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Monitoring and instrumentation system of acycloergometer for the rehabilitation of patients

TESIS

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Abstract

Nowadays, fuzzy-logic systems are implemented to control machinery or processes that previously required human manipulation. The main objective of this research is to propose a controller based on fuzzy-logic that uses bio-signals for decision making. The study presents the implementation of a fuzzy-speed controller for a therapeutic machine called cycloergometer. It is used in patients who require rehabilitation therapy to improve their mobility in the lower body or to increase their relaxation or flexibility; the cycloergometer, together with the controller, is intended to be beneficial for the rehabilitation of patients. In this project, not only a fuzzy controller is developed, but also the controller membership functions are adapted to the patient using the cycloergometer. A user interface is implemented where it is possible to decide whether to work in a manual mode where the person directly manipulates the speed of the cycloergometer, or an automatic mode where it is necessary to enter the patient's health data: weight, age, height, if he has hypertension and, or diabetes; these parameters are those that adjust and determine the membership functions and in turn the controller itself. When is in automatic mode, the speed of the therapy equipment is adjusted using the heart rate of the patient. In this way, a bio-signal is used to determine whether a person is tired or relaxed. Therefore, a mechanism is obtained that is not subject to the visual criteria of the therapist. A detailed review of the literature illustrates that one of the main limitations of electroencephalography and electromyography recordings is the low signal-to-noise ratio and the fact that the signals captured at the electrodes are a mixture of sources that cannot be observed directly with non-invasive methods. Therefore, it was decided to work with electrocardiogram-based signals for better robustness of the proposed system. The controller output is a voltage signal in PWM, which is determined by the membership and error functions. The behavior of the implemented controller is validated by different experimental tests that were done with simulated tests and with patients. Finally, to determine if the project can be helpful for rehabilitation, a Likert survey was proposed for the patients to measure how viable the project is for their rehabilitation.

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CHAPTER 1

Introduction

Cycloergometer as the one is shown in figure 1.1a and 1.1b is used in non-invasive tests that allows studying the response of the heart to physical exercise. There are numerous diseases that directly affect the heart, which impact the mobility and quality of life of patients. Certain studies highlight the increase in the number of people who have some type of cardiovascular disease and its notable influence on the normal social performance of the patient [11, 12, 13]. The majority of affected people require cardiovascular exercise as part of the treatment, which is achieved through controlled physical activity. The therapies are carried out in the different health centers under the supervision of physiotherapists. During these rehabilitation therapies, heart rate measurement is essential, as it provides information on the condition of the patient.

(a) (b)

Figure 1.1: Device: (a) Cycloergomter (b) Cycloergomter in use.

Nowadays, most therapies are led by an expert in the field. However, in many cases, systems are needed to accurately determine the condition of the patient and indicate the action to be taken. Possible states such as “very tired”, “relaxed” and “regularly rested” belong to human language only and cannot be translated using a binary “machine” language to measure heart rate and determine fatigue. A tool that interprets human language is necessary to translate the aforementioned linguistic variables to control the intensity of movement [14].

Unlike traditional algorithm models as PID, fuzzy control is capable of modeling and controlling processes whose model is imprecise or non-linear [15]. There are studies that present a comparison of the use of controllers based on fuzzy logic and classical control techniques [16]. The main results describe that fuzzy logic controllers perform better in relation to classical control. The non-linear characteristics of these controllers provide great adaptability to plant non-linearities, which implies good performance throughout the operating range [17]. This characteristic becomes even more noticeable in plants with more pronounced non-linearities. This is not noticeable in classic controllers due to their linear behavior [18, 19].

Since heart rate is normally measured every second, it can be considered slow compared to other environmental variables that are measured in ranges less than or equal to milliseconds. Therefore, between measurements there may be relevant variations that are not linear, and although different PID controllers for heart rate feedback have already been proposed as [20] it is believed that a fuzzy algorithm strategy works to adapt to unpredictable human behavior [21]. Thus, a fuzzy controller is proposed that is able to adapt to the heart rate of the patient as if this regulator were a second expert helping the patient.

Fuzzy-logic works with real-world variables called linguistic variables or called Crispi values Reddy2019. Each variable has a degree of membership in one or more terms, also known as fuzzy sets and defined in the range from 0 to 1. Non-membership is denoted by 0 and 1 that belongs entirely to the set. This process of going from real data to a fuzzy one is called fuzzification Wu2019. After obtaining the membership values for each fuzzy set, the values are assigned to a rule that will generate fuzzy terms based on two or more given membership values. Finally, these terms are passed to a defuzzification module, which passes the fuzzy data output to Crispi values Wang2019.

For the first part of this research, a fuzzy algorithm has been defined based on a reference and measured heart rate. Depending on the error and the reference is how the rules will be defined, to finally make defuzification and obtain an output voltage to translate it to a PWM signal. Then, take that signal to the cycloergometer *On-Motion*, while the heart rate is being measured every second by means of an oximeter which by means of Bluetooth 4.2 sends data to a *WIFI-BLE esp82* module and this one by means of the SPI protocol sends the data to the *stm32f303re* microcontroller card, which takes care of the processing and control of the process.

For the final part of this research, have been proposed a way to automate the membership functions of each patient based on parameters that indicate their current health status; also, with the help of the MIT app inventor, it has been implemented an app where the user of the application can enter these health parameters, which will be transmitted from the cell phone to a Bluetooth receiver HC-05 and forwarded by USART to the microcontroller, where the information will be processed.

1.1 Motivation

As already mentioned, a physiotherapist always has to be aware of the patient's cardiac signs to determine whether to apply any change in the cycloergometer speed. What the expert is doing is a classification of the cardiac rhythm and thus makes a control decision; therfore, the following questions arise:

- Is it possible to determine the patient's fatigue and how?
- Is it possible to automate the process of the actions to be performed?

There is no broad disclosure about cycloergometer automation or therapeutic devices. Therefore, this invention will be a great addition to the world of bio-medicine, therapy, and exercise.

1.2 Objectives

The general objective and the specific objectives of this project are as follows:

1.2.1 General objective

To propose and develop a control system for a cycloergometermotor, which works based on the measurement of biosignals from a patient.

1.2.2 Specific Objectives

- Acquire a bio-signal from a person.
- Study the different cardiac rhythms that a person can have.
- Design a methodology to propose a control.
- Proposing a way to automate membership functions.
- Implement an interface to acquire constant health parameters from the user.

1.3 Hypothesis

From the instrumentation and automation of a bio-signal feedback cycloergometer, it is possible to meet the physiotherapeutic needs of patients requiring lower body treatment.

1.4 Thesis Structure

The thesis is organized as follows:

- Chapter 2 it is a compilation of previous research related to the field of intelligent signal acquisition and control.
- Chapter 3 the theory used for this research is described in detail.
- Chapter 4 presents the proposed methodology and the obtained results.
- Chapter 5 presents the conclusions and future works raised from this research.

CHAPTER 2

State of the art

This chapter presents works related to this research project; it has been divided in two subsections, Expert Systems field, and Bio-signals field; the first one is focused on those works where the main focus is the development of fuzzy systems, the second one is the one where the primary source of work was the bio-signals processing. At the end of this chapter, there are the tables 2.1 and 2.2 where the previously explained works are summarized in one sentence.

2.1 Fuzzy Systems field

The author [22] begins by talking about data uncertainty, for the author fuzzy logic can be of great help in handling these uncertainties, especially those of the type associated with human cognitive processes. In his work, he uses this advantage of fuzzy logic to develop a fuzzy logic-based reasoning system applied to a medical diagnostic problem. Specifically, the author focuses on heart-related diseases. To determine diseases he uses the following linguistic variables:

1. Chest pain: This variable has numerical values: 1 = typical angina, 2 = atypical angina, 3 = non-anginal pain and 4 = asymptomatic.
2. Blood pressure: This variable has 4 values: Low, Medium, High and Very High, defined as fuzzy sets.
3. Cholesterol: Defined by four fuzzy sets, Low, Medium, High and very High.
4. Blood sugar (diabetes): Although it has only one linguistic variable called "true" it is divided into two fuzzy sets as it measures whether your blood sugar levels are too high or too low.
5. Resting electrocardiography (ECG): This variable has 3 linguistic values: Normal, ST-T Abnormal, Hypertrophy.
6. Thalium scan:This variable does not have fuzzy sets but rather has 3 numerical values; that are 3, 6 and 7 named Normal, Fixed Defect and Reversible Defect, respectively.
7. Sex: It has two numerical values, 0 = male and 1 = female.
8. Age: This input fields has 4 linguistic values: Young, Mild, Old and Very Old,

9. Maximum heart rate: It represents the heart rate that a person had in 24 hours, it is divided into 3 fuzzy sets: Low, Medium and High.

10. Exercise: has 2 values: if doctor determines exercise test for patient, value is 1 and, otherwise, value is 0.

The author uses only one output variable that refers to presence of heart disease in the patient. This variable takes a value between 0 and 4; in this range he inserts 5 fuzzy sets called: Healthy, Sick1, Sick2, Sick3 and Sick4; the further away from Healthy the patient is, the sicker he will be and since these fuzzy sets are of the triangular type, his heart disease could belong to either one type or the other. Finally, the author uses a basic scheme of fuzzy logic of the Mamdani type, and by combining the different inputs, he can classify the four types of diseases. The number of input variables used plus the uncertainty of each of these leads him to use fuzzy logic to carry out his research with satisfactory results [22].

Using a wearable heart rate sensor and fuzzy logic, [23] propose a customized fuzzy logic-based method for classifying perceived exertion in workplaces. He basis that there are currently different methods and systems involved in measuring the health of people working in a given place; however, although portable heart rate sensors represent an effective way of capturing perceived exertion, ergonomic methods are generic and do not take into account the diffuse nature of the ranges that classify exertion.

Thanks to this classification, the worker benefits directly. Thanks to verifying his physical effort, he will be assigned a job appropriate to his health condition and abilities, designing an ideal position, promoting occupational accidents and disease prevention, among others. He classifies what he calls the relative cardiac cost (RCC) as follows.

1. Intense: 60-69 RCC.
2. Heavy: 50-59 RCC.
3. Slightly heavy: 40-49 RCC.
4. Moderate: 30-39 RCC.
5. Slightly moderate: 20-29 RCC.
6. Light: 10-19 RCC.
7. Very Light: 0-9 RCC.

It also divides a person's experience in a specific job as follows:

1. Not habituated: 0-0.4
2. Moderately habituated: 0.2-0.8
3. Habituated: 0.6-1

Thanks to this combination of variables, it is possible to measure a person's effort based on their heart rate and work expertise. The author [23] concludes that using a wearable device with capacities of measurement of physiological parameters and fuzzy logic computational methods provokes expert knowledge that represents a viable automatic solution for perceived exertion induces.

The research work of [24] was developed thinking that the human body and health are uncertain environments and processes, so they decided to use fuzzy logic to adapt to these uncertainties. Its objective was to make health recommendations based on fuzzy sets of different health indicators such as blood pressure, cholesterol classification, blood glucose level, etc. For [24], Fuzzy Theory, comes into play to determine values between 0 and 100, where there were intermediate values that benefited the description of a particular process, being much more flexible than a binary system. Some of the fuzzy rules used by the author are the following:

1. IF systolic blood pressure is less than 120 AND diastolic is less than 80 THEN bloodpressure is mostly normal.

2. IF systolic blood pressure is 120-129 AND diastolic is less than 80 THEN blood pressure iselevated.

3. IF systolic blood pressure is 130-139 AND diastolic is 80-89 THEN blood pressure isindicative of moderate hypertension.

