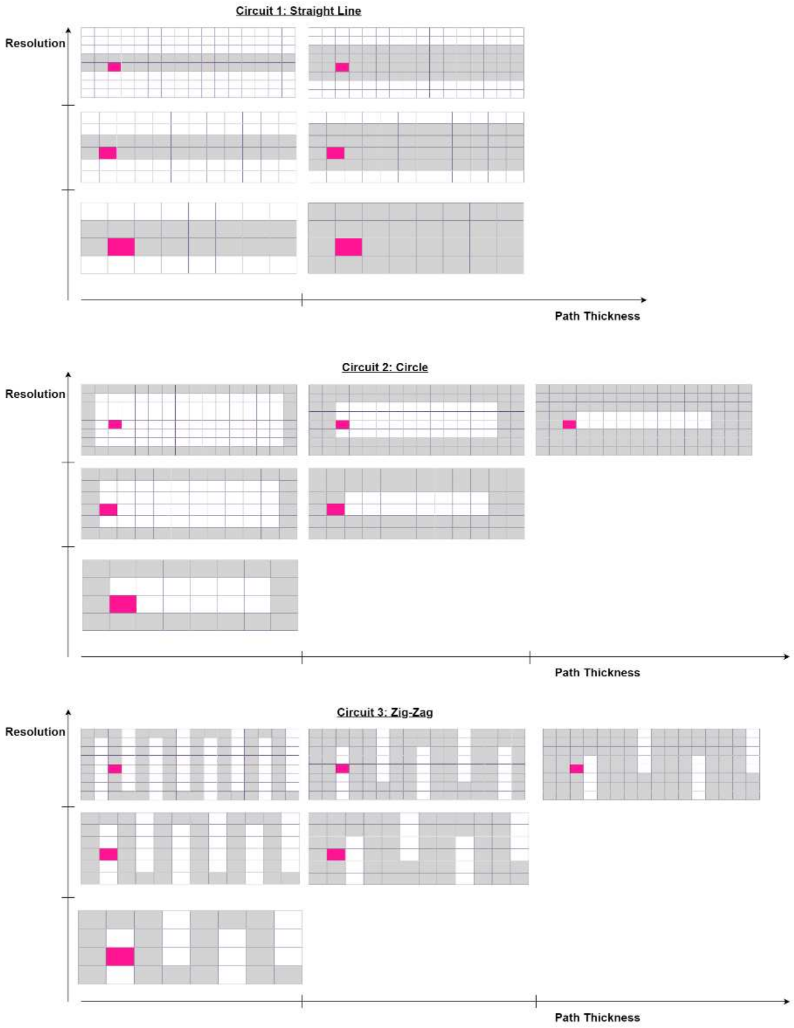
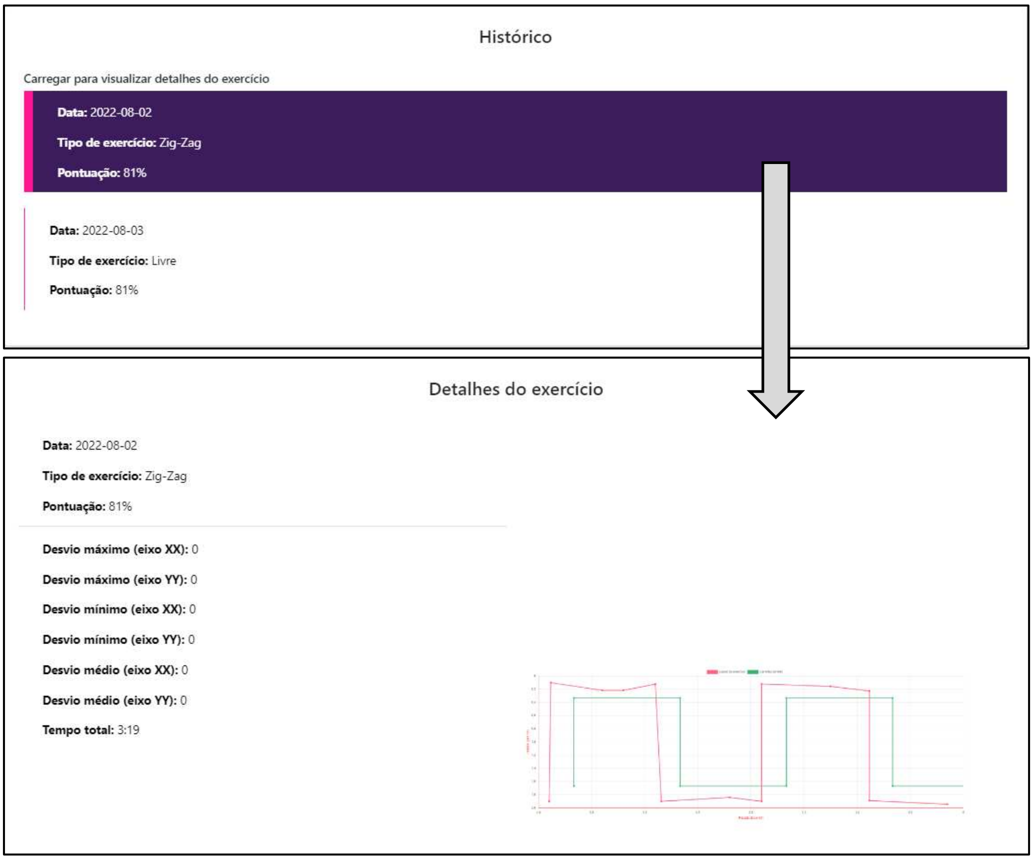


Figure 47 - Graphical representation of the virtual path concept applied for gait rehabilitation (pink cell corresponds to the user's current position, grey cells correspond to the virtual path the user needs to follow)

In this specific project, **Chart.js** library was used in order to create and display graphs after each exercise is finished. Chart.js is a free JavaScript library for making HTML-based charts, with a simple, intuitive interface. This library offers a variety of possibilities and graph types, form scatter plots, to line, bar, pie, donut, area charts. To create the charts displayed at the end of each exercise, scatter plots were used, with lines interconnecting each point.

The numeric results shown after each exercise is completed include the time the patient took to finish the exercise, corresponding X and Y axis minimum, maximum and average deviations, and final score. These deviations and score calculations will be explained further in more technical detail, in the "**Score Metrics**" section. Numerical results are always stored and saved in the corresponding exercise. As to the generated charts, healthcare professionals are given the option to save them or not.

The recorded exercises (and corresponding charts) are then bound to the patients. In this regard, by clicking the "History" button, a new Bootstrap Modal shows and displays past exercises, with valuable information about axis deviations and associated graphs (if existing), as shown in **Figure 48**.



Histórico

Carregar para visualizar detalhes do exercício

Data: 2022-08-02
Tipo de exercício: Zig-Zag
Pontuação: 81%

Data: 2022-08-03
Tipo de exercício: Livre
Pontuação: 81%

Detalhes do exercício

Data: 2022-08-02
Tipo de exercício: Zig-Zag
Pontuação: 81%

Desvio máximo (eixo XX): 0
Desvio máximo (eixo YY): 0
Desvio mínimo (eixo XX): 0
Desvio mínimo (eixo YY): 0
Desvio médio (eixo XX): 0
Desvio médio (eixo YY): 0
Tempo total: 3:19

Figure 48 - Patient's exercise history and exercise details

AWS RDS + MySQL Database

Since the SensFloor data is not being stored in a persistent way, and only unstructured NoSQL databases are being used to store the users' personal data, there was a need to also store that data in an SQL database. That said, a **MySQL** database was created locally, with several tables to accommodate all different types of data to be saved permanently. This database instance receives data from several sources, as further explained:

1. When the web application gathers the SensFloor data from Amazon DynamoDB and the exercise is being recorded, it also stores this data in the MySQL instance.
2. When a new user registers (be it in the web or mobile application), or when a user updates their personal data, it is also saved in the MySQL instance.
3. When patients enter new measurements through their mobile application, these are also saved in the MySQL instance.

Using a SQL database, it is also easier for third-party software and APIs (such as Microsoft Power BI) to retrieve this data in a structured manner. **Figure 49** shows the different database tables, and corresponding fields and connections.

- The "**sensfloor**" table receives all measurements, from (x,y) position to the virtual path type and difficulty level, and corresponding axis deviations for each measurement, as well as a boolean[15] field that checks if the user is in or out of the virtual path's bounds. Also, it has a "**userId**" bound to it when the prescribed exercises have a corresponding patient, and a "**exercicioId**" field, so that each set of measurements are all part of the same exercise.
- The "**exercicios**" table represents an exercise, which is composed of a set of SensFloor measurements. This table has also a "**userId**" field, so that the exercise is bound to the corresponding user, and some statistics about the exercise, in particular the average deviations and final score.
- The "**utilizadores**" table represents the registered patients and receives the same fields as Firebase Cloud Firestore, to keep them synchronized.
- Tables "**altura**", "**peso**", "**glucose**" and "**pressao**" correspond to the manually introduced measures. These tables also contain a "**userId**" field.
- Finally, "**exercicioTipos**" and "**dificuldade**" are auxiliary tables with static data.

---

[15] **Boolean** – a true or false field

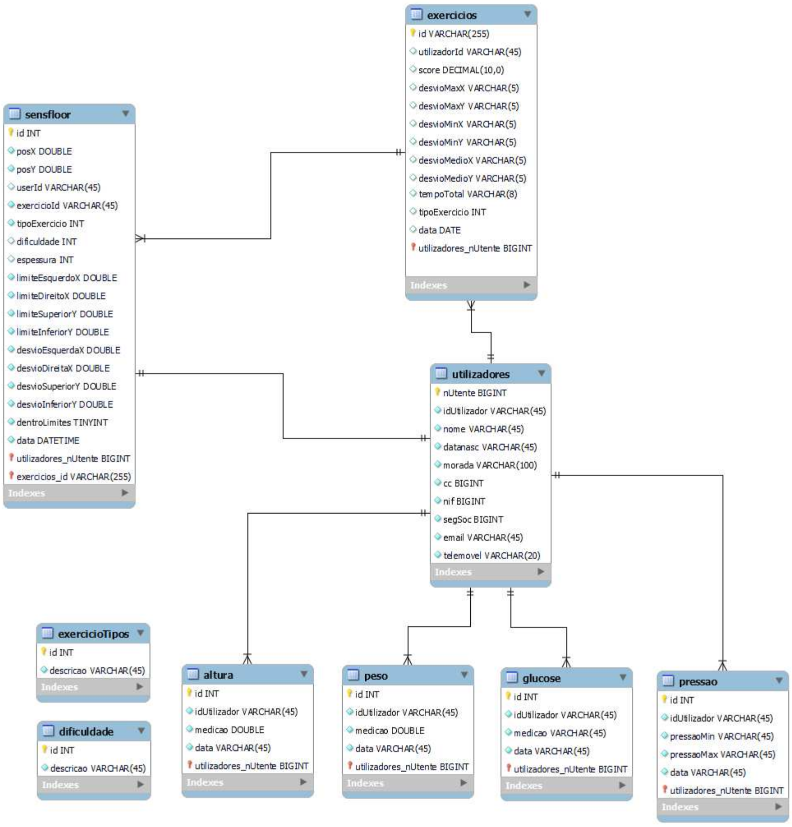
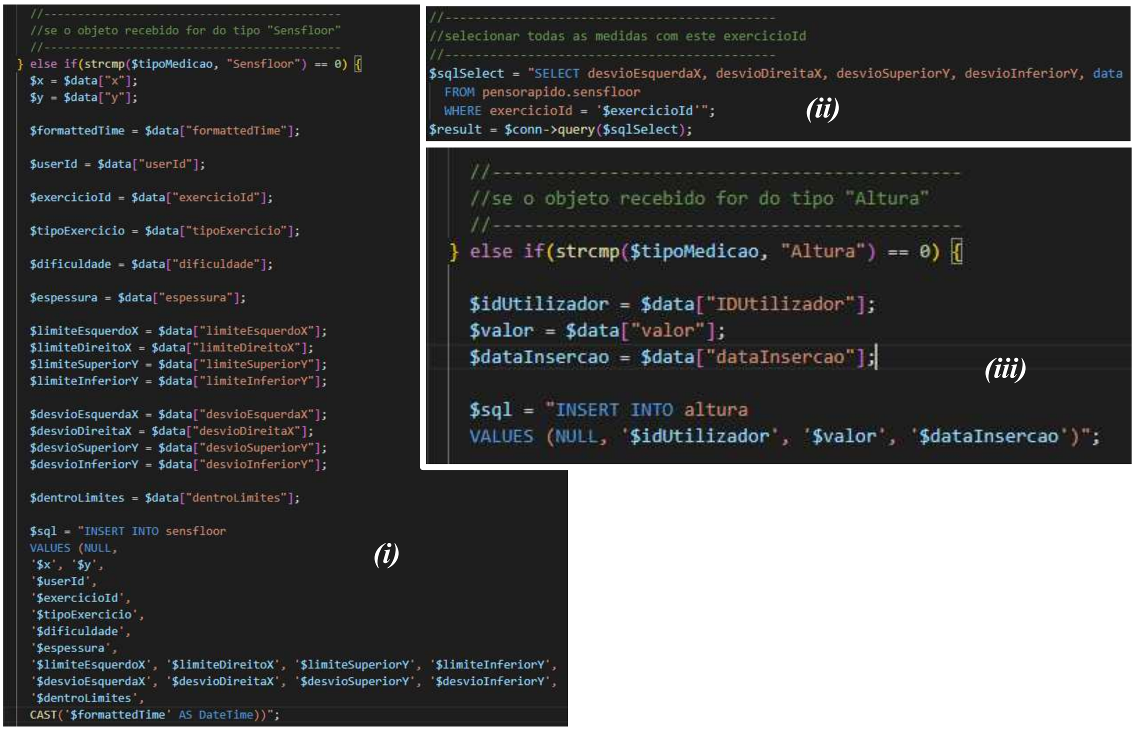


Figure 49 - MySQL Database tables and structure

However, this database was not yet accessible by other applications or third-party software/APIs, so **AWS Relational Database Service (RDS)** was used. AWS RDS is a fully self-managed collection of services to ease the process of set up, operate, and scale databases in the cloud. This means that AWS RDS offers the possibility to host and configure relational databases directly in the cloud, becoming available to other applications. It currently supports seven different engines – Amazon Aurora with MySQL compatibility, Amazon Aurora with PostgreSQL compatibility, MySQL, MariaDB, PostgreSQL, Oracle, and SQL Server.

To set AWS RDS up, and connect it to an existing local database, the developer must access this service through the AWS console and create a new database instance. After that, some engine options are prompted, such as the engine type (in this case MySQL), version, database identifier and username settings, storage type, connectivity (publicly accessed or not), security options, automatic backups, and other features. After concluding the setup, the created database instance provides a public endpoint and port, and the local MySQL database can now be associated with it, making it available and accessible by other applications.