The author [24] concludes by mentioning that implementing technology in this process would greatly benefit the health sector by streamlining the diagnostic process through a mobile application containing this fuzzy logic and in turn, making a recommendation to fully adopt fuzzy diagnostic programs, as both their accuracy and the added benefits to the sector would increase dramatically.

The research of [25] begins by talking about the paradigm of the Internet of Things (IoT), which is defined as the application of various technological devices located around the world to acquire, manage and analyze information, to provide intelligent services.Several of these devices transmit information that can be interpreted in natural language, so the implementation of fuzzy logic may be suitable for this type of information. The same author mentions that thanks to the above factors, the use of digital platforms and the implementation of fuzzy logic have managed and obtained excellent results in different sectors.

In the same research of [25] focused on the presence of cardiovascular diseases. In this study, a heart rate sensor device was applied on the wrist of the research subjects, however, different limitations such as lack of time, limited area and access to health services were present. The interaction of the researchers and the results was through a mobile cloud platform, using a linguistic approach. The biggest challenge was the collection of large amounts of information from the data obtained through the device. To solve this challenge, their work presented a methodology that generates textual information, summarized from the heart rate flows of patients with ischemic heart disease by means of protoforms and fuzzy logic.

The methodology of [25] is based on three important points:

1. “To allow the cardiac rehabilitation team to supervise a huge number of sessions and patients by means of linguistic summaries, which integrate an intuitive representation” [25].

2. “To model a proposed methodology where the linguistic summaries are focused on rich expressiveness, including linguistic temporal terms and linguistic quantifers by means of linguistic aggregation operators” [25].

3. “ To provide a flexible linguistic methodology where the cardiac rehabilitation team intuitively defnes the key interest indicators using protoforms based on expert knowledge in order to recover and dynamically select the rehabilitation sessions that suit and match the expert criteria” [25].

Thanks to these implementation processes of [25], a greater scope of verification of symptomatology in various patients is achieved, resulting in the following: Providing the cardiology rehabilitation team with linguistic summaries of the rehabilitation sessions based on the heart rate streams of patients.

The research made by [26] mentions that light therapy with light-emitting diodes (LED) has been used in different processes of aesthetic medical interventions. According to his study, this method has taken great relevance due to its great benefits and an accessible cost to the general public, so it is essential to know its inner workings.

The operation that brings with this therapy is through the wavelength and power density. The problem that arises is the variation of the LED power density proportional to the use of the device's battery. To cope with this problem the author [26] proposes a fuzzy logic that controls the LED power density and operating time to develop an efficient design based on LED light therapy in different colors to cope with this problem.

The author [26] controls the power density of each LED color (red, green, and blue) by varying a PWM signal. Since the power density of each color varies with time, the author takes as input this same time and power density, thus having four linguistic variables: the power density of red, green, and blue and the operating time of each color.

The proposal and design of the LED light therapy device in [26] verify the importance of power density in phototherapy, being necessary the stabilization of the LED power intensity. It should be considered that both the relationship between the LED power density and its operating time belong to an imprecise language. Hence, this research shows that the design of a fuzzy controller effectively provides a constant LED power density under the variation of the battery during recharging.

To provide a more accurate diagnosis, the work of [27] focuses mainly on the design of type 1 and 2 fuzzy systems to find the best heart rate classification; this is achieved by optimizing the membership function. To achieve this optimization, the Bird Swarm algorithm was used, which, as explained in the article, was designed to solve optimization problems by mimicking the behavior of birds in a swarm.

In [27] they first designed two type-1 fuzzy systems for heart rate classification, one with Gaussian functions and the other with trapezoidal functions, to observe which of the two offered a better classification. The design is based mainly on the experience of a cardiologist. In this type 1 design, its inputs are age and heart rate trend. At the end of the regular tests to observe the classification, the Bird Swarm Algorithm was introduced to optimize this classification.

Once the tests on the type-1 systems were completed, the design of a type-2 system was continued. [27] argument for the type-2 design is that this type of fuzzy system can be used to handle higher levels of uncertainty, which in theory is effective since, in certain patients, the information can be imprecise.

In [27] Experiments were conducted with 30 people using the Bird Swarms Algorithm, with type-1 and type-2; some algorithm parameters were varied and compared with another optimization algorithm; however, the Bird Swarms Algorithm had 86% better performance.

Unfortunately, cardiovascular disease (CVD) is a leading cause of death among diabetes and those who smoke. The paper of [28] intends to explain the impact and relationship between diabetes, smoking, high blood pressure (BP), high heart rate, and CVD risk.

According to [28], their work stems from the following concern: "data from the National Heart Association (2012) showed that 65% of people with diabetes die from some form of heart disease or stroke".

The work of [28] proposes a fuzzy logic prediction system to assess the risk of CVD among people suffering from diabetes and smoking. As inputs, it takes the following variables: whether the person smokes, whether they have diabetes, their age, blood pressure, heart rate, electro rest, chest pain, and angina exercise. For the development of its work, the car followed the following steps:

1. Data preprocessing.
2. Definition of linguistic variables and their operating ranges.
3. Construction of the membership functions.
4. Conversion of crispy data to fuzzy values.
5. Definition of fuzzy rules.
6. Conversion of fuzzy values to real output values.

The algorithm proposed by [28] makes it easier for experts to predict cardiovascular disease based on the patient's current lifestyle. The results of their experiments prove to be a starting point for future training of expert systems focused on disease prediction.

2.2 Bio-signals field

Stress is considered a global health problem, affecting a large part of the population. If this problem is not treated in time, it will lead to behavioral problems (anxiety, depression, among others) and health problems (cardiovascular, digestive, dermatological, etc.). Therefore, [29] proposes a work using Artificial Intelligence Assisted Petri Nets (AI-FAS) for stress assessment in heart rate and blood preassure monitoring. For this purpose, the study uses the recognition and processing of electrocardiograms (ECG), which is a problem since this type of signal carries with it a lot of noise that mixes with the subject's physiological signals.

The research conducted by [29] mentioned that the primary physiological signal that occurs when an individual has stressed is through heart rate and blood pressure, so the author review and propose the following:

- The artificial intelligence-based fuzzy assisted Petri net (AIFAS) method is used for stress assessment on HR and BP monitoring.
- Blood pressure measurement for stress management.
- Heart rate monitoring for stress management.
- A R-wave estimation model.
- Decreasing of the entropy concept.
- Petri Net evaluation.
- Pulse wave velocity—BP relationship design.

This research delves deeper and gives information about stress, as well as the long-term consequences. Many people ignore this data provided by their body and let the disease progress. [29] through AI-FAS is achieved by monitoring HR and BP for mental stress assessment. BP monitoring for stress management is achieved by transient timing of each pulse. Fuzzy-assisted Petri nets are used in stress assessment for heart rate.

The work of [30] describes the management of robots or prosthetic devices using thought through electrodes, electroencephalograms in a brain activity order. The implementation of this technology has been limited to simple tasks.

According to the work of [30], combining these three elements is sufficient to control a robot: non-invasive recording of brain activity, asynchronous analysis of the electroencephalogram (EEG), and machine learning techniques. With this combination, they have been able to make two subjects move a robot between several rooms, using an EEG-based brain-machine interface that recognized three mental states.

The author of [30] points out that EEG signals are convenient to use on subjects, however their resolution and the fact that they suffer from a large amount of noise, make them signals that are difficult to manipulate or observe.

In this work [30] to conduct their research, they use an asynchronous protocol and analyze the ongoing EEG activity to determine the mental state of the subjects. Usually, the bit rate in brain-machine interfaces is 0.5 b/s; however, it almost doubles the usual bit rate with this approach.

According to the results of [30] by mapping high-level mental commands in a finite and limited environment, they can open the possibility for the physically disabled to use a portable EEG-based brain-machine interface to control wheelchairs and prostheses.

In the research done by [31] it can be seen that technology has intervened in various aspects of human life so that most of the processes that are carried out have a technological potential that intervenes in the participation of different parts of these individuals.

Several computer devices read bioelectrical signals such as electrocardiographic, skin biopotential, facial or muscle tension, which are read and translated into computers. In their work of [31], they have investigated how to use a low-cost device to achieve control of a domestic robot with the biosignals of a person.

The authors of [31] use the concept of brain-machine interface (BMI) and explain that it involves one-way or two-way communication between a human brain and an external computing device. They used a basic BMI to control an iRobot® Roomba vacuum cleaner; the interface used was the OCZ NIA neural pulse actuator.

With these instruments, [31] proposes two methods for robot control, one direct and one indirect. The direct one is the one where the user modifies his bio-signals to decide the robot's actions; the indirect one is the one where the robot acts depending on the subject's emotional state.

In the direct method, [31] maps the muscle tension detected by the BMI to the speed of the robot motor. To achieve the mapping, they converted the bioelectrical signal into four discrete values, in addition to various filtering and other signal processing.

In the indirect method, [31] infers the emotional state from the subject's muscle tension. Its control software reinterprets the natural muscle tension to estimate the stress level: the more muscle tension, the more stress is inferred. The authors divide stress into four levels, depending on how the robot performs one action or another. For example, when a person shows high stress (levels 3 and 4), the robot goes into cleaning mode but moves away from the user not to disturb him. When a person is relaxed (level 1), the robot (if cleaning) approaches the person and then stops, simulating a pet sitting next to its owner.

Based on the results of [31], they conclude: “mapping emotional state of a user to the emotional state of a robot is not only possible with today’s technology but that it opens up many exciting possibilities that have yet to be explored entirely”.

In [21] they remind us that different types of pathologies intervene in the process of daily activities and some more complex activities of people who suffer from it, so scientists and engineers have been given the task of conducting experimental research on the implementation of cooperative robots, to intervene in these processes and raise the quality of life of people who have it.

Therefore, a novel rehabilitation method for patients with upper limb disability is presented in [21], where utilizing physiological signals feedback. This allows the robot to regulate the amount of assistance or resistance in each therapy, which means that the robot can adapt to the needs of each patient.

The robot used in the [21] investigation was a Stäubli RX90 of 6 degrees of freedom equipped with a JR3 force/torque sensor, this model is an anti-spastic hand-arm orthosis. The sensor is responsible for sending force interaction information between the robot and the patient.

In [21] the Biopac MP 150 system is in charge of measuring the different patient signals. As in other research of this type, filters, a series of amplifiers, and other complex signal processing techniques are used to achieve a reliable reading of every kind of signal. The signals that they manage to obtain in this research and with which they work are Electrocardiogram (ECG), from which the heart rate (HR), galvanic skin response (GSR), and skin temperature (SKT).

To achieve effective control, [21] indicates that an effective manipulation strategy that blends position and force control should be sought. His robot implemented two methods: “hybrid force-position control” and “biocooperative control”.

The proposed hybrid force-position control in [21] is based on the mixture of impedance control, which is often used to control robots that have human interaction, and the “minimum jerk” strategy that provides friendly movements during rehabilitation sessions.

On the other hand, the bio-cooperative control strategy in [21] is based on the integration of the patient’s physiological measurements into the control loop as a feedback signal of the patient’s overall process. Its strategy achieves a smooth increase in the sympathetic force if it detects that the patient needs help. On the other hand, if it is seen that the patient is carrying the task very easily, the control strategy reacts oppositely, the assistive force will decrease, forcing the patient to exert more force.

As seen in [21], complex control must be performed in order to adapt to the non-linearity of the patient’s bio-signals. This is one of the reasons why [21] does not recommend classical control strategies such as PID. They conclude that thanks to their control strategies, there is a significant improvement in the user experience. These improvements are reflected in the psychophysiological responses obtained from the participants of their experiments.

In [32] they question the possibility of controlling a piece of sports equipment, in this case, a treadmill, solely based on the subject’s heart rate. In this work, it is constantly reminded that the heart rate of a person is not linear. Therefore the authors decide to create a novel Hammerstein control with an integrated approach for identifying the system.

In [32] Support vector regression is adopted to obtain sparse representations of the static nonlinearity inversion to obtain an approximate linear model of the Hammerstein system. This model is designed to achieve robust performance and tracking by focusing this method through a computer-controlled treadmill, regulating the heart rate during exercise employed during the treadmill, minimizing heart rate deviations from a preset profile.

As mentioned in the work of [32] commercial treadmills already have a control that regulates their internal speed based on heart rate, however these controls are too basic. Basic controls such as PID are used in factories due to their simplicity, however as the authors of the paper demonstrate, PID is not advisable to use it in nonlinear systems such as heart rate regulation.

The approach for the development of the control in [32] is divided into two parts: the identification of the Hammerstein model and the robust control based on the model. For the identification part, they used the Least Square Support Vector Machine (LS-SVM) method; the main task of this part is to identify the physiological processes of the subject using the running machine. Finally, a $H\infty$ robust control is developed for the second part to achieve robust tracking performance.

The results of [32] show that robust control can follow the heart rate of a person, remain stable, and adapt to abrupt changes, on the other hand in the results with PID control implemented to show that this control is not able to adapt to changes in heart rate, in addition to having irregular control peaks.

In the same paper by [32] they conclude: "We believe that the ability to track a predetermined heart rate profile may be useful in cardiac rehabilitation programs or for safer exercise for individuals at risk".

According to [33], the measurement of the intensity of the exercise can be raised by measuring the heart rate; this process will help us in the early intervention of any anomaly or decrease the intensity of exercise. This process is very useful in high-performance athletes or people suffering from obesity or cardiovascular problems, greatly benefiting each person's health situation in this process.

The main objective of [33] is to show how previous controls proposed for regulating heart rate on treadmills can be used on cyclo-ergometers. Their experiments demonstrate the effectiveness of robust controls versus the efficacy of classical proportional-integral controls.

In [33] they mention that heart rate can be effectively used as a measure of exercise intensity; in their work, they assume that HR is dynamic, so their experiments are based on controls that adapt to the nonlinearity of HR. They show that a nonlinear, nonlocal, non-switched control can be adapted to a cyclo-ergometer; however due to different workloads, there may be slight spikes of irregularity in the speed of the equipment.

Thanks to the work of [33], one can only begin to visualize the classical interpretation of trainer behavior that adjusts exercise intensity based on the corresponding responses it represents in the individual by integrating more novel processes that require a technological exchange.

In this chapter, have seen how fuzzy control is beneficial for classification when its variables are imprecise, nonlinear, or are better described in a "human" language; we have also seen how bio-signals are used for the control of different systems; however, these bio-signals need complex processing, which can translate into time and money. This research work implements a fuzzy controller to manipulate the speed of a motor based on the patient's heart rate obtained from an oximeter. This is a difference and an addition to previous works since in previous works, fuzzy logic had been used more for classification than for control; in this work, an indirect classification is performed, and action is executed based on that classification.

Table 2.1: Research related to the field of expert systems.

Reference	Contribution to the field of study
[22] (Iancu, 2018)	An expert system based on this type of fuzzy-logic is designed in order to diagnose possible heart disease in a patient.
[23] (Pancardo et al., 2018)	A personalized method based on heart rate is proposed to assess perceived exertion.
[24] (Sallam and Hashmi, 2019)	Fuzzy categories were determined for a variety of health indicators, like cholesterol, blood sugar, blood pressure, and resting heart rate.
[25] (Pel aez-Aguilera et al., 2019)	A methodology is presented to assess the heart rate flows of patients with ischemic heart disease using a linguistic approach.
[26] (Phan et al., 2020)	Fuzzy control is presented to control the power density emerging from LED lights.
[27] (Miramontes et al., 2018)	The optimal designs of type-1 and interval type-2 fuzzy systems for the classification of the heart rate level are presented.
[28] (Saxena and Banodha, 2019)	A fuzzy-logic-based prediction system to evaluate the Cardio vascular disease (CVD) risk among the people having diabetes with smoking habits is presented.

Table 2.2: Table 2. Research related to the biosignal field.

Reference	Contribution to the field of study
[29] (Lin et al., 2020)	The research proposes a fuzzy assisted Petri net method based on Artificial Intelligence (AI-FAS) for the evaluation of stress in the monitoring of HR and BP.
[30] (del R. Millan et al., 2004)	The manipulation of a robot is achieved through a Brain-Machine Interface (BMI).
[31] (Saulnier et al., 2009)	Determine the user's stress level and thereby determine whether the robot approaches or moves away from the use
[21] (Rodrıguez-Guerrero et al., 2011)	It consisted of force adjustment of an assistive robot for upper limb rehabilitation tasks by acquiring and processing the subject's heart rate and hand strength.
[32] (Su et al., 2006)	Development of an $H\infty$ control for the manipulation of a treadmill according to the patient's heart rate.
[33] (Paradiso et al., 2013)	Adaptation of treadmill controls to cycloergometers.

CHAPTER 3

Theoretical foundation

3.1 Control systems

A control system is a set of devices responsible for managing, ordering, directing or regulating the behavior of another system, in order to obtain a desired output or reduce the possibility of failure [2].

In Figure 3.1 the two common types of control system are observed, those that have no feedback called open-loop systems, and those that do have feedback called closed-loop systems.

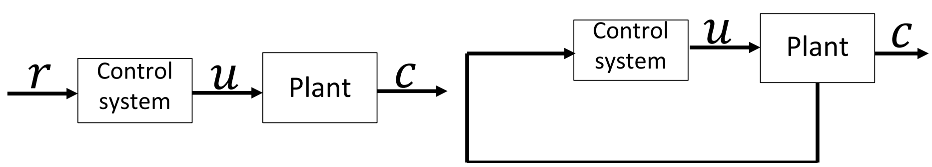


Figure 3.1: Open-loop and closed-loop control system [1].

Where:
r: input reference.
u: control system output.
c: plant output.

3.1.1 Controllers

As shown in the figure 3.2 there is a reference signal which is the desired signal or commonly referred to as reference signal, which is compared against the output of an observer or sensor. At the output of the comparator is an error signal, which in turn is the input of the system or plant controller, an observer monitors the behavior of the plant, and the value of the behavior is again compared with the reference signal. What is sought with closed-loop controllers is that the error signal is zero or very close to zero [2] and [3]. There are several control techniques, however, the common ones are: proportional control (P), derivative control (PD), integral control (PI) and derivative integral control (PID) [1].

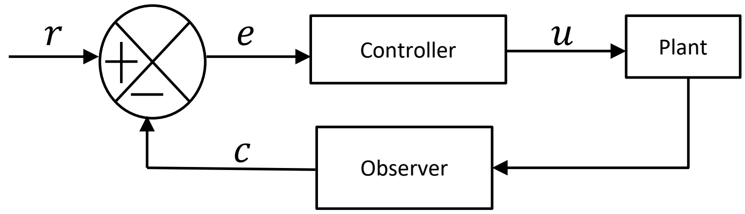


Figure 3.2: Parts of a closed-loop control system [2] y [3]

Where:
R: Desired or reference signal.
E: Error signal.
U: Input signal to the plant. C: Plant output signal.

3.1.2 PID Controller

A PID (proportional, integral, derivative) controller, such as the one in the figure 3.3 is a common technique used to control a wide variety of machinery, including vehicles, robots, and even rockets. This controller has all the advantages of the previous controllers, so it increases the system's stability in the integral and derivative parts and quickly increases the system's response. Its main disadvantage is that it can output an infinite signal with small oscillatory values, which causes the system lifetime to be reduced. [1].

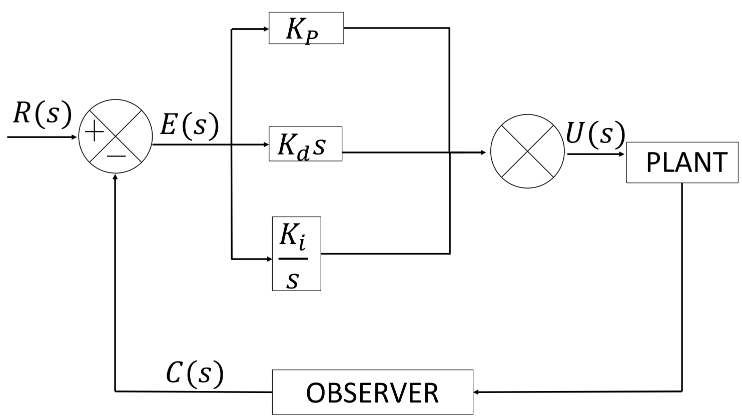


Figure 3.3: PID controller [1]

Where:
$R(s)$: Desired or reference signal in Laplace's domain.
$E(s)$: Error signal in the Laplace domain.
$U(s)$: Input signal to the plant in the Laplace domain. $C(s)$: Plant output signal in Laplace domain.
K_p: Gain of the proportional controller.
K_d: Derivative controller gain.
K_i: Integral controller gain.
s: Independent variable in the Laplace domain.

3.1.3 Basic control of a cycloergometer

As mentioned by [4] the basic instrumentation of a therapeutic cycloergometer consists of a system sensitive to the effort made by the user when pedaling, capable of varying the transmission ratio when the exerted torque is more significant than a predetermined value.

This concept is used to implement an automatic mechanical power transmission to help the person making an effort to maintain a fixed torque by increasing or decreasing the transmission ratio of mechanical power to the bicycle wheel. To maintain a fixed torque value, the developed system has a PID type electronic control module as shown in the figure 3.4.

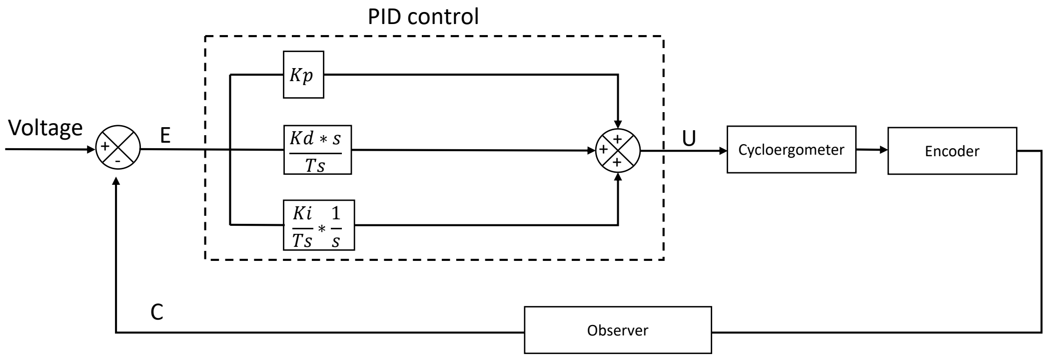


Figure 3.4: PID electronic controller for cycloergometer [4] y [5].

3.2 Fuzzy logic

In human language, to give a value to a particular state of an object or process, relative terms such as "very dry," "moderately dry," "wet," etc., are often used. It is a problem when the same language is required to be used by machines; these do not speak in relative terms but in absolute terms, such as "true" or "false." So when we want to describe a process using human terminology, a good tool is fuzzy logic. Fuzzy logic is the mathematical tool that allows the translation of a "natural" language to a "machine" language and vice versa [34].

Fuzzy logic seeks to create mathematical approximations in the resolution of certain types of problems. They aim to produce exact results from inaccurate data, which is why they are instrumental in electronic or computational applications [35].