The web application may now run a PHP backend file to connect to this database instance and execute CRUD queries, *e.g.*, insert the smart carpet data into the "**sensfloor**" table *(i)*, retrieve all measurements associated with a particular "**exerciseId**" *(ii)* or insert new PHC measures *(iii)*, as shown in **Figure 50**.



```
  //-----------------------------------------------
  //se o objeto recebido for do tipo "Sensfloor"
  //-----------------------------------------------
} else if(strcmp($tipoMedicao, "Sensfloor") == 0) {
  $x = $data["x"];
  $y = $data["y"];

  $formattedTime = $data["formattedTime"];

  $userId = $data["userId"];

  $exercicioId = $data["exercicioId"];

  $tipoExercicio = $data["tipoExercicio"];

  $dificuldade = $data["dificuldade"];

  $espessura = $data["espessura"];

  $limiteEsquerdoX = $data["limiteEsquerdoX"];
  $limiteDireitoX = $data["limiteDireitoX"];
  $limiteSuperiorY = $data["limiteSuperiorY"];
  $limiteInferiorY = $data["limiteInferiorY"];

  $desvioEsquerdaX = $data["desvioEsquerdaX"];
  $desvioDireitaX = $data["desvioDireitaX"];
  $desvioSuperiorY = $data["desvioSuperiorY"];
  $desvioInferiorY = $data["desvioInferiorY"];

  $dentroLimites = $data["dentroLimites"];

  $sql = "INSERT INTO sensfloor
  VALUES (NULL,
  '$x', '$y',
  '$userId',
  '$exercicioId',
  '$tipoExercicio',
  '$dificuldade',
  '$espessura',
  '$limiteEsquerdoX', '$limiteDireitoX', '$limiteSuperiorY', '$limiteInferiorY',
  '$desvioEsquerdaX', '$desvioDireitaX', '$desvioSuperiorY', '$desvioInferiorY',
  '$dentroLimites',
  CAST('$formattedTime' AS DateTime))";
```

```
//-----------------------------------------------
//selecionar todas as medidas com este exercicioId
//-----------------------------------------------
$sqlSelect = "SELECT desvioEsquerdaX, desvioDireitaX, desvioSuperiorY, desvioInferiorY, data
  FROM pensorapido.sensfloor
  WHERE exercicioId = '$exercicioId'";
$result = $conn->query($sqlSelect);
```

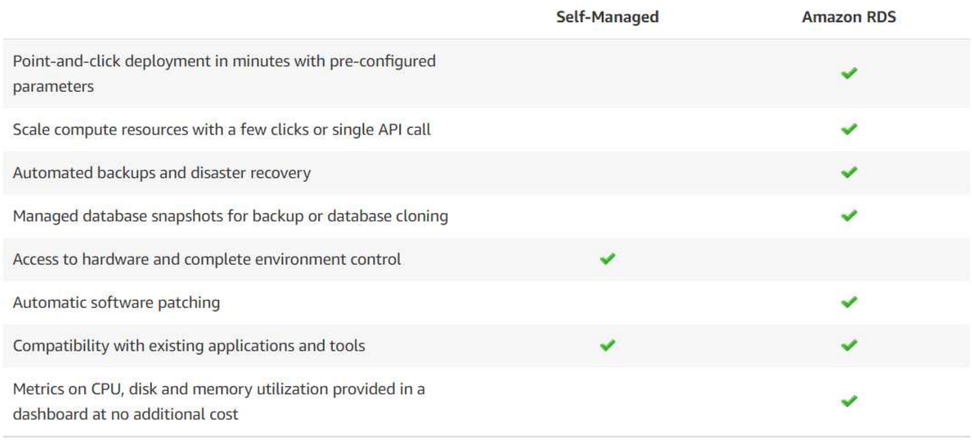
```
  //-----------------------------------------------
  //se o objeto recebido for do tipo "Altura"
  //-----------------------------------------------
} else if(strcmp($tipoMedicao, "Altura") == 0) {

  $idUtilizador = $data["IDUtilizador"];
  $valor = $data["valor"];
  $dataInsercao = $data["dataInsercao"];

  $sql = "INSERT INTO altura
  VALUES (NULL, '$idUtilizador', '$valor', '$dataInsercao')";
```

Figure 50 - Insert data into the sensfloor table *(i)*, select all measurements for a given exercise *(ii)* and insert a new PHC value *(iii)* PHP queries

AWS RDS free tier's characteristics are shown below:

- 750 hours of Amazon RDS Single-AZ db.t2.micro, db.t3.micro, and db.t4g.micro Instances usage running MySQL, MariaDB, PostgreSQL databases each month. If running more than one instance, usage is aggregated across instance classes.
- 750 hours of Amazon RDS Single-AZ db.t2.micro Instance usage running SQL Server (running SQL Server Express Edition) each month.
- 20 GB of General Purpose (SSD) DB Storage
- 20 GB of backup storage for your automated database backups and any user-initiated DB Snapshots

It would also be possible to have a self-managed database instance, however AWS RDS has some benefits and advantages, shown in **Figure 51**.



	Self-Managed	Amazon RDS
Point-and-click deployment in minutes with pre-configured parameters		✓
Scale compute resources with a few clicks or single API call		✓
Automated backups and disaster recovery		✓
Managed database snapshots for backup or database cloning		✓
Access to hardware and complete environment control	✓	
Automatic software patching		✓
Compatibility with existing applications and tools	✓	✓
Metrics on CPU, disk and memory utilization provided in a dashboard at no additional cost		✓

Figure 51 - Self-Managed vs AWS RDS managed database (taken from https://aws.amazon.com/rds/free/)

3.2.2 Mobile Application

The developed mobile application is a platform that keeps users updated about their current and past-prescribed exams and medication, as well as physical rehabilitation exercises results and charts. This app's functionalities are following described:

- Registration and login forms, with different authentication methods.
- Edit and update own personal data and profile picture.
- Verify account and change password.
- Manually enter new values for height, weight, glucose level and blood pressure.
- Keep track of exams and medication prescribed, with information about the healthcare clinician that prescribed them.
- Physical rehabilitation exercises are also stored, along with their results and aggregated charts (if existing).

Google's Flutter

Patients' mobile application was developed using **Google's Flutter**. Flutter is an opensource framework by Google, based on Dart programming language, which makes it possible to create natively compiled[16] applications, for Android, iOS, Windows, Mac, Linux, Google Fuchsia, and web.

Other cross-platform development technologies, such as React Native or Xamarin, could have been used, however Flutter had some advantages in the context of this project, the most impactful one being the high level of connectivity to Firebase and "ease of learning", straightforward syntax and documentation. **Appendix F** shows the main differences between popular cross-platform mobile development platforms.

---

[16] **Native compiler** – generates code for the same platform on which it runs, converting high language into computer's native language. As opposition, **cross compiler** generates executable code for the platform on which the compiler is running.

Flutter uses **Widgets** as a unit of composition. Widgets describe what the UI should look like given their current configuration and state. Widgets are composed of other “sub-Widgets”, that are subclasses of either StatelessWidget or StatefulWidget, depending on whether it manages any state. Some basic subclass Widgets include:

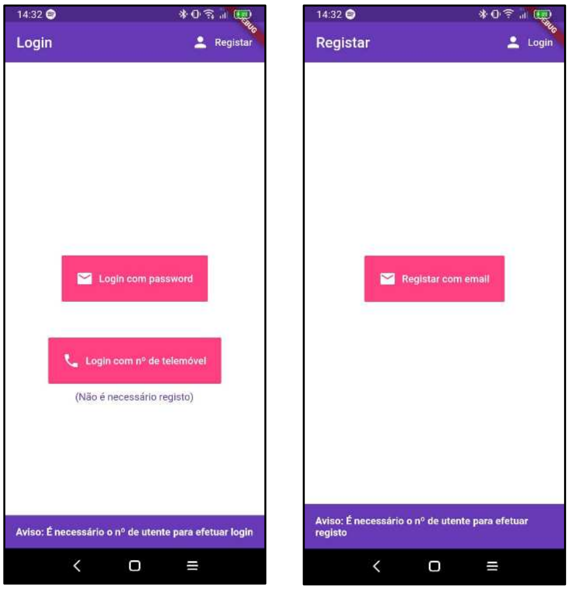
- **Text** – for creating styled text.
- **Row/Column** – for creating flexible layouts horizontally or vertically.
- **Stack** – for placing widgets on top of each other.
- **Container** – a “box” around given elements, that may have visual decoration or margins, paddings, and constraints.

Since both Firebase and Flutter were developed by Google, “FlutterFire” is possible, and the mobile application Firebase setup is similar with the web application (as seen in the “**Google’s Firebase**” section). Firstly, a new mobile application must be added to the current project (where the web application was created). After that, a JSON file is generated with information about the Firebase and project URLs and IDs, and some dependencies need to be added to the mobile application project. Finally, similarly to the web application, the developer may choose from the different Firebase services and add them in the project dependencies.

Authentication

When patients register on the mobile application, healthcare professionals have access to their personal data updated in real-time, and may prescribe exams/medication to them, as well as start new physical rehabilitation exercises.

Firebase Authentication service offers several different authentication methods, as previously explained. In this regard, as shown in **Figure 52**, it is possible to sign in using a password or a phone number.



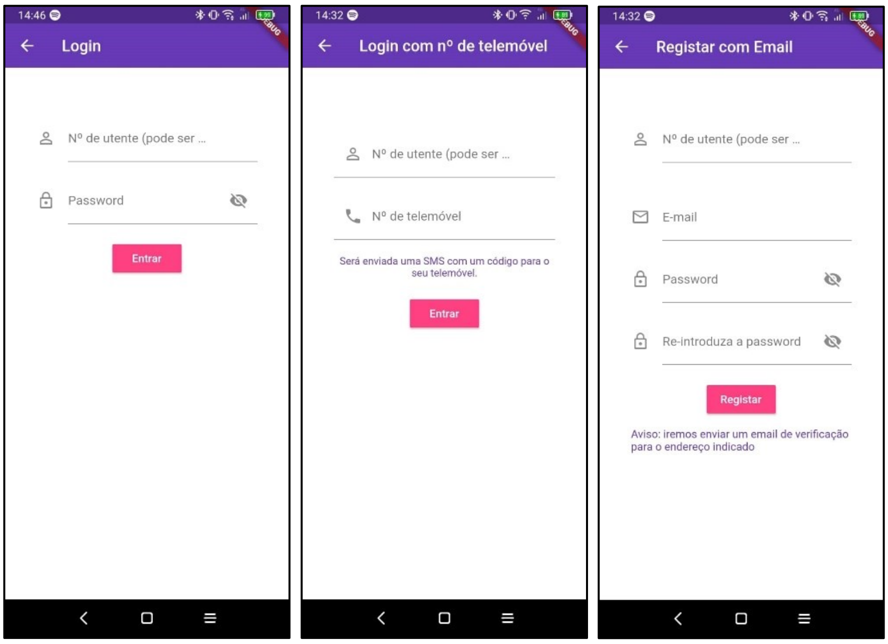
(Não é necessário registo)

Aviso: É necessário o nº de utente para efetuar login

Aviso: É necessário o nº de utente para efetuar registo

Figure 52 - Mobile app login and registration methods

As with the web applications, when users register in the mobile application (through the Firebase Authentication Service), their data is also stored and synced in the Firebase Cloud Firestore. In order to login or register in the mobile application, users must have their **Número de cartão de utente (NCU)**, which is a unique personal identifier used mainly in national healthcare services. As seen in **Figure 53**, this field is required in order to login or register in the mobile application, regardless of which authentication method was chosen.

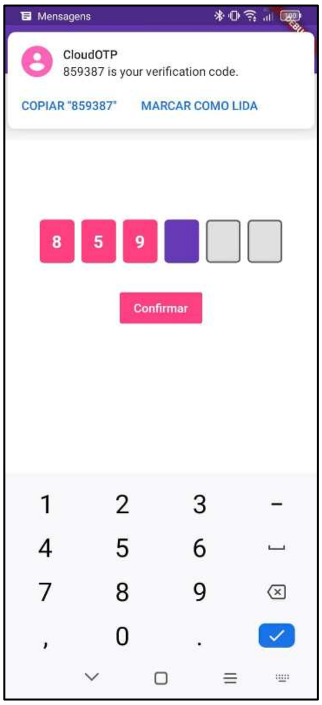


Será enviada uma SMS com um código para o seu telemóvel.

Aviso: iremos enviar um email de verificação para o endereço indicado

Figure 53 - Mobile app login and registration required fields

It is worth noting that mobile phone login does not require previous registration, since this registration is automatically performed by this particular authentication service in background. After introducing their NCU and phone number, a text message is sent with a 6-digits verification code the user needs to introduce in the mobile application, as seen in **Figure 54**.



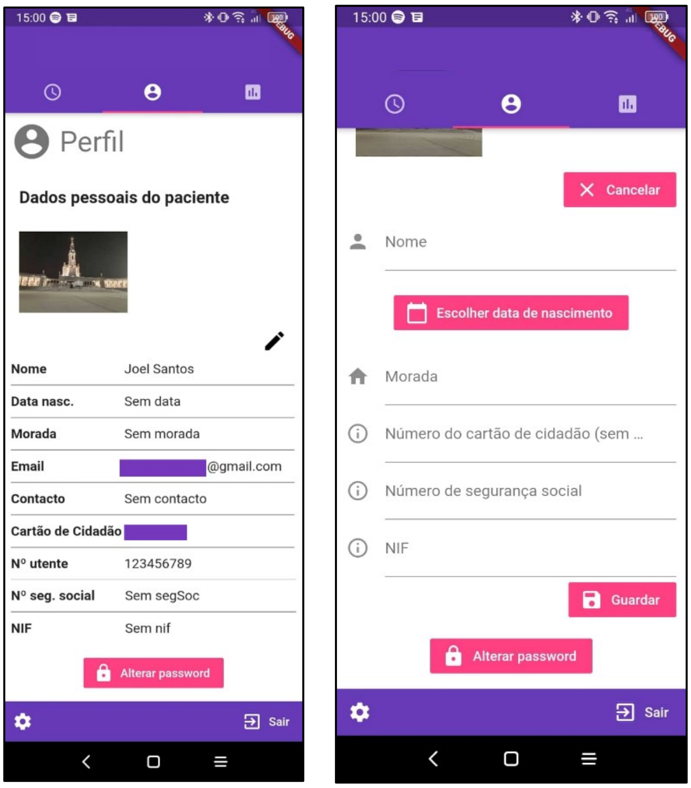
CloudOTP
859387 is your verification code.

Figure 54 - Mobile application phone number sign in

Profile

In the profile tab, users have access to their personal data, and may edit and update it whenever they want, as shown in **Figure 55**. Users may also add and update their profile picture by choosing a picture from the local phone gallery or by taking a picture using the mobile phone camera, which is then stored in the Firebase Storage. When updating their personal data or profile picture, all applications connected with the same Firebase instance are also updated in real-time.