In medicine and physiotherapy, the level of pain or symptom expressed by one patient may not be the same as that of another, so there is some uncertainty in the input data. Fuzzy logic helps to reduce this uncertainty by interpreting the natural language of a symptom or even a vital sign [36].

3.3 Fuzzy controller

The fuzzy logic takes values of natural language, and according to these values, it makes a classification to a set. The fuzzy control uses this classification to carry out the manipulation or observation of a process [37].

3.3.1 Fuzzification

Before speaking directly about fuzzification, some concepts should be mentioned. A universe of discourse can be defined as a set A of measurable real-world values such as temperature, the height of a person, distance, heart rate, etc. This universe A is evaluated in different fuzzy sets. The fuzzy sets measure the level of membership of the different values in A, that is why they are commonly called membership functions $\mu_A(x)$.

Unlike classical logic where only 0 or 1 is evaluated, the membership functions assess the level of membership between real values from 0 to 1; the closer the x value is to 1 means that it belongs entirely to the membership set and the closer x is to 0 standards that its membership is almost null or null [37, 35]. For example, assume the following discrete universe of discourse $A = \{55, 65, 70, 90, 110, 120\}$ and the membership function defined by the following equation:

$$\mu_A(x) = e^{-0.005(x-100)^2} \tag{3.1}$$

In the figure 3.5 the equation (3.1) can be observed graphically.

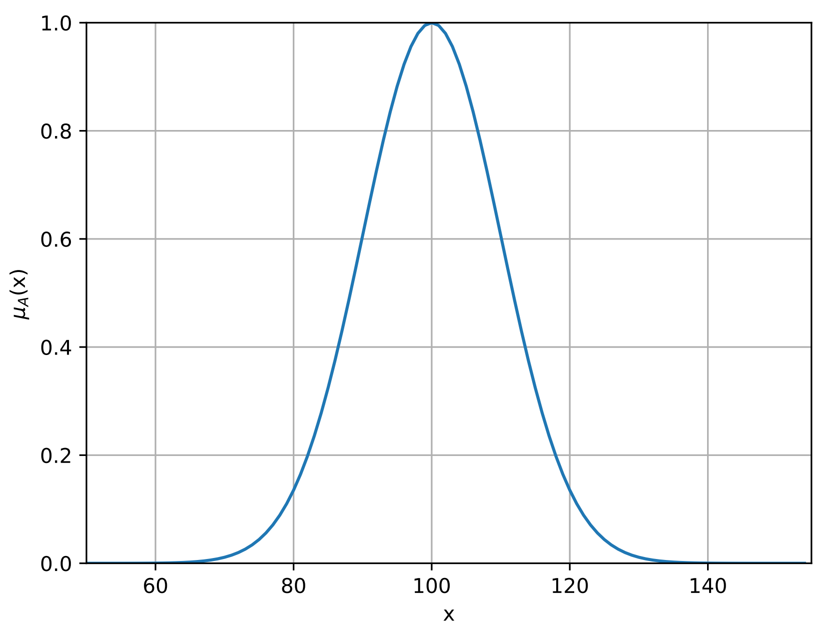


Figure 3.5: Membership function $\mu_A(x)$.

If we evaluate the membership level of each of the values of A, we can obtain the table 3.1 and we can see the same result graphically in figure 3.6

Table 3.1: Membership level of A values.

x	$\mu_A(x)$
55	0
65	0.002187
70	0.011108
90	0.60653
110	0.60653
120	0.13534

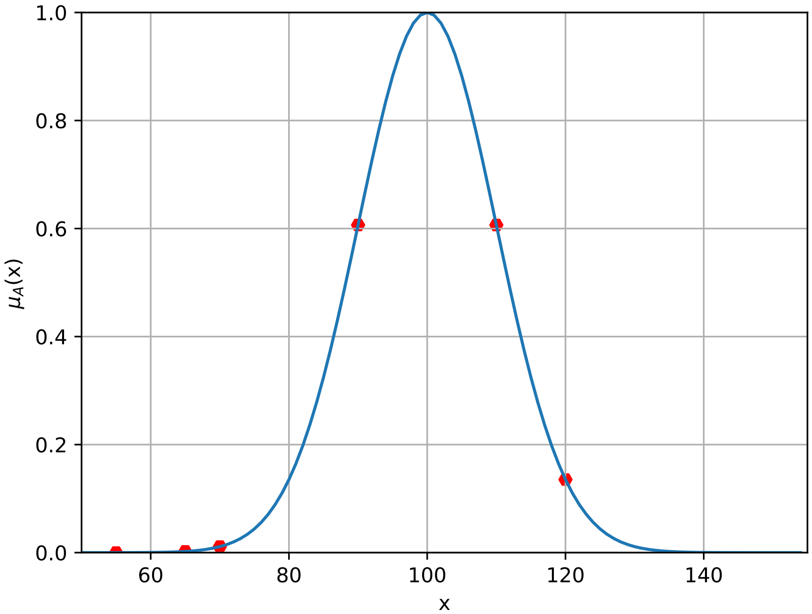


Figure 3.6: Membership function $\mu_A(x)$.

This is fuzzification, moving from a real measurable value to a value of membership, like the previous example [37]. Usually, fuzzy sets have names in natural language to evaluate in a more intuitive way the membership level of a value; for example: "very wet," "wet," "dry," "very dry." A value x is evaluated in each of the fuzzy sets to determine the level of membership of x in each set. For example, suppose the following two fuzzy sets grouping different values and ranges of heart rates: High Heart Rate (HHR), and Very High Heart Rate (VHHR).

$$HHR = e^{-0.005(x-100)^2} \tag{3.2}$$

$$VHHR(x) = \begin{cases} x < 100 & VHHR = 0 \\ x >= 100 \text{ and } x <= 130 & VHHR = \frac{(x-100)}{30} \\ x > 130 & VHHR = 1 \end{cases} \tag{3.3}$$

If, as in figure 3.7 we evaluate the heart rate $hr = 108$, it will see that it will have a membership value of 0.72 in HHR and 0.266 in VHHR. So although the heart rate 108 can be classified as a Very High Heart Rate, it has more membership in a High Heart Rate.

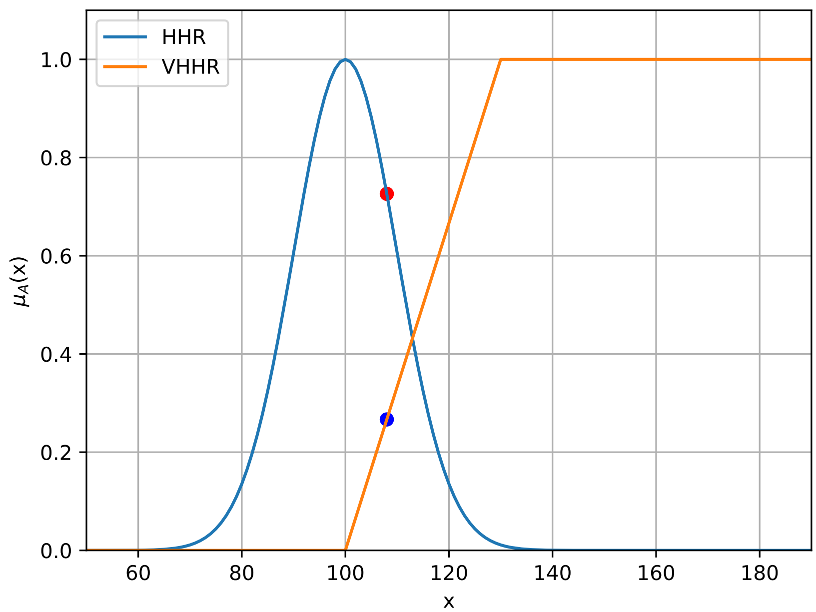


Figure 3.7: Membership functions

There are multiple membership functions, but for this project, we have decided to use three [38]:

- Gaussian

$$\mu_A(x) = e^{-k(x-m)^2} \tag{3.4}$$

  Where:
  k: is the aperture width of the Gaussian curve.
  m: is the center of the curve.

- Trapezoidal

$$\mu_A(x) = \begin{cases} x < a & \mu_A(x) = 0 \\ x >= a \text{ and } x <= b & \mu_A(x) = \frac{x-a}{b-a} \\ x > b & \mu_A(x) = 1 \end{cases} \tag{3.5}$$

Where:
a: is the beginning of the straight line.
b: is the end of the the straight line.

- Triangle

$$\mu_A(x) = \begin{cases} x < a & \mu_A(x) = 0 \\ x >= a \text{ and } x <= m & \mu_A(x) = \frac{x-a}{m-a} \\ x > m \text{ and } x <= b & \mu_A(x) = \frac{b-x}{b-m} \end{cases} \tag{3.6}$$

Where:
a: is the beginning of the triangle
b: is the end of the the triangle.
m: is the center of the triangle.

3.3.2 Control rules

The control rules are the rules that dictate which fuzzy type output should be produced at the output depending on the membership values of the fuzzification. These rules are realized employing a dual comparison of each of the fuzzy sets based on the control phrase "if-then". For example, the following fuzzy sets are assumed [39, 40].
For the reference:

- Small Reference (SR).
- Normal Reference (NR).
- Big Reference (BR).

For the error:

- Small Error (SE).
- Normal Error (NE).
- Big Error (BE).

For the voltage output:

- Small Voltage (SV).
- Normal Voltage (NV).
- Big Voltage (BV).

A comparison of each fuzzy set of the error against each set of the reference is made, and for each combination, it is decided which fuzzy output will be chosen.

If the reference is SR **and** the error is SE **then** voltage is SV.
If the reference is NR **and** the error is SE **then** voltage is SV.

If the reference is BR **and** the error is SE **then** voltage is SV.

If the reference is SR **and** the error is NE **then** voltage is SV.
If the reference is NR **and** the error is NE **then** voltage is NV.
If the reference is BR **and** the error is NE **then** voltage is SV.

If the reference is SR **and** the error is BE **then** voltage is NV.
If the reference is NR **and** the error is BE **then** voltage is NV.
If the reference is BR **and** the error is BE **then** voltage is BV.

The above sentences can be summarized with the table 3.2.

Table 3.2: Control rules.

error \ reference	SR	NR	BR
SE	SV	SV	SV
NE	SV	NV	SV
BE	NV	NV	BV

The value that each fuzzy output will have will be the minimum value among the compared fuzzy sets. Assume the following values for the fuzzy sets of the reference and error. $SR = 0.1, NR = 0.6, BR = 1.0, SE = 0.6, NE = 0.3, BE = 0.0$. The table 3.2 is transformed into the tables 3.3 and 3.4.