The user may also change the account password if the account is already verified. If it is not yet verified, the user may resend a verification email, making it possible to verify the account and consequently change its password.



Perfil

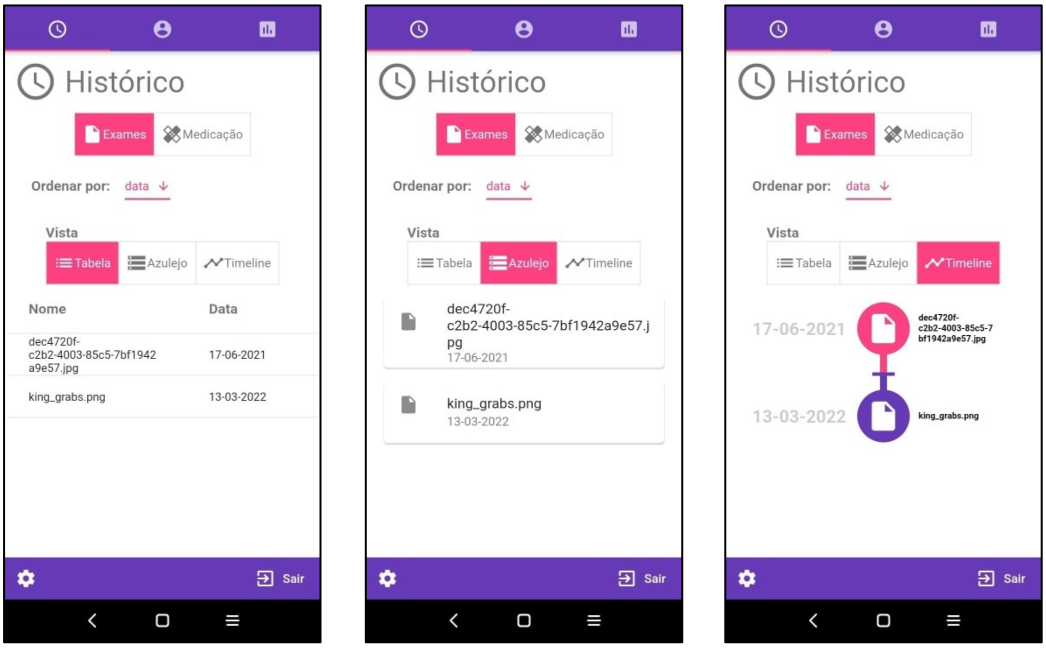
Dados pessoais do paciente

Nome	Joel Santos
Data nasc.	Sem data
Morada	Sem morada
Email	[redacted]@gmail.com
Contacto	Sem contacto
Cartão de Cidadão	[redacted]
Nº utente	123456789
Nº seg. social	Sem segSoc
NIF	Sem nif

Figure 55 - Mobile application's profile tab

Exams and Medication History

Considering that one key issue with the implementation of eHealth systems is the ability to keep an organized medical history record of patients, by storing and transmitting this data to be displayed in real-time, this functionality was considered in this work. The main goal is that patients can easily visualize their medical history and access their prescribed exams and medication immediately. Thus, as shown in **Figure 56**, the interface accomplishes these goals by transmitting easy-to-read information, with the possibility for the user to configure different views to present the files (table, grid, or timeline). The user may also alternate between exam and medication files, and sort them by date or filename.



Nome	Data
dec4720f-c2b2-4003-85c5-7bf1942a9e57.jpg	17-06-2021
king_grabs.png	13-03-2022

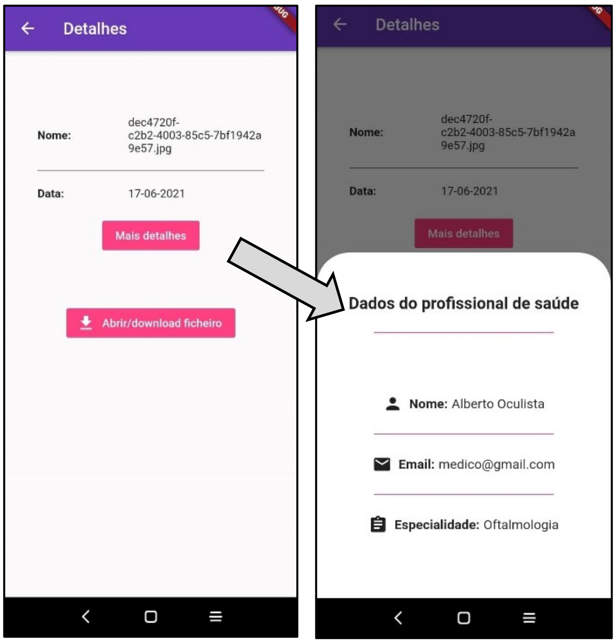
dec4720f-c2b2-4003-85c5-7bf1942a9e57.jpg
17-06-2021

king_grabs.png
13-03-2022

17-06-2021 dec4720f-c2b2-4003-85c5-7bf1942a9e57.jpg
13-03-2022 king_grabs.png

Figure 56 - History tab's different file views (table, grid, and timeline)

In all three file views, the files are clickable, and when clicked, the file details are displayed, as shown in **Figure 57**. In the file details screen, the user may click the "More details" button to trigger a new bottom sheet modal with the associated healthcare professional's information. It is worth noting that if the associated healthcare clinician updates this information in his/her profile area (in the web application) this information is also updated in real-time in the patient's mobile application. In the file details screen, the user may also click "Open/download file" to open the prescribed exam/medication from the Firebase Storage and/or download it to the local phone storage.



Nome: dec4720f-c2b2-4003-85c5-7bf1942a9e57.jpg
Data: 17-06-2021

Nome: Alberto Oculista
Email: medico@gmail.com
Especialidade: Oftalmologia

Figure 57 - Exams/medication details screen

Graphs and charts

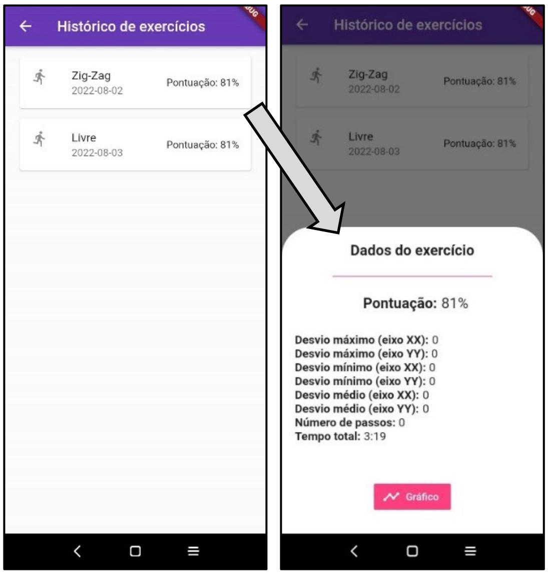
A third tab is inserted in the mobile application, whose function is to display or generate graphs associated with the user's physical measurements. As shown in **Figure 58**, these measurements include the history of physical rehabilitation exercises done by the patient or entering new measures.

Carregar para ver histórico de exercícios realizados e respetivos dados.

Pressão arterial, glicose, peso, e altura.

Figure 58 - Graphs and charts tab

By clicking "Exercises", the mobile application searches the Firebase Cloud Firestore database for exercise data associated with that user, and displays a list with all past exercises, as seen in **Figure 59**. By clicking in an exercise, a bottom sheet modal appears with more details about the final score, deviations, and time it took to finish the exercise. Users may also open the corresponding exercise chart (if existing) to analyze their positions and route characteristics. As stated previously, exercises may not always have an associated graph, and in this case, the button used to open the charts becomes disabled.



Zig-Zag 2022-08-02 Pontuação: 81%

Livre 2022-08-03 Pontuação: 81%

Dados do exercício

Pontuação: 81%

Desvio máximo (eixo XX): 0
Desvio máximo (eixo YY): 0
Desvio mínimo (eixo XX): 0
Desvio mínimo (eixo YY): 0
Desvio médio (eixo XX): 0
Desvio médio (eixo YY): 0
Número de passos: 0
Tempo total: 3:19

Figure 59 - Exercise history and details

As to the "Add measurement" functionality, the interface (shown in **Figure 60**) prompts the user with four different types of physical measurements, height, weight, blood pressure and glucose level. By clicking in one of the measurements, the user may enter the data manually, which will be then stored in Firebase Cloud Firestore. As described previously, this project makes use of a persistent MySQL database, to store data permanently, thus, when the healthcare professional opens the corresponding Power BI dashboard, the data is migrated from Cloud Firestore to MySQL, and the measurements are then deleted from Cloud Firestore which, for this case, acts as a temporary database. Since the Power BI dashboards are refreshed daily, the introduced measurements will become available after the next refresh, and the corresponding charts are similar with the one displayed in **Figure 39**.

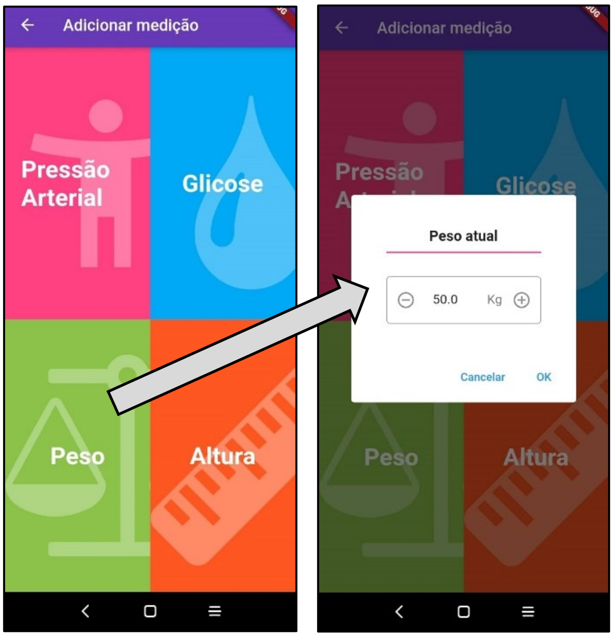


Figure 60 - Adding a new measurement (weight)

3.3 Score Metrics

By implementing the presented system, one question remains: how to score the patient achievements during the physical rehabilitation plan based on the proposed solution? Thus, some metrics based on statistics can be very useful for patient evaluation, resulting in two different mathematical relations.

3.3.1 Average deviations

The first relation consists in obtaining the total number of measurements during the time the user takes to complete the exercise (**N**), the number of measurements out of the virtual path's bounds (**NO**), the real SensFloor dimensions, in meters (in this case, **MaxX** = 4 and **MaxY** = 2) and the maximum X and Y deviations (**MaxDevX** and **MaxDevY**).

It is also possible to calculate the average X and Y deviations, **AvDevX** and **AvDevY**, respectively, as follows:

$$AvDevX = \frac{\sum_0^{NO} devX}{N}; \ AvDevY = \frac{\sum_0^{NO} devY}{N}$$

Equation 2 - Average X and Y deviations

in which ***dev(X/Y)*** represents the array with all deviations. By doing so, the final score formula is achieved, shown in **Equation 3**.

$$score = \frac{N - NO}{N} * \frac{MaxX - MaxDevX}{MaxX} * \frac{MaxY - MaxDevY}{MaxY} * \frac{MaxX - AvDevX}{MaxX} * \frac{MaxY - AvDevY}{MaxY} * 100$$

Equation 3 – Final score formula, using calculated average deviations

In an ideal scenario, variables **NO**, **MaxDevX**, **MaxDevY**, **AvDevX** and **AvDevY** are equal to zero, corresponding to a perfect score (100%). However, in the worst-case scenario, if **MaxDevX** = **MaxX**, **MaxDevY** = **MaxY**, **AvDevX** = **MaxX** or **AvDevY** = **MaxY**, the score is automatically 0%. By analyzing the first term of the equation, if the user spends most of the time outside bounds, the score tends to be lower.

3.3.2 Root Mean Square Error (RMSE)

As to the second solution, it makes use of **RMSE (Root Mean Square Error)**, as a way to measure differences between the correct values and the deviations. RMSE is considered an optimal general purpose error metric, and is used to measure and predict errors, giving information about how concentrated the data is around the average values.

RSME is calculated as follows:

$$RMSE = \sqrt{\sum_{i=1}^{N} \frac{(y"_i - y_i)^2}{N}}$$

Equation 4 - RMSE formula

The term $(\boldsymbol{y"_i - y_i})$ corresponds to the deviations calculated previously. This gives an estimation of how deviated the measurements are from the ideal. RMSE = 0 corresponds to a perfect scenario, where no deviations were made throughout the path, which means that the lower the RMSE, the lower the error. By testing the IoT system, the worst-case scenarios reached to a RMSE $\simeq$ 0.15. These RMSE values can be converted to a percentage, as to generate the final score, using **Equation 5**.

$$score = \frac{k}{RMSE + k} * 100$$

Equation 5 - Final score formula, using RMSE

It is possible to conclude that if RMSE = 0, score = 100%, thus for a bigger RMSE value, the score is lower. By incrementing/decrementing the parameter **k**, the score is less/more sensible to the RMSE value, respectively. By testing the system, an optimized value for this constant is **k**

= 0.06, corresponding to the graph shown in **Figure *61***. Using this formula, however, it is not possible to obtain a score = 0% since **Equation *5*** does not have zero as a possible solution. By analyzing **Figure 61**, it is also possible to see that the function never reaches zero in the x axis.

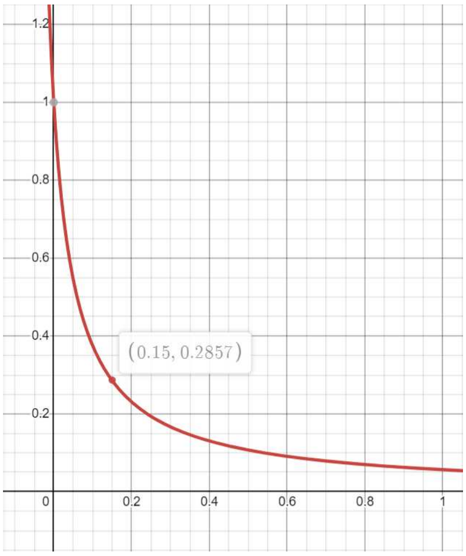


Figure 61 - Score, using **Equation 5**

3.3.3 Developed metrics appraisal

To appraise which score relation performs better, *i.e.*, leads to higher scores, several tests were made using both. The tests included simulating the perfect paths, walking the virtual paths with few deviations, and walking in the worst-case scenarios, for each type of preset routes, resolution, and path thickness. **Appendix G** shows different types of deviations used to test the developed system, with theoretical paths (upper), paths with minor deviations (middle) and paths with major deviations (bottom). The user's path is represented in pink, and theoretical "perfect" path in green (with x,y axis in meters).

The proposed metrics were tested by numerical simulation. Thus, when simulating perfect paths, both **Equation 3** and **Equation 5** led to a score of 100%.