Table 3.3: Control rules.

error \ reference	SR	NR	BR
SE	$\text{SV}_1 = min(SR, SE)$	$\text{SV}_2 = min(NR, SE)$	$\text{SV}_3 = min(BR, SE)$
NE	$\text{SV}_4 = min(SR, NE)$	$\text{NV}_1 = min(NR, NE)$	$\text{SV}_5 = min(BR, NE)$
BE	$\text{NV}_2 = min(SR, BE)$	$\text{NV}_3 = min(NR, BE)$	$\text{BV}_1 = min(BR, BE)$

Table 3.4: Control rules.

error \ reference	SR	NR	BR
SE	$\text{SV}_1 = min(0.1, 0.6)$	$\text{SV}_2 = min(0.6, 0.6)$	$\text{SV}_3 = min(1.0, 0.6)$
NE	$\text{SV}_4 = min(0.1, 0.3)$	$\text{NV}_1 = min(0.6, 0.3)$	$\text{SV}_5 = min(1.0, 0.3)$
BE	$\text{NV}_2 = min(0.1, 0.0)$	$\text{NV}_3 = min(0.6, 0.0)$	$\text{BV}_1 = min(1.0, 0.0)$

The set of fuzzy values for SV is as follows $SV_1 = 0.1, SV_2 = 0.6, SV_3 = 0.6, SV_4 = 0.1, SV_5 = 0.3$. For NV $NV_1 = 0.3, NV_2 = 0.0, NV_3 = 0.0$ and for BV $BV_1 = 0.0$. Note that more than one value is available for SV and NV, and only one value is needed for each fuzzy set. Then the max function will select the maximum value among the values belonging to the same fuzzy set. Observe the equations (3.7), (3.8), (3.9) and (3.10)

$$\begin{aligned} SV_{max} &= max(SV_1, SV_2, SV_3, S_4, SV_5). \\ NV_{max} &= max(NV_1, NV_2, NV_3). \\ BV_{max} &= max(BV_1). \end{aligned} \tag{3.7}$$

$$\begin{aligned} SV_{max} &= max(0.1, 0.6, 0.6, 0.1, 0.3). \\ NV_{max} &= max(0.3, 0.0, 0.0). \\ BV_{max} &= max(0.0). \end{aligned} \tag{3.8}$$

For better understanding, the variables SV_{max}, NV_{max} and BV_{max} are simply named SV, NV and BV respectively.

$$\begin{aligned} SV &= max(0.1, 0.6, 0.6, 0.1, 0.3). \\ NV &= max(0.3, 0.0, 0.0). \\ BV &= max(0.0). \end{aligned} \tag{3.9}$$

$$\begin{aligned} SV &= 0.6. \\ NV &= 0.3. \\ BV &= 0.0. \end{aligned} \tag{3.10}$$

3.3.3 Defuzzification

Defuzzification consists of converting the fuzzy linguistic data from the fuzzy output of the control rules to a numerical output. This is achieved employing the centroid method, which is nothing more than a weighting and normalization of the antecedent logic sentences [41, 42]. Using the previous example, the centroid method is described by the equation (3.11)

$$v_0 = \frac{\sum v[\mu(v)]}{\sum \mu(v)} \tag{3.11}$$

Where:
v_0 : represents the final output voltage.
v : is a set of values of the output volatge speech universe
$\mu(v)$: represents a set of fuzzy values of the output.

Equation 3.11 can be expanded as follows:

$$\sum(\mu(v)) = SV + NV + BV = 0.6 + 0.3 + 0.0 = 0.9 \tag{3.12}$$

$$v_0 = \frac{v_1(VS) + v_2(NV) + v_3(BV)}{\sum(\mu(v))} \tag{3.13}$$

Finally suppose that $v_1 = 1$, $v_2 = 5$, $v_3 = 12$. Substituting in (3.13)

$$v_0 = \frac{1(VS) + 5(NV) + 12(BV)}{0.9} = \frac{1(0.6) + 5(0.3) + 12(0.0)}{0.9} = \frac{2.1}{0.9} = 2.3 \tag{3.14}$$

3.4 Bio-sensors

In clinical diagnosis and patient treatment, many biological parameters must be measured and monitored. Bio-sensors are the elements in charge of acquiring these signals for further processing [43]. Some sensors work outside the body, while others are designed to be implanted inside the body. Sensors help healthcare providers and patients monitor health conditions and ensure they can make informed treatment decisions [44]. A common vital sign to monitor is the heart rate. There are common two ways to obtain a person's heart rate:

- Electrical: consists of 2 elements which are a monitor and a receiver. A radio signal is transmitted when a heartbeat is detected, which the receiver uses to display/determine the current heart rate [45].

- Optical: uses a light that shines through human skin to measure the amount of light reflected. The light reflections will vary as the blood pulses under the skin pass the light, then interpreted as heartbeats [45].

Another commonly measured parameter is the amount of oxygen a patient has. There are two ways to measure it:

- Pulse oximeter-estimated oxygen saturation measurements (SpO2): Measures the amount of oxygen carried by the blood compared to its total capacity. It estimates how much oxygen the hemoglobin in the blood contains compared to how much it could have [46].

- Spectrophotometrically in arterial blood (SaO2) [46].

3.4.1 Oximeter

An easy-to-use and relatively inexpensive device for measuring both oxygen saturation and heart rate is the oximeter, such as the one shown in the figure 3.9. As seen in the figure 3.8 consists of a light emitting source and a photodetector, as a light emitting source usually red (630nm) and infrared (940nm) light emitting diodes (LEDs) are used [6].

Figure 3.8: Oximeter

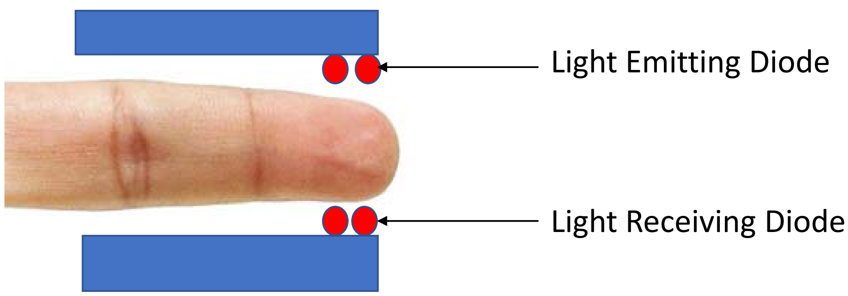


Figure 3.9: Oximeter operation [6].

Pulse oximetry is one of the fundamental tools in SpO2 monitoring. It is often considered the fifth vital sign after heart rate, blood pressure, temperature, and respiratory rate [6]. Through a photo emitter, a red and infrared light is passed through a pulsating capillary, usually the person's finger. These lights pass through hemoglobin, which is a protein molecule in charge of transporting oxygen.

Hemoglobin absorbs different amounts and lengths of light depending on the level of oxygen it carries. When hemoglobin has a lot of oxygen, this molecule absorbs more infrared radiation [47, 6, 46]. It allows more red light to pass through, while hemoglobin carrying a small amount of oxygen absorbs more red light and allows more infrared light. The oxygen saturation level is measured as a percentage and is described by the equation 3.15 [6]. It is essential to mention that the normal oxygenation of a person is between 95% and 98% [48]. If this is lowered, it is a sign that the person needs medical attention.

$$SpO2 = \frac{\text{Red light absorption}}{\text{Infrared light absorption}} \tag{3.15}$$

The heart rate signal is obtained similarly by placing an obstacle between the light emitter and the receiver; a decrease in the current is observed, which will depend on the degree of opacity of the block. This obstacle can be a finger. The signal obtained in the photo-transistor carries information on the variation in blood flow and blood pressure [49, 48, 50].

3.5 Embedded systems

Many authors describe embedded systems as follows:

- "An embedded system is any device that includes a programmable computer, but is not itself a general-purpose computer." [51, 7].
- "An embedded system is an electronic system that contains a microprocessor or microcontroller; however, we do not think of them as a computer." [7, 52].
- "An embedded system is a system whose primary function is not computational but is controlled by an embedded computer. This computer can be a microcontroller or a microprocessor. The word embedded implies that it is within the overall system, hidden from view, and is part of a larger whole." [7, 53].

However, what many authors agree on is that they are systems designed to fulfill one or a few specific functions; for example:

- The braking control of an automobile.
- The GPS of an airplane.
- An embedding for communication between cell phones.
- Video games.
- Remote control of a drone.

An embedded system has both software and hardware inside; it can work independently or together with other systems; for its execution, the embedded program is stored in ROM (Read Only Memory). The embedded has two main components [7].

- Hardware.
- Software that tells hardware logs how to operate under certain conditions. This software will be in charge of carrying out the main task.

In some cases, the embedded systems can carry a real-time operating system that is used when the time to make decisions is crucial to the objective of the embedded system. Figure 3.10 illustrates the architecture of a basic embedded system [7].

- RISC (Reduced Instruction Set Computer) processor of 32 bits.
- FLASH memory is used for persistent storage of programs.

- The main memory (SDRAM) in which temporary values are stored for program execution.
- Wireless access point.
- Different interfaces for communication with external devices (UART, USB, ETHERNET).

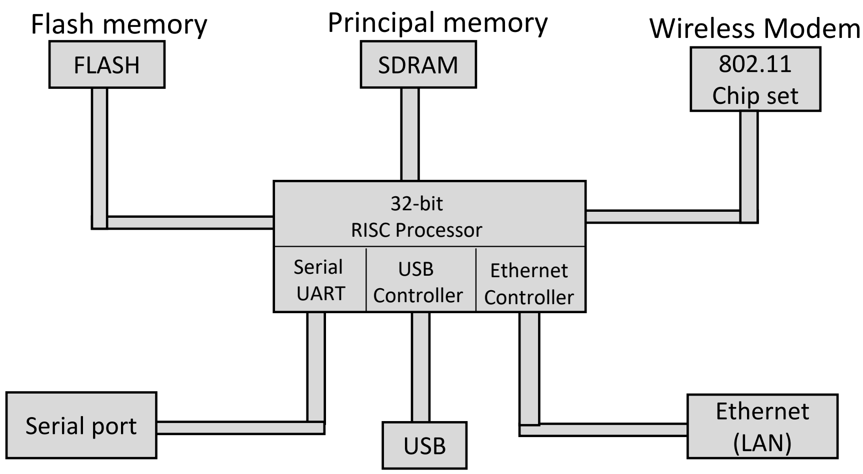


Figure 3.10: Embedded system block components [7].

3.5.1 Hardware in an embedded system

Embedded hardware is a special embedded system for executing programs or software instructions. The most common hardware used is described below.

- Microprocesador: It is an integrated logic circuit that performs many functions, tasks, or operations in a minor component [7, 54]. In general, a microprocessor consists of the following parts:

    1. PC (Program Counter). It is a parallel-load incremental counter that generates the address of the current instruction in program memory [54].
    2. IR (Instruction Register). It is the register that stores the current instruction to be executed read from the program memory [54].
    3. Instruction decoder. It is a combinational circuit that delivers at its output a unique state that identifies the instruction to be executed [54].
    4. TC (Time Counter). It is an incremental counter that generates the execution time base of the instructions [54].

- General purpose processor: Programmable device in charge of the execution of programs, they are composed by registers where instructions are stored and by different ALUs (Arithmetic Logic Units) [7].

- Sensors: To obtain a signal from the outside and execute an action based on that signal requires a sensor. Although this is not always the case, it is typical for an embedded system to have an integrated ADC, temperature sensor, or proximity sensor [7].

- Memory: There are different types of memory; however, the main common ones are RAM (Random Access Memory) and ROM (Read Only Memory).

  - RAM (Random Access memory): It is a memory where data can be read and written. This memory will be in operation as long as it is fed to the current; as soon as it does not have current, it will lose the stored information [54, 7].
  - ROM (Read Only Memory): It is the memory where the instructions to be executed by the microprocessor are stored [54]. A ROM is non-volatile. In addition, it is often used to store library subroutines for frequently used functions, system programs, etc [7].

3.5.2 STM32 board

STM32 is a family of programmable Microcontroller Units (MCU) using the ARM Cortex processor. As the author [55] says; Cortex-M is a family of physical cores designed to be further integrated with vendor-specific silicon devices to form a finished microcontroller.

The Cortex-M family was designed for low-cost MCUs that are focused on low power consumption. ST Microelectronics is one of the industries producing this processor to be used in its own MCU. Its MCUs are intended for applications of the Internet of Things, connectivity, motor control, smart metering, human interface devices, automotive and industrial control systems, domestic household appliances, consumer products, and medical instruments [55].

These cores and MCUs use a powerful tool for handling signals known as Interrupts and exceptions. These are asynchronous events that alter the program flow. When one of these events occurs, the operations being executed in the system are stopped, and specific instruction is executed. As soon as this special instruction finishes, the system will return to the point where it had stopped previously [55]. The difference between Interrupts and exceptions is that interrupts come from an external signal, such as a sensor, a switch or a clock signal, and exceptions are internal, described within the program itself, and come from timers and counters. The interruptions used in this research are:

- SPI Interrupt: Used to indicate a transmission or reception of the SPI communication protocol.

- Timmers: Used to execute fuzzy control every 60 seconds and for PWM generation. USART interrupt: Used to communicate with the HC-05 Bluetooth module and transmit and receive information from the app.

- Encoder interrupt: Used only in tests to measure the speed in rpm (revolutions per minute) of the cycloergometer motor.

Advantages of using an STM32 board:

- Free use for developers: There are multiple tools and IDEs for free use by developers.

- Libraries made by the manufacturer: There is code and development environments made by STMicroelectronics that makes it very easy to program the board without the need to program at a register level.
- Low cost. Unlike other cards, STM32 cards are inexpensive.
- Have specialized handling of floating point number operations.

The board to be used in this project is STM32F401RE and has the following features:

- Up to 72 MHz clock frequency.
- Up to 1 Mb of memory flash.
- Up to 96 Kb RAM memory.
- Multiple general-purporse timers.
- Up to 16-bit SPI communication.
- Operating voltage range is 1.8V to 3.6V.
- Specific purpose input and output pins.

Figure 3.11 shows how the development board to be used looks like. And figure 3.12 shows the main GPIO's (General Purpose Input Output) pins.

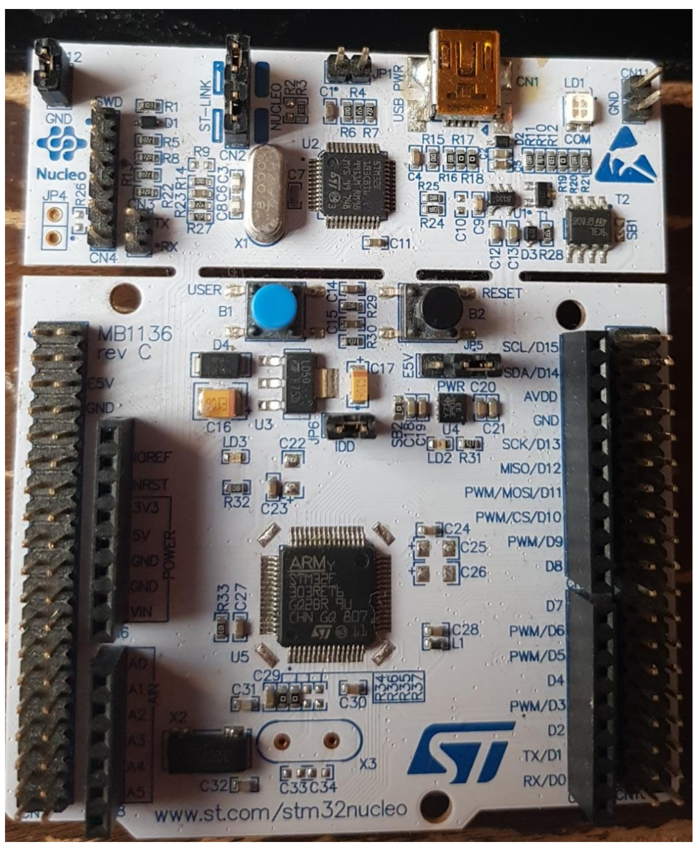


Figure 3.11: STM32 board.

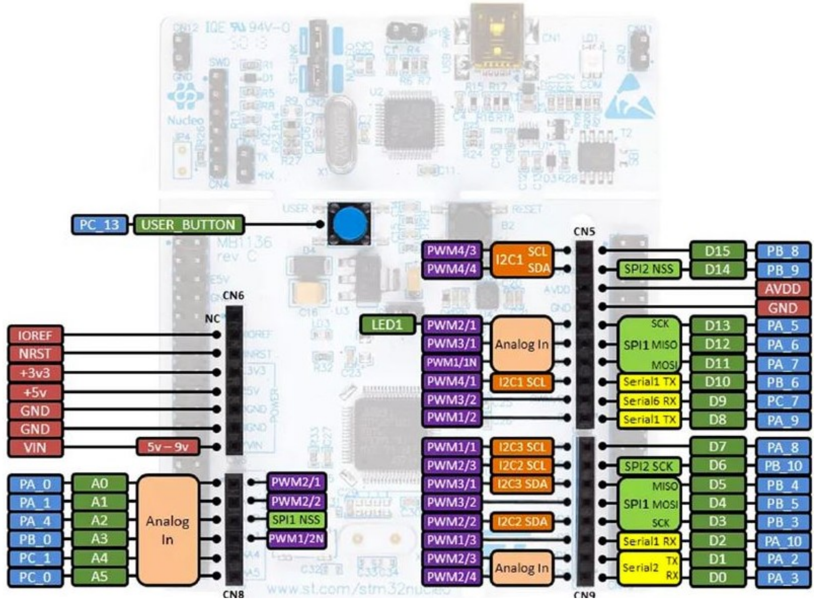


Figure 3.12: STM32 pins.

3.5.3 ESP32 board

The ESP32 is an embedded system designed for IoT (Internet of Things) related issues. It is a low-power, low-cost SoC (System on a chip) that has integrated WiFi and BLE (Bluetooth Low Energy) capabilities. Individual components such as Xbee, WiFi, BLE, etc., are relatively expensive; however, the ESP32 board already has all these modules integrated for a lower price [56]. The ESP32 has the following characteristics:

- Up to 240MHz clock frequency.
- SRAM de 520 KB.
- Voltage 2.2V to 3.6V.
- WiFi.
- BLE.
- Communication protocols: I2C, UART, SPI.
- 12 bit ADC.

As shown in the figure 3.13, the module is tiny, measuring 2.8 cm wide and 5.5 cm long. In the same figure, you can see how the pins are distributed along with the module.

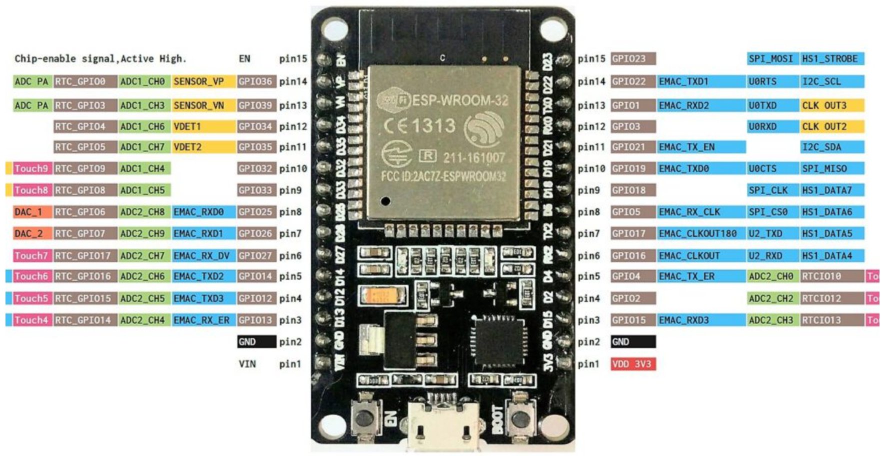


Figure 3.13: ESP32 pins.

3.6 Communication protocols

For different systems and peripherals to exchange information, rules are needed to indicate how the devices must be linked, how the bits must be read, and the time period in which these bits must be read; this set of rules is known as a communication protocol. There are several protocols for this project three have been used: BLE, SPI, and UART.

3.6.1 BLE

BLE is a new wireless standard that implements the standard Bluetooth protocol with energy-saving and resource-saving improvements [57]. Because of these kinds of advantages, BLE is widely used in smart devices, such as smartwatches, fitness trackers, oximeters, and other IoT devices. Initially, Bluetooth was designed by the Bluetooth SIG as a short-range, wireless, local area network protocol for devices that could be moved without losing connectivity or data transmission, for example, communication between a mouse and a PC [10].

Although BLE is designed based on the classic Bluetooth, BLE is not used in all scenarios in which Bluetooth can be used, for example, to transmit streaming music or video or the exchange of huge files. This is because to achieve energy savings; the BLE device has periods of ”sleep” during data transmission, then transmits and then sleeps again, and so on until the connection is lost [57, 10].

A significant difference between classic Bluetooth and BLE is that BLE is designed as a one-to-many connection, while classic Bluetooth is only intended for one-to-one connections. The author [10] presents in table 3.5 the main differences between classic Bluetooth and BLE in the table below. Among the 40 channels on which BLE operates, there are channels 37 to 39, wherein time intervals, the MAC addresses of the device to be connected are announced. So when another BLE device matches these time slots, a connection can be made [10].

Table 3.5: Classic Bluetooth vs BLE [10]

Feature	Classic Bluetooth	BLE
Symbol rate	1-3 Mbps	1 Mbps
Power consumption	1 (normalized)	0.01 - 0.5
Throughput	0.7-2.1 Mbps	305 kbps
Connection Latency	10 ms	6 ms
Channels	79	40
Channel Bandwidth	1 MHz	2 Mhz

Among the 40 channels on which BLE operates, there are channels 37 to 39, wherein time intervals, the MAC addresses of the device to be connected are announced. So when another BLE device matches these time slots, a connection can be made this form of interconnection is known as the Advertising Process [10].

The second step for the connection is through GATT (Generic Attribute Profile), allowing two BLE devices to communicate using Services and Features. The communication is done through a protocol known as ATT; in this protocol, services, characteristics, and data are exposed in the form of a table; it is a hierarchical structure of attributes that allows the transfer of information between a Client and a Server [58].

Within the services are the characteristics, and within the characteristics are the data; both services and characteristics have an identifier of 16 bits called universally unique identifier (UUID). The peripheral that searches or scans for a UUID is known as the GATT server, and the peripheral that advertises its UUIDs is known as the GATT client [58].

When the connection is established, the GTT device peripheral suggests a connection interval to connect to the GTT server device. The server will always try to communicate at this interval to send and receive data. The server device is also called a peripheral, which usually has data to be read. In contrast, the client device is called the central device, which generally reads the data and writes to the peripheral device. Figure 3.14 illustrates how this connection is executed.

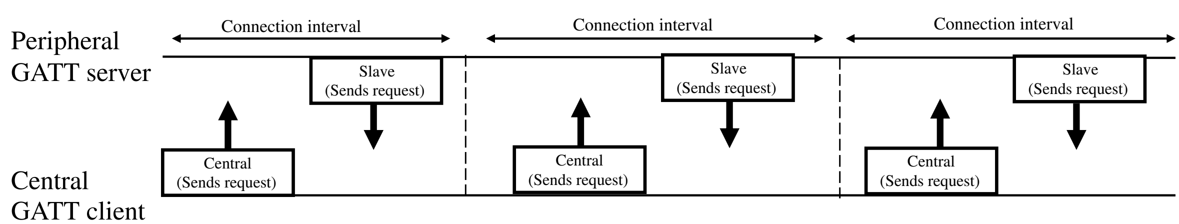


Figure 3.14: GATT communication [8].

The central GATT device tries to connect to one or several service UUIDs; once the connection is made, it tries to connect to a feature UUID. In the image 3.15 can see how the services, features are hierarchically divided.