When simulating minor deviations, things get a bit different. **Equation 3** led to overall higher scores, whereas using **Equation 5**, scores tend to be (non-significantly) lower, with a maximum difference of 10% score between both relations.

However, while simulating worst-case scenarios for all types of paths, both relations tend to perform differently. In general, regardless of the score used relation, and chosen path type, for higher path thicknesses, final scores are not very low. For instance, for a straight line exercise, with maximum path thickness, the lowest simulated score was 36% for the used **Equation 3**, and 59% for the used **Equation 5**.

That said, in these worst-case scenarios, using **Equation 5**, the scores are, in general, significantly higher than using **Equation 3**. For instance, by choosing one of the hardest exercises, the circle path with maximum cell resolution and lowest path thickness, the lowest obtained score was 15% using **Equation 5** and 4% using **Equation 3**. Simulated tests also concluded that if the user spends more time (*i.e.*, has a higher number of measurements) outside bounds, the score tends to be lower, regardless of the formula used, as both consider the total number of measurements and the total number of deviations.

It is possible to conclude that **Equation 3** performs slightly better for paths with little deviations, while **Equation 5** performs better when users tend to deviate more times outside bounds.

Chapter 4. Experimental Results and Discussions

This section refers to the evaluation of each of the tests carried out, both in a simulation context and in a real context. The proposed system was tested by some healthy, young adult volunteers, and all combinations of virtual path types, cell resolution and path thickness were tested, as well as the free exercise. The tests carried out are enumerated in **Table 4**.

Straight line path	Free exercise	Circle path	Zig-zag path
Lowest cell resolution, lowest path thickness	Walking around the smart carpet area following the professional's orders and indications	Lowest cell resolution, lowest path thickness	Lowest cell resolution, lowest path thickness
Middle cell resolution, lowest path thickness		Middle cell resolution, lowest path thickness	Middle cell resolution, lowest path thickness
Middle cell resolution, highest path thickness		Middle cell resolution, highest path thickness	Middle cell resolution, highest path thickness
Highest cell resolution, lowest path thickness		Highest cell resolution, lowest path thickness	Highest cell resolution, lowest path thickness
Highest cell resolution, highest path thickness		Highest cell resolution, middle path thickness	Highest cell resolution, middle path thickness
-		Highest cell resolution, highest path thickness	Highest cell resolution, highest path thickness

Table 4 - Tests carried out

4.1 Prototype Testing and Evaluation

When simulating all combinations of virtual path types, cell resolution and path thickness (shown in **Figure 47**), in certain combinations it is nearly impossible to achieve a perfect score – this happens only for the circle and zig-zag virtual paths. **Figure 62** and **Figure 63** show these scenarios, in which users walk correctly (or with little deviations), but score poorly, regardless of which score relation used.

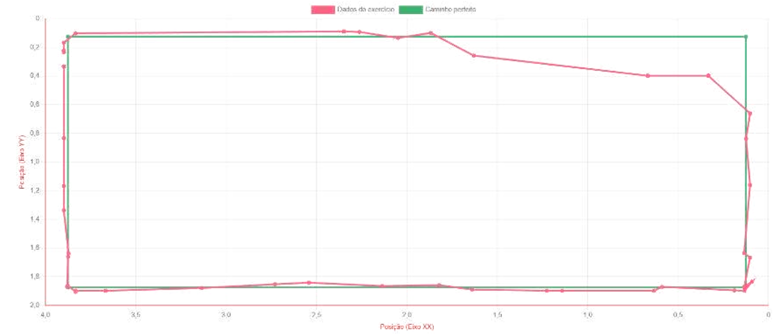


Figure 62 - Circle path training with maximum cell resolution and lowest path thickness - using **Equation 3** (57% achieved score)

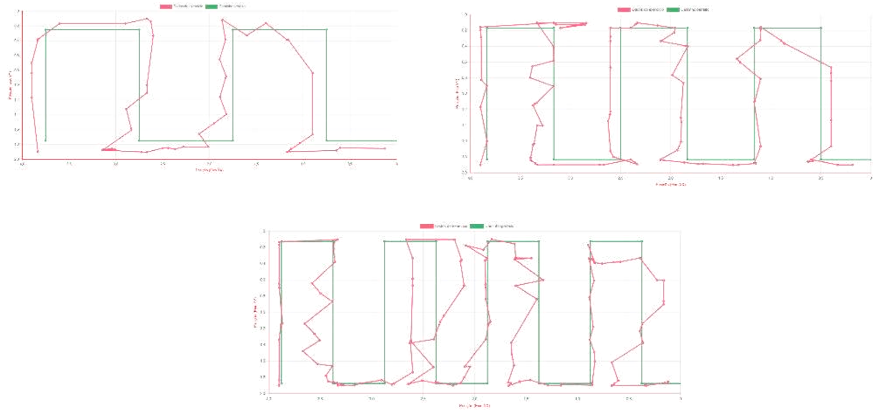


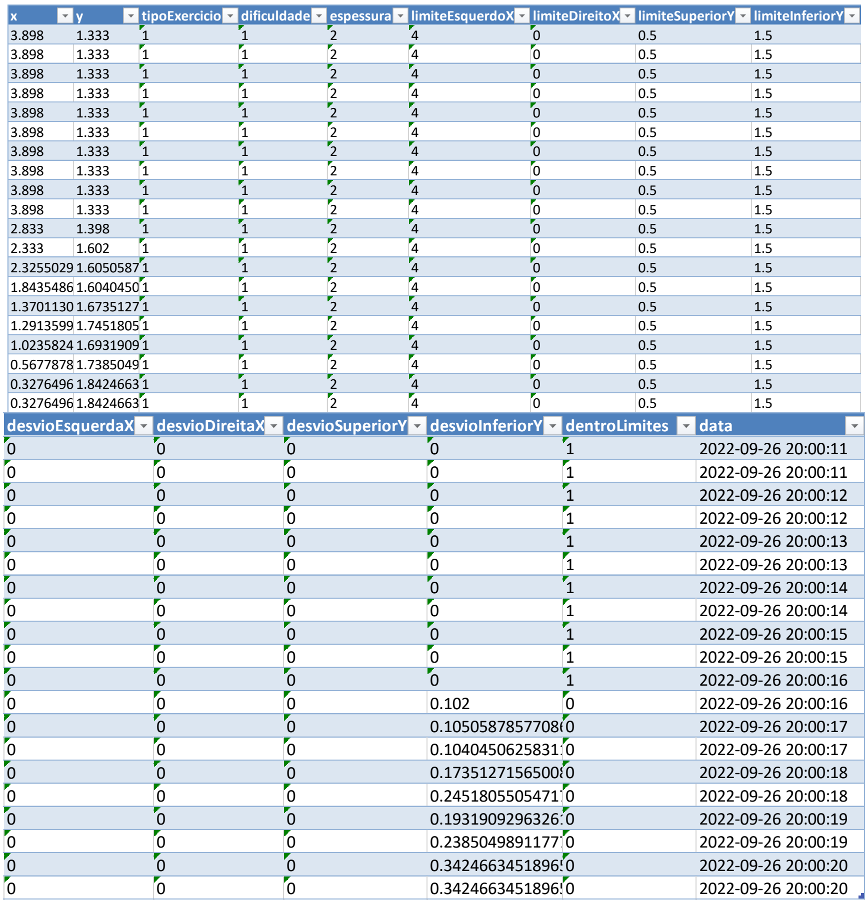
Figure 63 - Zig-zag paths training with different cell resolutions and lowest path thickness – using **Equation 3**, (achieved scores: 18%, 14% and 9%)

In these particular combinations of exercises, it is recommended that users walk in "baby-steps", that is, walking with one foot in front of the other. By doing so, the score may be improved, and deviations are not so pronounced, as shown in **Figure 64**. Comparing baby-steps charts with normal charts results in more position points, corresponding to more steps taken to finish the exercise, and consequently more accuracy and precision, leading to overall higher scores. In these exercises, the time the user took to finish the exercise is not as important as the precision with which the exercise is done.

Figure 64 - Normal exercise (top) vs "baby-steps" exercise (bottom)

The adaptability and system's "easiness" was also tested by volunteers, and results show that the more time the user repeats the exercises, the more adapted they become. The first attempts reveal some lack of awareness of the physical space of the carpet, as it is below the floor and is not directly visible. However, the volunteers quickly adapted and achieved better results, as shown in **Figure 65**. By analyzing **Table 5** and **Table 6**, it is also possible to observe an improvement, mainly in the Y axis deviations. In this specific case, in her first try (being the first contact ever with the system), the user started far from the ideal route, scoring poorly, but in her next try, the volunteer approached the ideal line, scoring 100%.

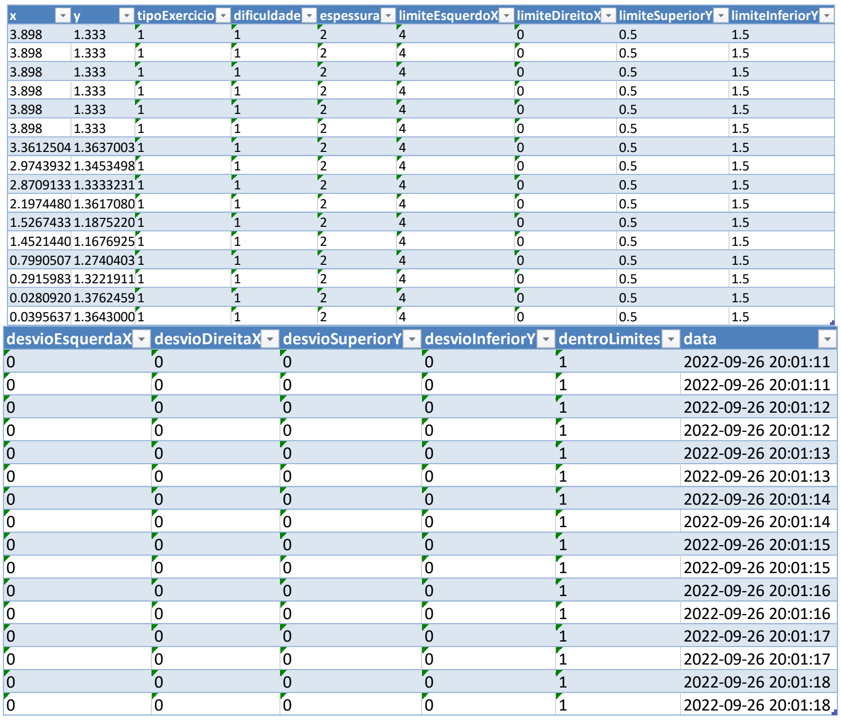
Figure 65 - Testing the system – Straight line exercise: User's first and second tries



x	y	tipoExercicio	dificuldade	espessura	limiteEsquerdoX	limiteDireitoX	limiteSuperiorY	limiteInferiorY
3.898	1.333	1	1	2	4	0	0.5	1.5
3.898	1.333	1	1	2	4	0	0.5	1.5
3.898	1.333	1	1	2	4	0	0.5	1.5
3.898	1.333	1	1	2	4	0	0.5	1.5
3.898	1.333	1	1	2	4	0	0.5	1.5
3.898	1.333	1	1	2	4	0	0.5	1.5
3.898	1.333	1	1	2	4	0	0.5	1.5
3.898	1.333	1	1	2	4	0	0.5	1.5
3.898	1.333	1	1	2	4	0	0.5	1.5
3.898	1.333	1	1	2	4	0	0.5	1.5
2.833	1.398	1	1	2	4	0	0.5	1.5
2.333	1.602	1	1	2	4	0	0.5	1.5
2.3255029	1.6050587	1	1	2	4	0	0.5	1.5
1.8435486	1.6040450	1	1	2	4	0	0.5	1.5
1.3701130	1.6735127	1	1	2	4	0	0.5	1.5
1.2913599	1.7451805	1	1	2	4	0	0.5	1.5
1.0235824	1.6931909	1	1	2	4	0	0.5	1.5
0.5677878	1.7385049	1	1	2	4	0	0.5	1.5
0.3276496	1.8424663	1	1	2	4	0	0.5	1.5
0.3276496	1.8424663	1	1	2	4	0	0.5	1.5

desvioEsquerdaX	desvioDireitaX	desvioSuperiorY	desvioInferiorY	dentroLimites	data
0	0	0	0	1	2022-09-26 20:00:11
0	0	0	0	1	2022-09-26 20:00:11
0	0	0	0	1	2022-09-26 20:00:12
0	0	0	0	1	2022-09-26 20:00:12
0	0	0	0	1	2022-09-26 20:00:13
0	0	0	0	1	2022-09-26 20:00:13
0	0	0	0	1	2022-09-26 20:00:14
0	0	0	0	1	2022-09-26 20:00:14
0	0	0	0	1	2022-09-26 20:00:15
0	0	0	0	1	2022-09-26 20:00:15
0	0	0	0	1	2022-09-26 20:00:16
0	0	0	0.102	0	2022-09-26 20:00:16
0	0	0	0.1050587857708	0	2022-09-26 20:00:17
0	0	0	0.1040450625831	0	2022-09-26 20:00:17
0	0	0	0.1735127156500	0	2022-09-26 20:00:18
0	0	0	0.2451805505471	0	2022-09-26 20:00:18
0	0	0	0.1931909296326	0	2022-09-26 20:00:19
0	0	0	0.2385049891177	0	2022-09-26 20:00:19
0	0	0	0.3424663451896	0	2022-09-26 20:00:20
0	0	0	0.3424663451896	0	2022-09-26 20:00:20

Table 5 - Straight line exercise - first try exercise data



x	y	tipoExercicio	dificuldade	espessura	limiteEsquerdoX	limiteDireitoX	limiteSuperiorY	limiteInferiorY
3.898	1.333	1	1	2	4	0	0.5	1.5
3.898	1.333	1	1	2	4	0	0.5	1.5
3.898	1.333	1	1	2	4	0	0.5	1.5
3.898	1.333	1	1	2	4	0	0.5	1.5
3.898	1.333	1	1	2	4	0	0.5	1.5
3.898	1.333	1	1	2	4	0	0.5	1.5
3.3612504	1.3637003	1	1	2	4	0	0.5	1.5
2.9743932	1.3453498	1	1	2	4	0	0.5	1.5
2.8709133	1.3333231	1	1	2	4	0	0.5	1.5
2.1974480	1.3617080	1	1	2	4	0	0.5	1.5
1.5267433	1.1875220	1	1	2	4	0	0.5	1.5
1.4521440	1.1676925	1	1	2	4	0	0.5	1.5
0.7990507	1.2740403	1	1	2	4	0	0.5	1.5
0.2915983	1.3221911	1	1	2	4	0	0.5	1.5
0.0280920	1.3762459	1	1	2	4	0	0.5	1.5
0.0395637	1.3643000	1	1	2	4	0	0.5	1.5

desvioEsquerdaX	desvioDireitaX	desvioSuperiorY	desvioInferiorY	dentroLimites	data
0	0	0	0	1	2022-09-26 20:01:11
0	0	0	0	1	2022-09-26 20:01:11
0	0	0	0	1	2022-09-26 20:01:12
0	0	0	0	1	2022-09-26 20:01:12
0	0	0	0	1	2022-09-26 20:01:13
0	0	0	0	1	2022-09-26 20:01:13
0	0	0	0	1	2022-09-26 20:01:14
0	0	0	0	1	2022-09-26 20:01:14
0	0	0	0	1	2022-09-26 20:01:15
0	0	0	0	1	2022-09-26 20:01:15
0	0	0	0	1	2022-09-26 20:01:16
0	0	0	0	1	2022-09-26 20:01:16
0	0	0	0	1	2022-09-26 20:01:17
0	0	0	0	1	2022-09-26 20:01:17
0	0	0	0	1	2022-09-26 20:01:18
0	0	0	0	1	2022-09-26 20:01:18

Table 6 - Straight line exercise - second try exercise data

The same volunteer was then instructed to follow directions in a free exercise, making a “triangular-like” route. The user then proceeded to the results displayed in **Figure 66**, and stated that the instructions were clear and easy to understand. The user walked as expected, clearly following the instructions given, with no constraints or difficulties.