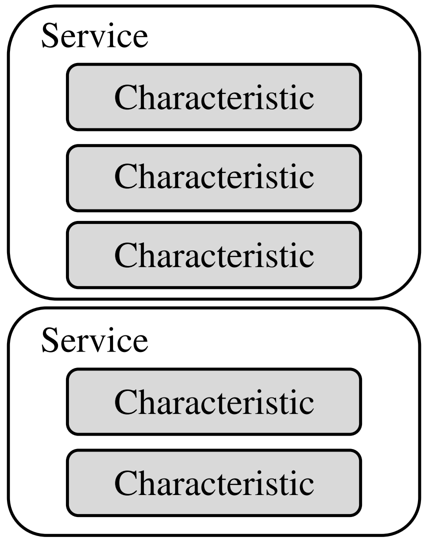


Figure 3.15: Services and characteristics [8].

As previously mentioned, the services have a 16-bit UUID; these services can contain one or more characteristics. For example, within a BLE oximeter, one could find a service such as "vital signs monitoring," this service includes heart rate and SPo2 measurement characteristics. Finally, the features encapsulate the data that the central device manipulates either in reading or written form. For example, a characteristic may contain the value of a person's heart rate measurement[58].

3.6.2 SPI

SPI (Serial Peripheral Interface) is a communication protocol based on master-slave communication. In this type of communication, the master indicates to one or more slaves when to transfer or receive data; SPI uses SCKL (Clock) signal and CS (Chip Select) signal. CS indicates when the data reception starts and when it ends for each of the slaves [9].

One of the main advantages of this protocol is that it is full-duplex communication, which means that it allows data transmission and reception at the same time; this is achieved through two signals: MISO (Master In Slave Out) and MOSI (Master Out Slave In). MISO is where the master device receives the data sent by the slave device, while MOSI is where the master sends the data to the slave [9]. Figure 3.16 shows how SPI can be configured with a single slave or with several slaves.

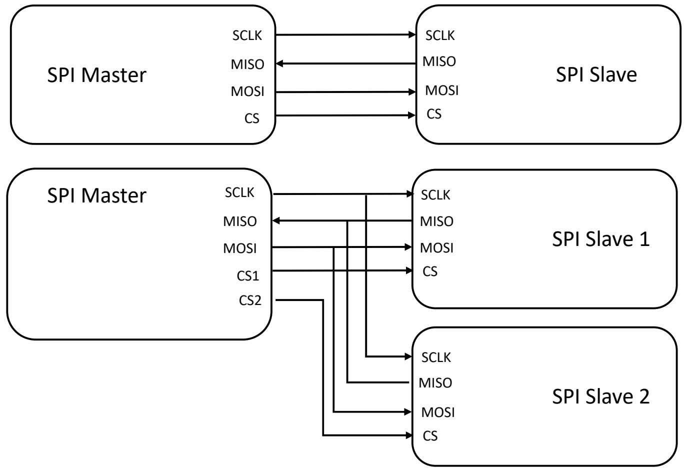


Figure 3.16: SPI topologies [9].

The following steps are used to transmit and receive data via the SPI bus:

1. The CS signal remains high until bit transmission begins. It goes low at the start of the communication; the slave reads the falling edge and prepares to transmit or receive data.

2. The SCLK clock starts to oscillate. Depending on the configuration in the slave, each time it detects a rising or falling edge in the clock, it will read the bit, always reading in the middle of the bit to ensure a reliable reading.

3. Once all bits have been read, the CS signal goes to a high state, waiting for the subsequent transmission.

Based on the previous steps, there are four combinations to achieve communication, depending on the polarity of the clock (CPOL) and its phase (CPHA). When CPOL = 0, while the SPI communication is inactive, the clock will always be as SCLK = 0, and the reading of the bits will be done on the falling edge. When CPOL = 1, while the SPI communication is inactive, the clock will always be as SCLK = 1, and the reading of the bits will be done on the rising edge. When CPHA= 0, the first reading will be done in the first clock cycle. While when CPHA= 1, the first read will be done up to the second clock cycle [9].

Figure 3.17 illustrates the data transmission with the combinations: CPHA = 0, CPOL = 0 and CPOL=1. While figure 3.18 illustrates data transmission with the combinations CPHA = 1, CPOL = 0 and CPOL = 1.

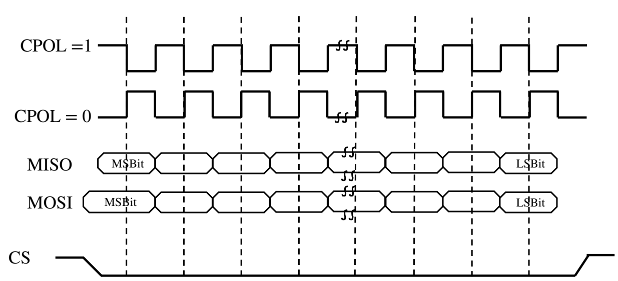


Figure 3.17: SPI transmission with CPHA = 0 [9].

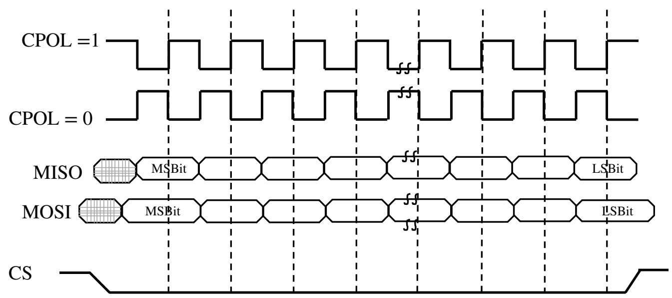


Figure 3.18: SPI transmission with CPHA = 1 [9].

3.6.3 UART

Universal Asynchronous Receiver/Transmitter (UART) is a communication protocol that, unlike SPI communication, does not have a synchronization clock and is half-duplex, i.e., it can only read or receive data one at a time but not at the same time. There is no clock in the transmitter and receiver; there must be a common configuration to read the sent bits correctly. The three configurations that should be in common between the two are: transmission speed in bauds per second, Data length in bits and Type of start and stop bit. The steps involved in UART transmission are as follows [59]:

1. The TX signal of the transmitter is high, and when you want to start the transmission, it goes low; this is called the start bit, so that the receiver detects when the transmission starts.

2. As mentioned above, there should be a common baud rate between transmitter and receiver in baud per second. This means a number of bit changes in one second. For example, a typical rate is 9600 bps (bauds per second), which means that one bit lasts $1/9600 = 104$ μs. At this moment, the receiver counts the duration that each bit should have and does its reading in the middle of the bit.

3. Once all the bits have been transmitted, the transmitter sends the stop bit, which is a high bit. Finally, the transmission is restarted.

Figure 3.19 shows a graphical representation of the steps to be followed for UART communication.

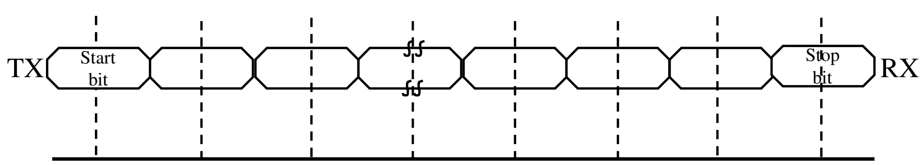


Figure 3.19: UART protocol.

CHAPTER 4

Methodology and results

In this chapter, the methodology used for this work is shown. Figure 4.1 reveals the steps of the project. Different tests are carried out to determineif the proposed algorithm is satisfactory. If any of these tests is not satisfactory, it is decided to go to previous steps and repeat it.

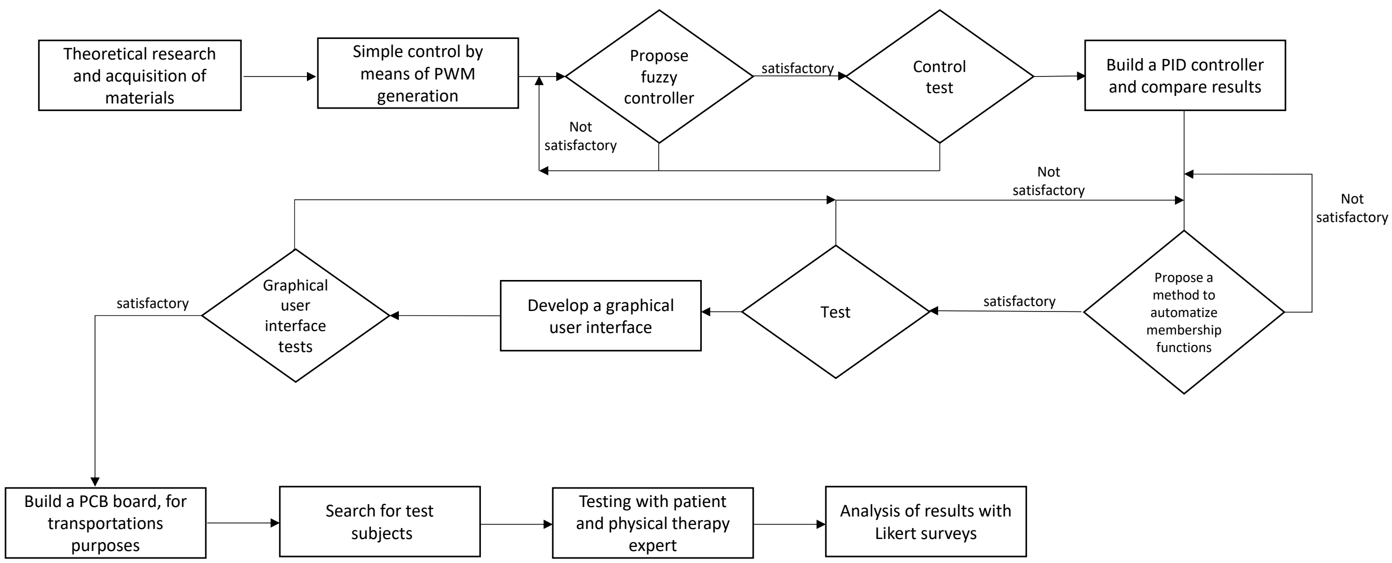


Figure 4.1: Methodology.

4.1 Materials

Cycloergometer *On-Motion*: It is the equipment to control, developed by Santiago Lopez in 2018[60]. At the beginning the only control he has is one where through a physical knob the speed is manipulated.

STM32F401 Microcontroller: It is the specialized hardware in charge of controlling the equipment and measuring the heart rate. This family of MCUs is chosen because intelligent control requires a high level of processing and precision in floating point numbers. This particular STM32 card is capable of working up to a frequency of 72 MHz. In addition to the fact that the STM families are specialized in floating point operations.

Bts7960 H-bridge: This is the driver in charge of handling the PWM obtained from the microcontroller according to the voltage source contacted and delivering it to the cycloergometer. The model of H-bridge is chosen because the cycloergometer sometimes requires up to 4 A of current.

OX-831 Oximeter: Is the commercial sensor in charge of measuring the heart rate. The device can send data by Bluetooth 4.1, and being commercial it ensures that the data is accurate.

ESP832: It is a small module specialized in WiFi and Bluetooth 4.1. Its job will be to capture data from the oximeter and send them by SPI protocol to the STM32 card.

KY-040 Encoder: Sensor that was used to make speed tests of the cycloergometer.

HC-05: Bluetooth device allowing connection between the user interface and the embedded card

Power supply and regulator: The 12 V power supply is used to power both the cycloergometer and the system that controls it. The regulator converts the 12 V into 5 V to supply the devices that require this voltage. A diagram of the interconnection of these devices is presented in the Figure 4.2.