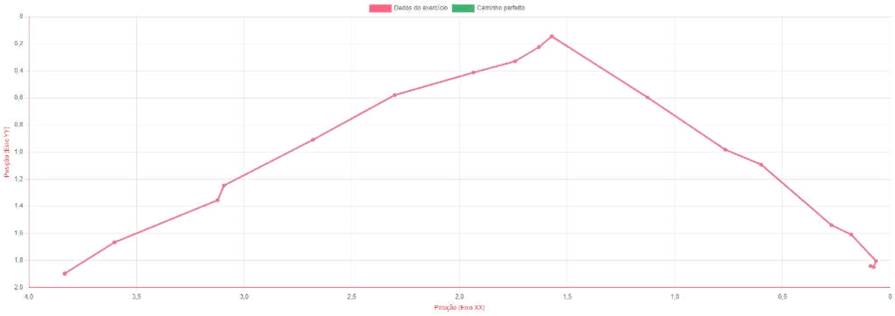


Figure 66 – Testing the system - Free exercise

After that, some more complex exercises were prescribed for the volunteers to follow, starting from the lowest cell resolution and highest path thickness to the highest cell resolution and lowest path thickness.

In straight line exercises, the different combinations of cell resolution and path thickness did not have a great impact in the user’s experience and difficulty, since this is the simplest path of all, and the volunteers were healthy and young. Volunteers stated that after getting used to the smart carpet area, it is easier to be aware of the area that is meant to be stepped. However, things change drastically for the other path types.

Starting with the circle path with lowest difficulty (*i.e.*, lowest cell resolution and highest path thickness), the volunteers showed an easy adaptation from the free and straight line exercise. When incrementing cell resolution and decrementing path thickness, users agreed that it gets harder to stay near the “perfect” route, and that performing the exercise with one foot in front of the other actually helps improving precision. Volunteers also refer that the circle path with the highest cell resolution and the lowest path thickness was similar to the intermediate cell resolution with the same path thickness, and therefore, no relevant differences were noted.

Users agreed that having a way to physically visualize the path and/or smart carpet area would help to improve awareness while performing physical rehabilitation exercises, for instance a LED projector placed over the carpet area instead of a big TV screen. This issue is even more noticeable in the zig-zag virtual paths, and therefore it is harder for users to know where they can step. **Figure 67** shows exactly that scenario, by displaying the user’s first and second tries on the zig-zag path with lowest cell resolution and highest path thickness, where it is possible to analyze that the user is not much aware of the correct path at first. However, similarly to what happened with the straight line path scenario (shown in **Figure 65**), the user adapted well and managed to approach the perfect line in her second try. On her first try, the user scored 28% (using **Equation 3**); on the next try, the user scored 41%.

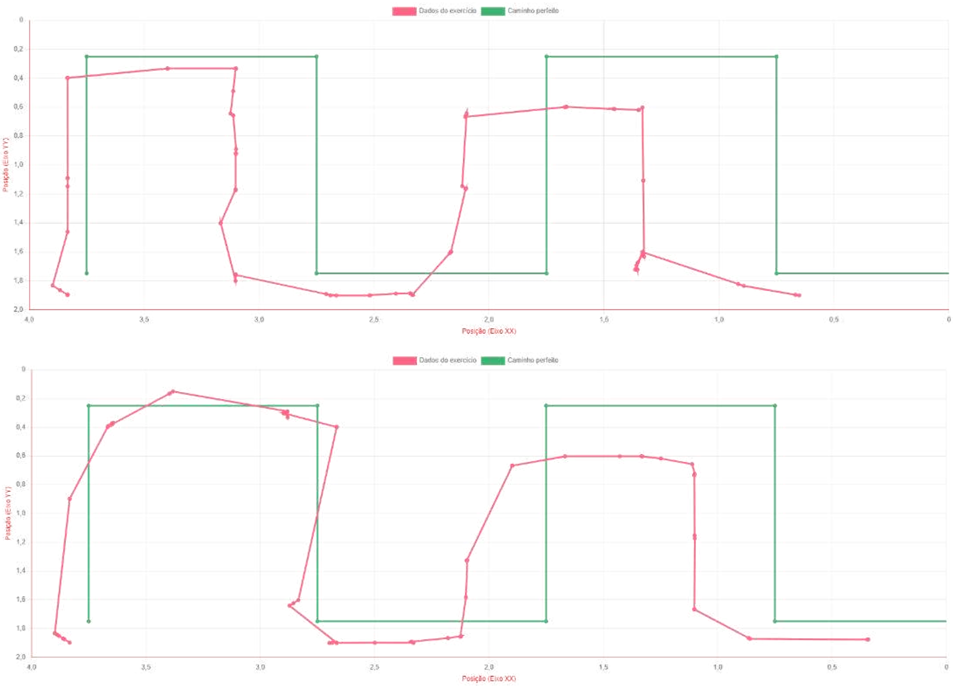


Figure 67 - Testing the system – Zig-zag exercise: User’s first and second tries

Since the laboratory where the smart carpet is installed was not always physically clear, some virtual paths were not possible to perform fully. Due to obstacles, users showed some performance issues, as shown in **Figure 68**.

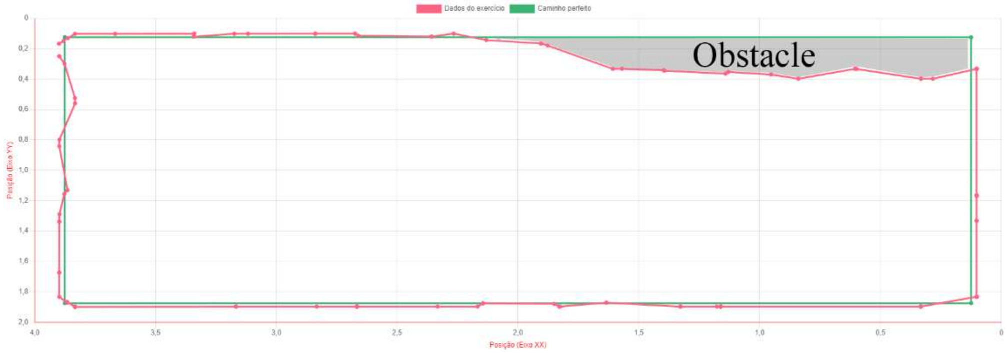


Figure 68 - Circle path walking while using "baby-steps" (using **Equation 3**, score was 41% instead of 100% due to the obstacle in the top right corner)

In the embedded platform application, using SensFloor API, whenever an update occurs, the data is immediately sent to a cloud database, and since Raspberry Pi presents limited capabilities, that may result in **outliers** (which directly affects the final score negatively, as shown in **Figure 69**), loss of packets or connection errors. This would be particularly problematic and more pronounced if this application kept running in background. Not only the limited RAM, but also the limited CPU capabilities may be a constraint – by testing the system, the developed embedded platform application may in some cases surpass a 70% CPU usage, and when this happens, it leads to DynamoDB connection errors.

As stated in the “**Hardware Characteristics and Embedded Platform Application**” section, the temporary solution was to implement a button in the interface, as a way to start/stop the process of gathering, filtering, and sending the measurements to the cloud database, although it would be useful to consider upgrading the microcontroller platform in the future.

Regarding this issue, one solution was to implement async/await functions, as a way to synchronize the received messages and send them to the cloud database. However, the embedded platform's browser (Chromium) does not support this feature, and therefore it cannot be implemented. By implementing delays between the received messages, the final results might not be so trustworthy and lag issues might occur.

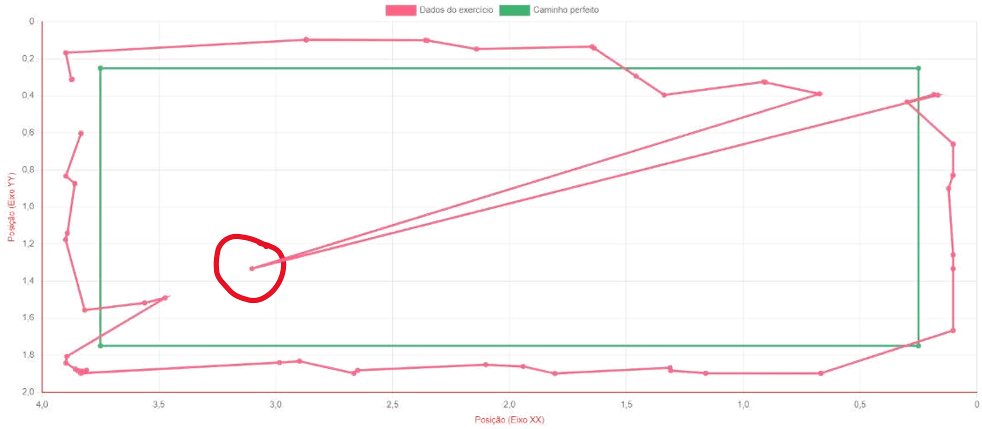


Figure 69 - Impact of an outlier – final score was 34% instead of 100%, using **Equation 3**

The "time-trial" mode was also tested, with the limit time adapted to each exercise. In most cases, this served only as auxiliary since the user was more focused on finishing the exercise correctly rather than within the time limit.

In addition to all previously described tests, **Appendix G** shows several tests using paths with perfect routes, routes with little deviations and paths taken with several deviations, which were used in the "**Score Metrics**" section.

As to the developed health-related data storage, it has proven useful in making data and documents available in real-time, both to the healthcare clinicians and the patients themselves. Volunteers also agreed to register in the mobile account and referred that it provides several advantages, mainly an easy access to exams, medication, and exercise history, providing better healthcare monitoring. They also agreed that the mobile application may help users to feel more motivated to exercise, since they have access to their exercise history, and may evaluate and follow their progress and evolution.

Chapter 5. Conclusion and Future Work

5.1 Final thoughts and appraisal

The proposed solution behaved as expected, providing useful information about the users' gait. Obtained results show that outliers are a possibility and that they may influence the final gait score negatively, and that the physical visualization of the virtual path would influence the users' perspective and, perhaps, motivation.

The developed software, *i.e.*, the mobile application and web interface had positive feedback from volunteers, stating it was very intuitive and easy to understand, and that it is very helpful to make all results available to both the healthcare professional and the user.

The described system is yet to be tested in a real-life physiotherapy environment. This method is a completely non-intrusive alternative to traditional physical rehabilitation techniques, as it allows the patient to walk around normally on a regular surface without noticing the sensing hardware.

5.2 Challenges and limitations

Handling with embedded platforms and microcontrollers may present some constraints and limitations, namely physical problems like overheating and a limited number of executions due to a reduced internal memory capacity (as stating in the "" section, this Raspberry Pi model only has 1 GB of RAM). In this regard, some issues were faced while using the Raspberry Pi 3, the main issue being the existence of several **outliers** in measurements. These outliers may happen not only because of Raspberry Pi, but also because of the floor itself on which the smart carpet is installed, which may not be ideal and may cause more pressure in some cells than others.

Another issue already stated previously in the "**Prototype Testing and Evaluation**" section is that some combinations of the virtual path types, path thickness and cell resolution it is impossible to achieve a perfect score. This happens especially for virtual paths with the lowest path thickness and highest cell resolution, making the correct route too slim for users to walk correctly with no deviations. However, this may not be an actual issue, and these combinations may be useful in more specific physiotherapy contexts, where score may not be as important as the route itself.

In this regard, in order to achieve more accurate and precise results, the room where the smart carpet is installed should be kept clear and unobstructed, which was not always possible due to the nature of the laboratory.

5.3 Future Work

In this project, only the (x,y) coordinates measured by the sensor were used, however it would be useful to keep other SensFloor variables in consideration. Fall alerts and presence detection are possible making use of other SensFloor characteristics, and when implementing more complex AI algorithms to evaluate gait patterns, it should also be possible to predict physical disabilities, such as Parkinson's Disease. Other types of serious games can be implemented in this system, which may be adapted to the age group of users, as a way to further their interaction and motivation. The developed system may also be applied in several sports activities, namely ballroom dancing and gym activities. It would also be possible to roughly calculate the user's average step size, by gathering the distance between consequential points, and calculating the total average.

As volunteers stated, it would be desirable to display the smart carpet values and interface directly on the floor (by means of lights or a LED projector placed above the user), making the whole system more interactive and easier to understand. Another possibility is to display the web interface in a tablet, which is then given to the patient whilst walking, making it easier to follow the virtual path.

When implementing other non-intrusive smart sensors (such as cameras, smart insoles, etc.) it is possible to create a more precise IoT ecosystem that displays other types of values related to the user's physical activity, such as balance control and feet pressure, which would prove particularly important, for instance, in gyms. This designed system could also be linked and synchronized with Google Fit or other similar technology so that users may keep track of their physical activity anywhere, adding even more interconnectivity with other devices (smart bands, smartwatches, Google account and services, etc.).

Regarding the developed software applications, some improvements would also be possible. In the Microsoft Power BI's charts, some tips could be implemented, stating if the user's measurements are in the healthy bounds or not (*e.g.*, checking if the blood pressure is elevated or if the user is overweighted or not). In this context, some more charts could be implemented by taking advantage of all measurements provided, for instance, a Body Mass Index (BMI) chart, or charts with information about past exercises (*e.g.*, the score evolution for each exercise type). In the mobile application, some other manual measurements could be implemented, such as heart rate and SpO2, and Power BI graphs developed accordingly.

Considering the exercise charts (made using Chart.js), some more detailed information about which points are out of bounds would also be useful. In time-trial mode, there should also be an option that discounts the user's final score if the time limit is exceeded.

Since the system deals with users' personal data, some security policies and data encryption mechanisms should also be implemented, following GDPR. In this regard, being HL7 compliant should be a priority, as a way to ensure more interconnectivity between different systems. There should also be a mechanism to register and authenticate healthcare professionals, mainly making use of their data in "Ordem dos Médicos", or by creating an administrator user that accepts or refuses new registrations. Healthcare professionals should also be given the possibility to create new patients themselves, easing the patients' registration process.

As to the tests carried out, it would be useful to implement the developed system in a real-life physiotherapy environment and evaluate its performance with patients in all group ages. By doing so, and by recording a group of patient's measurements over the time, the physiotherapist could analyze each individual's evolution over time, and appraise the general functioning of the developed project.

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Appendix A

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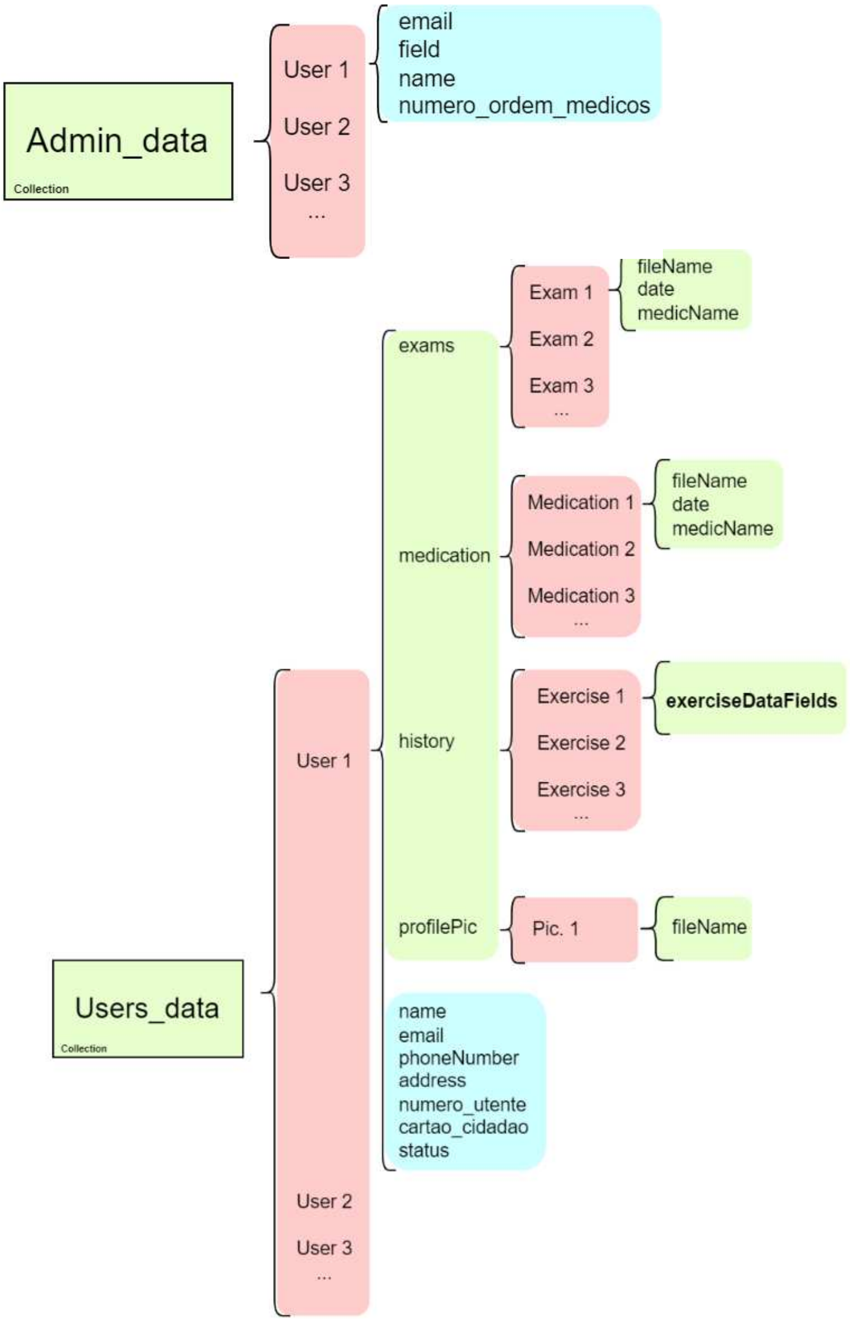
Appendix B

	Realtime Database	**Cloud Firestore**
Data model	• Stores data as one large JSON tree. • Complex, hierarchical data is harder to organize at scale.	• Stores data as collections of documents • Complex, hierarchical data is easier to organize at scale, using subcollections within documents.
Realtime and offline support	Offline support for Apple Android clients.	Offline support for Apple, Android, and web clients.
Presence (know when a client is online or offline)	Presence supported.	Not supported natively.
Querying	• Limited • Queries can sort or filter on a property, but not both.	• Allows more complex queries • chain filters and combine filtering and sorting on a property in a single query.
Writes and transactions	Basic write and transaction operations.	Advanced write and transaction operations
Reliability and performance	Regional solution.	Regional and multi-region solution that scales automatically.
Scalability	• Scaling requires sharding • Scale to around 200,000 concurrent connections and 1,000 writes/second in a single database. Scaling beyond that requires sharding your data across multiple databases.	• Scaling is automatic • Scaling limits are around 1 million concurrent connections and 10,000 writes/second.
Security	Cascading rules language that separates authorization and validation.	Non-cascading rules that combine authorization and validation.

Appendix C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numero_ordem_medicos
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Collection
User 1
User 2
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fileName
date
medicName
history
Exercise 1
Exercise 2
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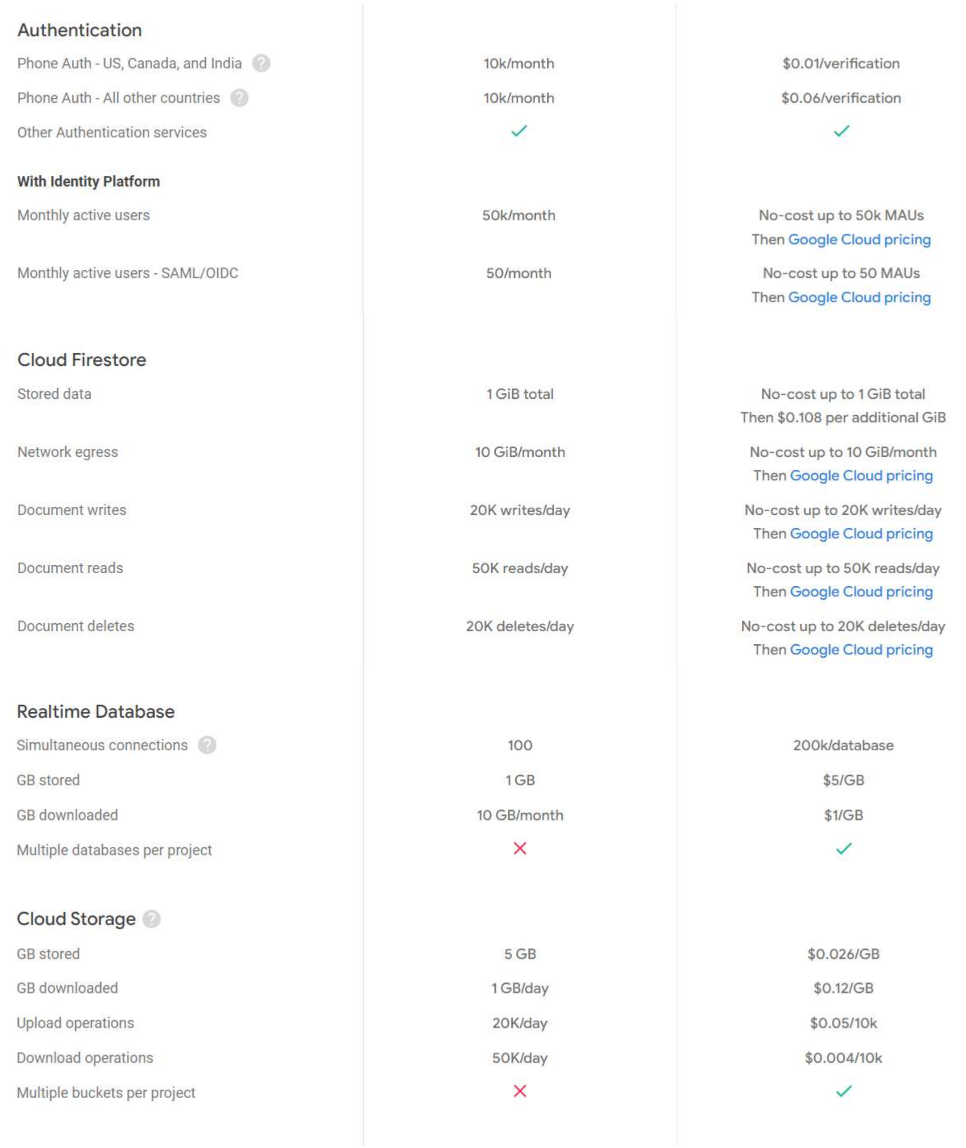
Appendix D



	Spark Plan (No-Cost)	Blaze Plan (Pay-as-you-go)
Authentication		
Phone Auth - US, Canada, and India	10k/month	$0.01/verification
Phone Auth - All other countries	10k/month	$0.06/verification
Other Authentication services	✓	✓
With Identity Platform		
Monthly active users	50k/month	No-cost up to 50k MAUs Then Google Cloud pricing
Monthly active users - SAML/OIDC	50/month	No-cost up to 50 MAUs Then Google Cloud pricing
Cloud Firestore		
Stored data	1 GiB total	No-cost up to 1 GiB total Then $0.108 per additional GiB
Network egress	10 GiB/month	No-cost up to 10 GiB/month Then Google Cloud pricing
Document writes	20K writes/day	No-cost up to 20K writes/day Then Google Cloud pricing
Document reads	50K reads/day	No-cost up to 50K reads/day Then Google Cloud pricing
Document deletes	20K deletes/day	No-cost up to 20K deletes/day Then Google Cloud pricing
Realtime Database		
Simultaneous connections	100	200k/database
GB stored	1 GB	$5/GB
GB downloaded	10 GB/month	$1/GB
Multiple databases per project	✗	✓
Cloud Storage		
GB stored	5 GB	$0.026/GB
GB downloaded	1 GB/day	$0.12/GB
Upload operations	20K/day	$0.05/10k
Download operations	50K/day	$0.004/10k
Multiple buckets per project	✗	✓

Appendix E

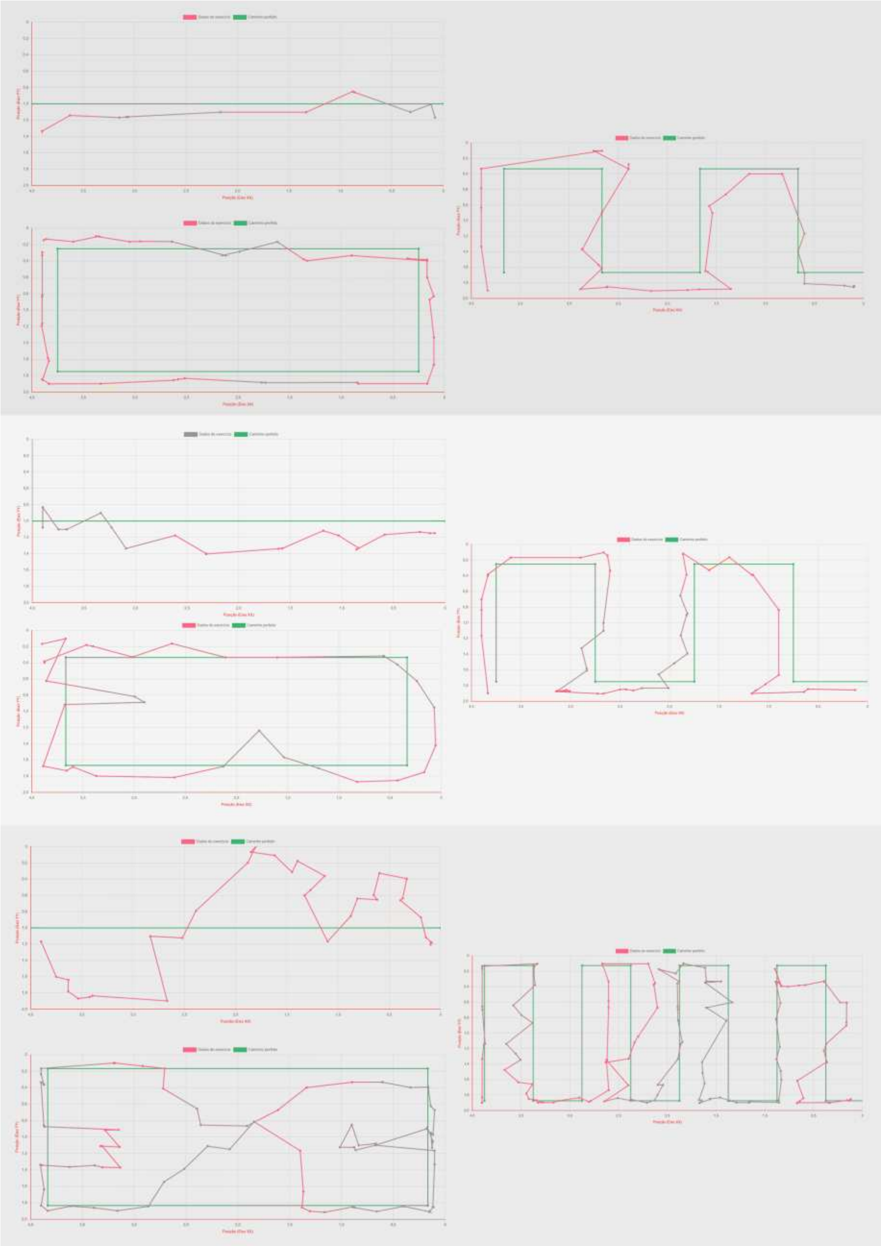
(adapted from https://powerbi.microsoft.com/en-us/pricing/)

Power BI Free	Power BI Pro	Power BI Premium	
Per user	Per user	Per user	Per capacity
0$ Per user/month Explore your reports to find and generate the quick insights you need for better business decisions. Collaborate on reports with colleagues, then easily share the reports and insights when and how you want – in workspaces, on the web, in apps, or using Microsoft Teams.	**$9.99** Per user/month License individual users with modern, self-service analytics to visualize data with live dashboards and reports, and share insights across your organization. • Power BI Pro is included in Microsoft 365 E5.	**$20** Per user/month License individual users to accelerate access to insights with advanced AI, unlock self-service data prep for big data, and simplify data management and access at enterprise scale. • Includes all the features available with Power BI Pro.	From **$4,995** Per capacity/month License your organization with capacity to accelerate access to insights with advanced AI, unlock self-service data prep for big data, and simplify data management and access at enterprise scale—without per-user licenses for content consumers. • Requires a Power BI Pro license for publishing content into Power BI Premium capacity. • Enable autoscale with your Azure subscription to automatically scale Power BI Premium capacity.

Appendix F

	Google's Flutter	**React Native**	**Xamarin**
Release date	2017	2015	2011
Made by	Google	Facebook	Microsoft
Documentation	Rich and easy to learn	Largest community support and documentation	Limited documentation and community support
Programming Language	Dart	JavaScript	C#
Architecture	Doesn't require a bridge to communicate with native components, making apps faster more responsive	Requires JavaScript bridge to interact with native elements, which makes debugging slower	Uses a non-JavaScript bridge to communicate with native components
Development time	Fast (as a hot reload feature, which reduces development time drastically)	Fastest	Slowest
Performance	Smoothest, best app performance, natively compiled applications. Compiling is faster in Dart than JavaScript	Close to native	Close to native
Updates	More resistant to updates. When the iOS or Android update, the app will remain the same	React Native depends on native elements, which means that when the update is released, some problems may appear	Delayed updates, if there's a new feature or update rolling out, there will usually be a delay until changes are made in the Xamarin tools, which may cause issues with the mobile app

Appendix G



Appendix H

Ambient Assisted Living using Non-intrusive Smart Sensing and IoT for Gait Rehabilitation

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Abstract— **Health monitoring of users in medical centers, nursing homes, physiotherapy clinics or other healthcare centers, is an important and recurring task. In addition, these facilities require a structured, organized system with access to all users' medical history. The design of a system that can measure individuals' physiological health characteristics (PHC) may also be applied to physical rehabilitation. In this context, this study presents a possible solution using a non-intrusive smart sensing system as part of an IoT ecosystem, that aims to solve all the issues stated. This IoT system uses a smart carpet, SensFloor, to measure several physical indicators, such as users' position and gait characteristics. The produced data by the system is stored in a real-time cloud database, thus physical therapists and patients are able to access it. Also, several dashboards are produced in real-time, to provide further analysis on users' gait and PHCs, so that action can be taken to improve the training plan with personalized exercises.**

Keywords— ***IoT, AAL, mHealth, eHealth, SensFloor, smart carpet, gait, monitoring, non-intrusive, unobtrusive***

INTRODUCTION

With the increment of global average life expectancy, the number of people who require constant health monitoring also increases. In this context, fast, reliable access to full medical records of patients should be a priority in healthcare facilities. The design of systems able to store and transmit medical data in real-time, while simultaneously implementing security policies, is a challenge [1], partly considering that some medical facilities do not have a sufficient budget to accommodate the implementation of such systems. In Portugal, the adoption of eHealth solutions in the public sector is mainly influenced by the following internal factors: *(i)* the size of the hospital/medical facility, *(ii)* the orientation towards quality in the provision of health services, and, more recently, *(iii)* the decentralization of management and *(iv)* the preparation of professionals to use the new solutions [2]. As a result, in small-sized, low-budget medical institutions, health professionals are given extra unnecessary work in monitoring all patients and their current health status and position, whilst managing all their medical history (exams, medication, etc.).

In nursing homes, in addition to their current health status and medical records, healthcare givers must also keep track of the elderly person's position in real-time, so they can act at the moment they need assistance. At more advanced ages, emotional health is also a very important factor that needs to be considered, as studies show that depression levels tend to increase in elderly people and are aggravated in nursing homes [3][4]. Physical exercise in nursing homes can prove effective in reducing the pain intensity, improving mobility, and psychological well-being of elderly people [5], and must be adapted according to each user. This may also be applied to physiotherapy clinics and gyms, where physical activity is essential, and keeping the user motivated is a must. In these facilities, it is crucial to assess the best exercises for each person, according to their needs. To accomplish this, the concept of IoT networks and Ambient Assisted Living (AAL) may be applied directly to healthcare systems, used to monitor patients remotely and measure their health characteristics, so that action can be taken accordingly. IoT-based systems may also be applied to physical rehabilitation [6].

Studies indicate that intrusive systems have a significant impact on the perceived usefulness and ease of use of the smart system [7], and some intrusive smart systems may not be applied directly to real circumstances, since *"no users will walk around continuously connected to a number of sensors so as to have an application that can monitor their state during the day"* [8]. AAL emerges as an unobtrusive IoT ecosystem for personal healthcare monitoring.

In this regard, SensFloor®, by Future Shape, is a discreet, non-intrusive smart carpet that measures multiple users' position, speed, step length, and many other physical characteristics simultaneously. This sensor may also be used to send fall alerts in real-time. Considering all issues stated previously, this article discusses an AAL-IoT system that uses SensFloor as a sensing unit and interface with the user during gait rehabilitation.

This paper is structured as follows: Section II presents related projects that make use of different technologies to accomplish common goals. Section III gives a description of the developed system architecture. Section IV shows how this solution can be implemented in a physical rehabilitation context. Section V presents experimental results from the tests carried out, and further discussion. To conclude this paper, Section VI presents final thoughts and future work.

RELATED WORK

Several senior healthcare facilities implemented smart sensing systems to accomplish physical health monitoring of patients [9]. In their opinion, the smart floor technology is an alternative to wearables or cameras, providing privacy and independence for residents, increasing opportunity for smart personal engagement and monitoring while maintaining resident privacy [9].

Other projects fall under the concept of gamification and serious games, which are approaches for improving patient motivation and engagement during physical rehabilitation sessions. Thus, by opposition with traditional rehabilitation, users show greater enjoyment, higher decision freedom, lower physical demand and anxiety, and less pressure, whilst improving their physical performance [10]. Games should provide clear feedback, text, and audio instructions, so that the patient can be informed how to achieve goals [11]. Some more intrusive solutions have been implemented with these objectives in scope, such as virtual, mixed, and augmented reality (VR/MR/AR) systems, and have proven beneficial in upper and lower-limb motor function, balance and gait [12][13][14][15]. However, being highly intrusive systems means it may discourage the user even further, by causing discomfort and, in some cases, pain.

Unobtrusive systems such as Microsoft Kinect show promising results in incorporating the concepts of gamification and serious games to several rehabilitation and healthcare areas [16][17], from using hand gestures for elderly care [18] to post-stroke rehabilitation [19]. However, other non-hands-free similar devices, such as Nintendo Wii, showed several injuries related to overuse or incorrect use of handheld controller, amongst them, tendinopathy and hand lacerations [20].

SensFloor is equipped with gait recording, providing useful data for health status assessments in Neurology, Geriatrics and Rehab. As seen in Fig. 1., using the gait pattern, the health professional can evaluate the effect of physical training and medication, and detect patterns associated with several diseases (*e.g.*, Parkinson's). It is possible to measure speed, average number of steps, etc. and analyze the data, which can prove helpful in recognizing asymmetric and unstable gait patterns. The data is structured and saved for medical record. According to FutureShape, SensFloor is also suitable for rollators and other walking supports [21].

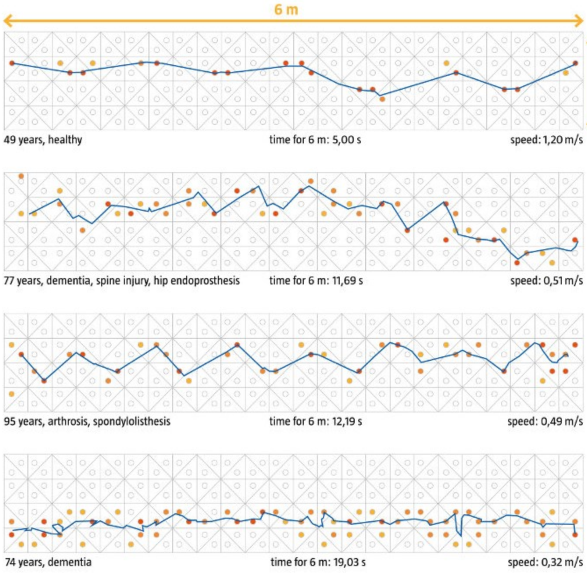

Fig. 1. Gait recording and analysis (taken from [21])

SYSTEM ARCHITECTURE

The system hereby presented is divided in following components: *(i)* the hardware, consisting of a sensing array and specific signal conditioning circuits, and a computation platform expressed by a Raspberry Pi, *(ii)* the developed healthcare professional web application and *(iii)* the developed patient mobile application.

Hardware Description

SensFloor®, by FutureShape, is a large area sensor floor, that can be installed beneath all kinds of flooring, making it invisible (Fig. 2). It is made of a 3 mm thick underlay with capacitive sensor arrays that can detect persons and conductive materials. This smart carpet makes use of a transceiver (SensFloor Transceiver SE10), which is an extension board for the Raspberry Pi embedded platform. This transceiver is used for the reception of wireless messages from SensFloor, and is plugged in directly into Raspberry Pi, as shown in Fig. 3. and Fig. 4. These received messages are sent wirelessly at 868 MHz using a proprietary protocol between SensFloor components, and include information about steps, presence detection, direction, velocity, counting users and persons lying on the floor.

Fig. 2. SensFloor, by FutureShape

Fig. 3. Raspberry Pi with SensFloor shield

Through the SensFloor API, information is available to be used in the individual application or to be forwarded to other systems. The embedded platform gathers this data, filters it, and may then store it in a cloud database, so that it is accessible by other systems, as shown in Fig. 4.

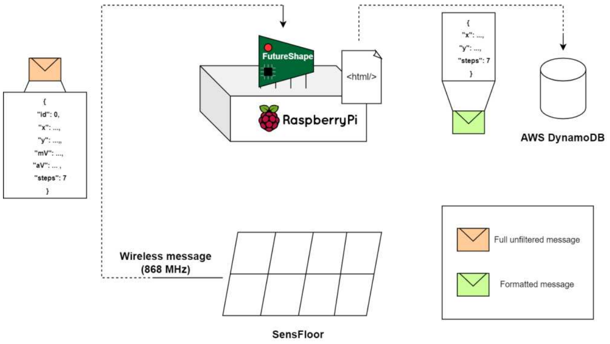

Fig. 4. Hardware diagram

Software Description

Hardware *(i)*, the web application *(ii)* and the mobile application *(iii)* require software and database components to perform the required functionalities that are described in Fig. 5. Thus, according to the figure, the interaction between different modules of the system is described.

(i) SensFloor is connected to a Raspberry Pi 3 microcontroller, via SensFloor Shield (as previously explained).

(ii) This microcontroller makes use of the SensFloor API to gather, filter and manipulate the data from this sensor. This API uses JavaScript, so a HTML file was created. In this file, the produced data is formatted and filtered according to what is more relevant, and is stored in a NoSQL, real-time cloud database, Amazon DynamoDB, so that it is available outside the microcontroller's environment.

(iii) The healthcare professionals' web application gets the data from DynamoDB and shows the corresponding users' (x,y) position in an interface grid (Fig. 6.), that is updated in real-time.

(iv) The values are stored in the implemented MySQL database, that is cloud-hosted with AWS RDS (Amazon Web Services Relational Database Service), so that the data is more structured and more easily to be accessed.

(v) The data stored in MySQL can be later accessed by dashboard-made software or APIs, such as JavaScript's Chart.js, so that intuitive charts are presented both to the healthcare professional and the patient.

(vi) If the patient is registered in the mobile application, data is also stored in a real-time, cloud database, and the user has access to it.

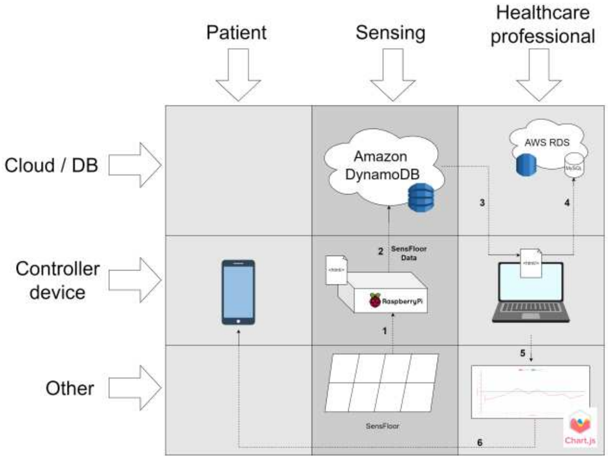

Fig. 5. SensFloor measurements system architecture

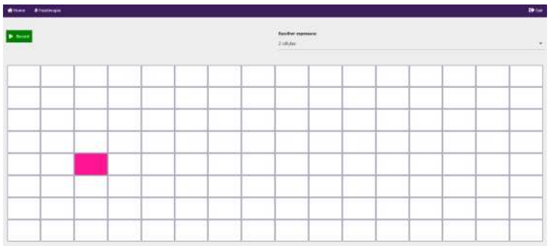

Fig. 6. SensFloor implemented web interface (pink cell corresponds to the user's current position)

Considering that one key issue with the implementation of eHealth systems is the ability to keep an organized medical history record of patients, by storing and transmitting this data to be displayed in real-time, this functionality was considered in this work and is presented in Fig. 7. Using Google's Firebase as a real-time database, with sole purpose to serve patients' and health professionals' data, the objectives can be accomplished, interconnecting both applications. Firebase is also a cloud-hosted, NoSQL database, which means that when a CRUD operation occurs (Create, Read, Update, Delete), all devices connected to the Firebase instance are updated in real-time – for example, when the healthcare professional prescribes a new exam, it is available in the patient's mobile application immediately. Patients' mobile application was developed using Google's Flutter. The chosen software technology represents a cross-platform for mobile application development with high level of connectivity to Firebase.

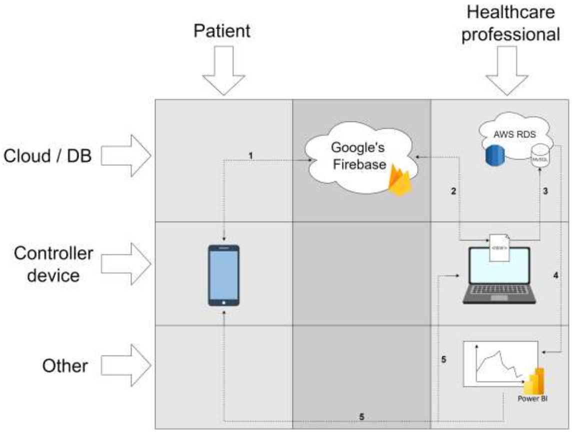

Fig. 7. Reading/writing data from/to Firebase

According to Fig. 7.:

(i) **[mobile app uploads data to Firebase]** The patient registers in the application, and their registration data is sent to Firebase's cloud database (Cloud Firestore). The user is able to update their profile data and save it in the database. An optional profile picture can also be uploaded by the user, and will be stored in the Firebase Storage. In addition, the patient can also register several personal physical measures, such as their weight, height, blood pressure and glucose level.

(ii) **[mobile app retrieves data from Firebase]** By sending their register and profile data to the cloud database, when the user accesses the app, it will automatically get the saved data (and optional profile picture from the Firebase Storage). If the user has any exams/medication prescribed by a healthcare professional, the files are loaded from the Firebase Storage and are shown in the mobile application; for this specific feature, a timeline-like interface was developed to ease the user's point of view.

(iii) **[web app uploads data to Firebase]** Similarly to the mobile application, healthcare professionals can register in the web application, and their registration data is saved to Cloud Firestore. Then, it is possible for professionals to upload exam/medication files to patients; these files are then saved in the Firebase Storage and are accessible in the patients' application almost immediately. It is worth pointing out that when a healthcare professional prescribes any file, their profile information is aggregated to it, so that the patient knows who prescribed it and when.

(iv) **[web app retrieves data from Firebase]** After loading, the web application retrieves a list of all registered users from Firebase, and offers the possibility to check what exams/medication each one has, keeping track of each patient medical history. Also, the measurements users send to the cloud database are also automatically acquired.

(v) After gathering data regarding users' physical measures, the acquired information is stored in the MySQL database, cloud-hosted with AWS RDS, so that it may be stored permanently and later accessed. After these measurements have been saved, they are deleted from Firebase, which, for this case, acts as a temporary database.

(vi) Microsoft Power BI acquires the data directly from the MySQL database and creates charts accordingly. The generated dashboards are published in a workspace accessible only to those granted access by the administrator.

(vii) Finally, the dashboards are embedded in the web application. It can also be accessed by the patient if he/she has been granted access to the workspace.

ASSESSMENT OF PHYSICAL REHABILITATION

Using the developed system, including hardware and software, it is possible to define several virtual paths with positions the user needs to follow, and coordinate intervals to evaluate if the user stays in the correct path. In this developed prototype, the virtual path and current user position is displayed in a TV screen for the user to visualize, although it would be desirable to display it directly on the floor (by means of lights or a LED projector placed above the user).

The application would then give feedback to the user about his/her deviations and evaluate the gait, calculating a final score. This process, shown in Fig. 8, is following described. Thus, the healthcare professionals access their web application and start the training, with the possibility to choose between several preset routes or a free exercise (that consists of evaluating the gait of the user without the need of a virtual path). It is possible to alter the difficulty of the path, by incrementing/decrementing its thickness (that is, the coordinate interval).

When the healthcare clinician ends the exercise, the application appraises the patient's gait, by comparing their coordinates with the virtual path, and calculates the corresponding deviations.

Finally, the application provides feedback to both the physical therapist and the patient, through the calculated general score. The feedback is provided through text and audio-based messages. It is also possible to generate a graph with the path the user has taken and compare with the correct/"perfect" path, as seen in Fig. 9.

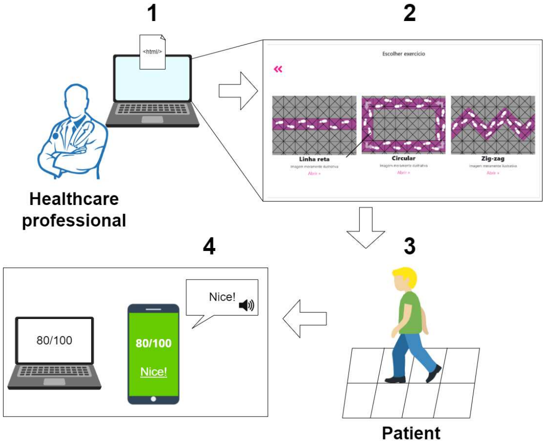

Fig. 8. The architecture of developed system applied to gait rehabilitation exercises

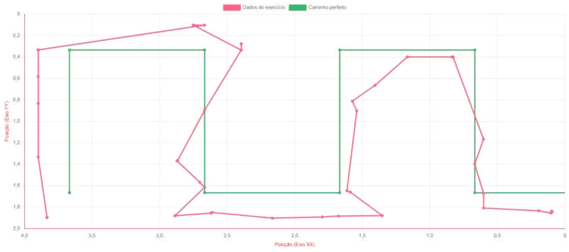

Fig. 9. User's path (pink) vs "theoretical (perfect)" path (green)

Fig. 10. shows concepts of different paths, with distinguished difficulties. When incrementing resolution, the web application offers more possibilities based on an extended number of cells for the user to step. By incrementing/decrementing the virtual path thickness, the healthcare professional is able to adapt the exercise according to the specific user. It is worth noting that, as stated previously, the values are then stored in a MySQL database and accessed by a dashboard-making software in order to create charts accordingly.

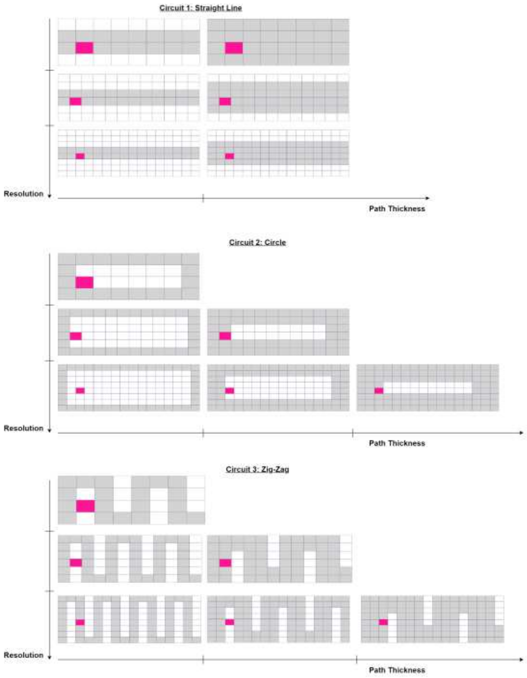

Fig. 10. Graphical representation of the virtual path concept applied for gait rehabilitation (pink cell corresponds to the user's current position)

It is possible to perform exercises and gather results and charts without the need for the user to create a mobile account, with the downside that the results are not stored. In addition, even if the healthcare professional chooses a free exercise, dashboards and results are still presented, as shown in Fig. 11.

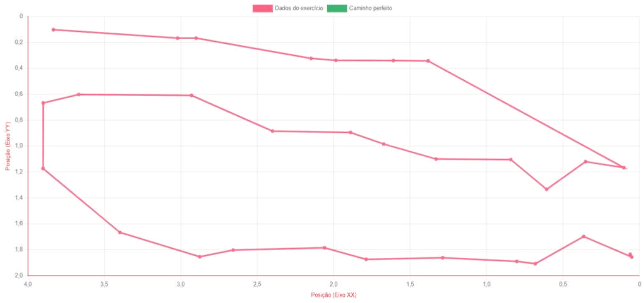

Fig. 11. Free exercise of gait rehabilitation (X and Y axis units in meters)

RESULTS AND DISCUSSIONS

By implementing the presented system, one question remains: how to score the patient achievements during the physical rehabilitation plan based on the proposed solution?

Thus, some metrics based on statistics can be very useful for patient evaluation, resulting in two different mathematical relations. The first metric consists in obtaining the total number of measurements during the time the user takes to complete the exercise (N), the number of measurements out of the virtual path's bounds (NO), the real SensFloor dimensions, in meters (in this case, MaxX = 4 and MaxY = 2) and the maximum X and Y deviations (MaxDevX and MaxDevY). It is also possible to calculate the average X and Y deviations, AvDevX and AvDevY, respectively, as follows:

$$AvDevX = \frac{\sum_{0}^{NO} devX}{N};\ AvDevY = \frac{\sum_{0}^{NO} devY}{N} \qquad (1)$$

in which ***dev(X/Y)*** represents the array with all deviations. By doing so, the final score formula is achieved, shown in (2).

$$score = \frac{N-NO}{N} * \frac{MaxX-MaxDevX}{MaxX} * \frac{MaxY-MaxDevY}{MaxY} * \frac{MaxX-AvDevX}{MaxX} * \frac{MaxY-AvDevY}{MaxY} * 100 \qquad (2)$$

In an ideal scenario, variables NO, MaxDevX, MaxDevY, AvDevX and AvDevY are equal to zero, corresponding to a perfect score (100%); however, in the worst-case scenario, if MaxDevX = MaxX, MaxDevY = MaxY, AvDevX = MaxX or AvDevY = MaxY, the score is automatically 0%. By analyzing the first term of the equation, if the user spends most of the time outside bounds, the score tends to be lower.

As to the second solution, it makes use of RMSE (Root Mean Square Error), as a way to measure differences between the correct values and the deviations. RSME is calculated as follows:

$$RMSE = \sqrt{\sum_{i=1}^{N} \frac{(y''_i - y_i)^2}{N}} \qquad (3)$$

The term $(y''_i - y_i)$ corresponds to the deviations calculated previously. This gives an estimation of how deviated the measurements are from the ideal. RMSE = 0 corresponds to a perfect scenario, where no deviations were made throughout the path. By testing the IoT system, the worst-case scenarios reached to a RMSE $\simeq 0.15$. These RMSE values can be converted to a percentage, as to generate the final score, using (4).

$$score = \frac{k}{RMSE+k} * 100 \qquad (4)$$

It is possible to conclude that if RMSE = 0, score = 100%, thus for a bigger the RMSE value, the score is lower. By incrementing/decrementing the parameter k, the score is less/more sensible to the RMSE value, respectively. By testing the system, an optimized value for this constant is k = 0.6, corresponding to the graph shown in Fig. 11. Using this formula, however, it is not possible to obtain a score = 0% since (4) does not have zero as a possible solution. By analyzing Fig. 11, it is also possible to see that the function never reaches zero in the x axis.

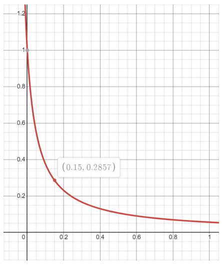

Fig. 11. Score, using (4) with k = 0.6

To appraise which score relation performs better, *i.e.*, leads to higher scores, several tests were made using both. The tests included simulating the perfect paths, walking the virtual paths with few deviations, and walking in the worst-case scenarios, for each type of preset routes, resolution, and path thickness. Fig. 12. shows different types of deviations used to test the developed system.

The proposed metrics were tested by numerical simulation. Thus, when simulating perfect paths, both (2) and (4) led to a score of 100%.

When simulating minor deviations, things get a bit different. Equation (2) led to overall higher scores, whereas using (4), scores tend to be (non-significantly) lower, with a maximum difference of 10% score between both relations.

However, while simulating worst-case scenarios for all types of paths, both relations tend to perform differently. In general, regardless of the score used relation, and chosen path type, for higher path thicknesses, final scores are not very low. For instance, for a straight line exercise, with maximum path thickness, the lowest simulated score was 36% for the used relation (2), and 59% for the used relation (4).

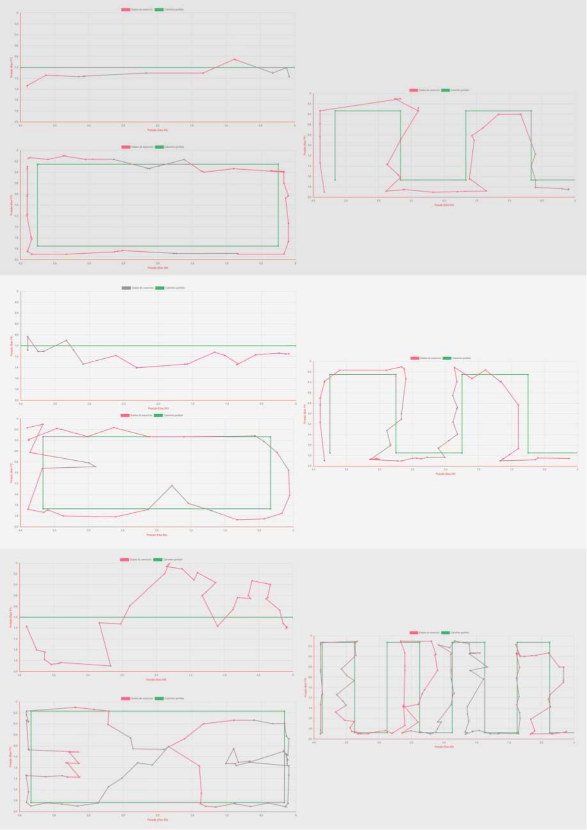

Fig. 12. Theoretical paths (upper), paths with minor deviations (middle) and paths with major deviations (bottom) – user's path in pink, "theoretical (perfect)" path in green) (x,y axis in meters)

That said, in these worst-case scenarios, using (4), the scores are, in general, significantly higher than using (2). For instance, by choosing one of the hardest exercises, the circle path with maximum cell resolution and lowest path thickness, the lowest obtained score was 15% using (4) and 4% using (2). Simulated tests also concluded that if the user spends more time (*i.e.*, has a higher number of measurements) outside bounds, the score tends to be lower, regardless of the formula used, as both consider the total number of measurements and the total number of deviations.

It is possible to conclude that (2) performs slightly better for paths with little deviations, while (4) performs better when users tend to deviate more times outside bounds.

The proposed system was tested by some healthy, young adult volunteers, and when simulating all combinations of virtual path types, cell resolution and path thickness (shown in Fig. 10.), in certain combinations it is nearly impossible to achieve a perfect score; this happens only for the circle and zig-zag virtual paths. Figures Fig. 13. and Fig.14. show these scenarios, in which users walk correctly (or with little deviations), but score poorly, regardless of which score relation used.

Fig. 13. Circle path training with maximum cell resolution and lowest path thickness – using (2), (57% achieved score)

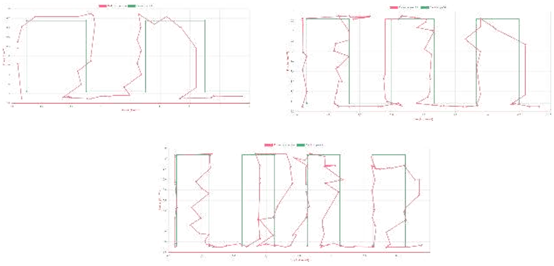

Fig. 14. Zig-zag paths training with different cell resolutions and lowest path thickness – using (2), (achieved scores: 18%, 14% and 9%)

CONCLUSION AND FUTURE WORK

The proposed system is characterized by good performances providing useful information to the physiotherapists users' gait based on VR scenario associated with SensFloor user interface. The obtained results show limitations related to the proposed scores for certain combinations of virtual path types, cell resolution and path thickness. However, these combinations may be useful in more specific physiotherapy contexts, where score may not be so important comparing with the route itself.

The developed system uses the (x,y) coordinates measured by the sensor and maps them into the adaptable interface. However, it is useful to keep other SensFloor variables in consideration; for instance, fall alerts and presence detection are also possible, and when implementing more complex AI algorithms, it should also be possible to predict physical rehabilitation outcome as so as the level of disabilities for a particular patient.

The described system is under test in a real-life physiotherapy environment. This method is a completely non-intrusive alternative to traditional physical rehabilitation techniques, as it allows the patient to walk around normally on a regular surface that materialize the interface between the real and virtual scenario.

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