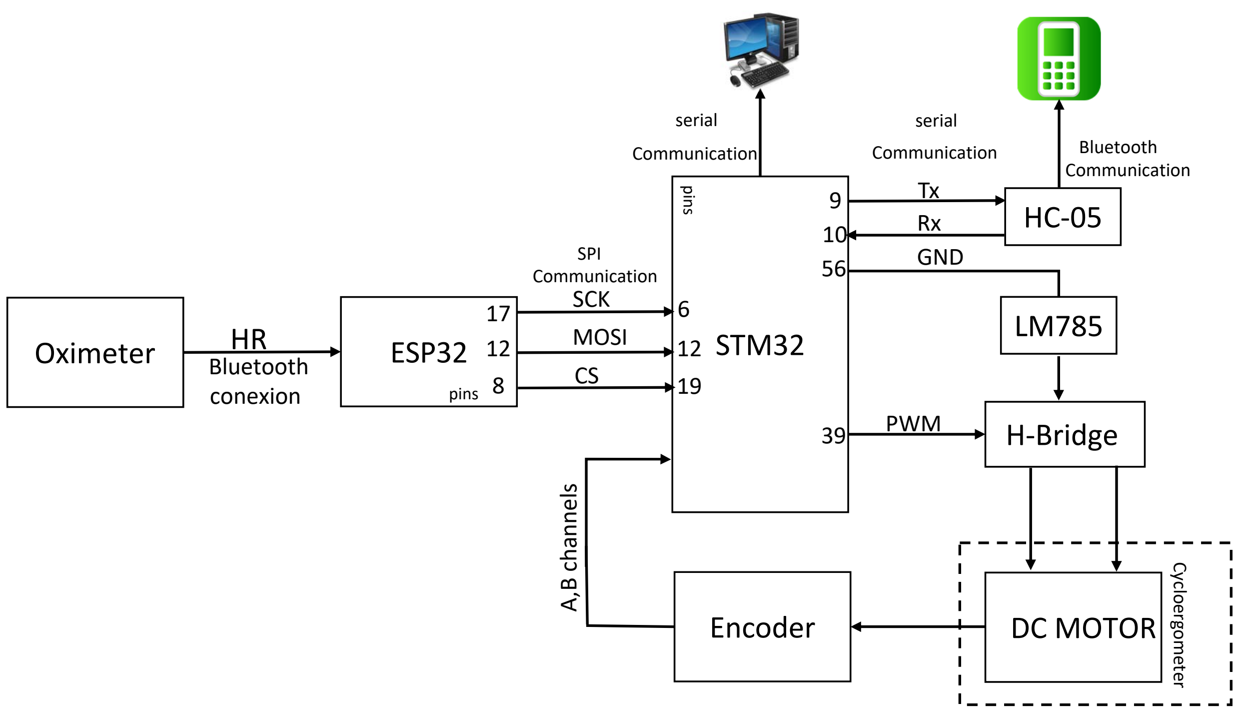


Figure 4.2: Connection diagram.

4.2 First proposed fuzzy control

The section describes the details of fuzzy control implementation.

4.2.1 Fuzzy heart rate sets

Cycloergometer therapies are mostly used by people 50-years old. Therefore, the first tests in this work were designed for people of that age and according to various research sources, adults in the resting state have a heart rate of between 60 and 100 beats per minute. It is possible to calculate the maximum heart rate of an adult when ther have a heart rate of 60%, for which we apply the following equation:

$$bpm = [(220 - age - 100)(0.6)] + 100 \tag{4.1}$$

Where bpm are the beats per minute.

The constant number 100 represents the maximum beat in rest. By applying (4.8) to different ages it is obtain the Table 4.1.

Table 4.1: Maximum heart rate per minute for different ages at a heart rate of 60%*.

Age	**Beats per Minute (bmp)**
20	160
30	154
35	151
40	148
45	145
50	142
55	139
60	136
65	133
70	130

*The minimum heart rate for all ages is considered to be 60 bpm.

Based on the table 4.1, the following fuzzy sets are proposed for the heart rate

Table 4.2: Diffuse sets defined.

Heart Rate	**Acronym**	**Beats per Minute**
Very Small Heart rate	VSHR	$-\infty$ to 90
Small Heart Rate	SHR	80 to 105
Normal Heart Rate	NHR	90 to 130
Big Heart Rat	BGR	120 to 140
Very Big Heart Rate	VBHR	132 to ∞

Considering the terms presented in Table 4.2, VSHR and VBHR correspond to trapezoidal type functions with slopes from 70 bpm to 90 bpm and 130 bpm to 150 bpm respectively. While SHR, NHR and BHR correspond to Gaussian type functions, SHR and BHR have a smaller opening than NHR. In the Figure 4.3, the x-axis represents the linguist variable heart rate measured in bpm while the y-axis represents the diffuse values of the same linguistic variable, thus forming the five fuzzy sets.

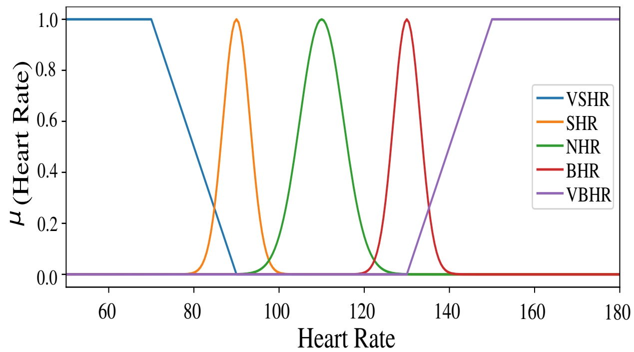


Figure 4.3: Beats per minute membership functions.

4.2.2 Error, output voltage fuzzy sets and control rules

The principal idea is to get the subject as close as possible to a heart rate established by the software. The speed of the cycloergometer changes by increasing or decreasing according to the previously measured heart rate. If a positive error is detected between the reference bpm and the measured bpm, the motor speed and pulses per minute increase, exhausting the patient. On the other hand, the error is negative and moves away from 0, then the speed decreases to 0, even stopping completely, which denotes that the patient has a high-heart rate and needs to rest. If the error is 0, the patient is considered to have a desired heart rate. Therefore, the speed of the cycloergometer is not too high or too low, in order to maintain that heart rate. The proposed diagram is presented in the Figure 4.4.

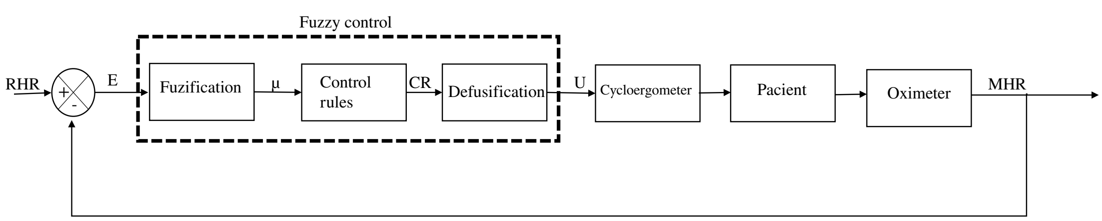


Figure 4.4: Proposed control loop for the project.

Where RHR is the reference heart rate, E is the error between the measured signal and the reference, μ is the heart rate fuzzy value, U is the PWM signal, CR are the rules and MHR is the measured heart rate.

The following fuzzy sets are considered for the error:

Table 4.3: Diffuse sets defined for the error.

Error Heart Rate	Acronym	Beats per Minute
Very Small Negative Error	VSNE	-∞ to-10
Small Negative Error	SNE	-30 to 0
Zero Error	ZEE	-15 to 15
Big Positive Error	BPE	0 to 30
Very Big Positive Error	VBPE	15 to ∞

In Figure 4.5 the fuzzy sets of the linguistic variable error are presented.

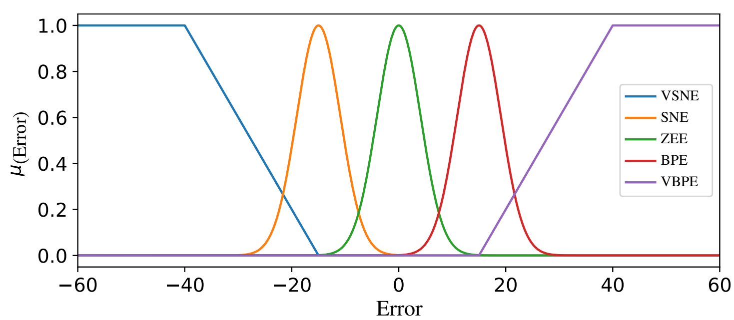


Figure 4.5: Error membership functions.

The speed of the motor of the cycloergometer depends directly on the applied voltage. The speed depends on the linguistic variables: bpm and error. Therefore, also the voltage depend on these variables.

Table 4.4: Defined voltage levels.

Level	Acronym	Value [V]
Very Small Voltage	VSV	0 to 1
Small Voltage	SV	0.5 to 1.5
Zero Voltage	ZEV	2.5 to 6.5
Big Voltage	BV	10 to 12
Very Big Voltage	VBV	11 to ∞

In Figure 4.6 are presented the diffuse sets of voltage. There are spaces between the membership functions where there are not values. However, this does not mean that these voltages will never be given, they may be given, because for the defuzzification is used the centroid method.

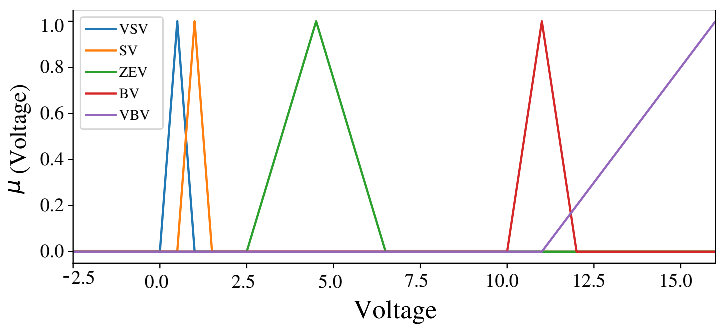


Figure 4.6: Voltage membership functions.

Control rules are the different possible linguistic outputs that the controller can take to calculate the outcome. In the rules there are 5-linguistic terms for the error and 5 for the reference bpm, which give 25-possible outputs and contain a linguistic term of the voltage. The rules use the Mamdani GarciaMartinez2020 method. In this case, for each linguistic term of the error and bpm a linguistic value of the voltage is obtained, for example: if RHR is RCMP and the error is VSNE, then the voltage is VSNE. The rules are summarized in Table 4.5.

Table 4.5: Control rules.

error \ bpm	**VSHR**	**SHR**	**NHR**	**BHR**	**VBHR**
VSNE	VSV	VSV	VSV	SV	ZEV
SNE	VSV	VSV	SV	ZEV	BV
ZEE	VSV	SV	ZEV	BV	VBV
BPE	SV	ZEV	BV	VBV	VBV
VBPE	ZEV	BV	VBV	VBV	VBV

4.2.3 Output voltage inference

As previously mentioned the Mamdani method is used and therefore in each control rule the AND operator is applied. In fuzzy-logic this operator can be represented as the minimum function of the background of each rule. The following two input vectors are assumed to better illustrate the previous statement.

$$bpm = 75,\ 85.5,\ 90,\ 95.5, \ldots,\ 150,\ 140 \tag{4.2}$$

$$error = -45,\ -44.5,\ -44, \ldots,\ 29.5,\ 30 \tag{4.3}$$

The vector (4.2) is evaluated in NHR and the vector (4.3) in VSNE, SNE, ZEE obtaining the Figures 4.7 and 4.8.

When evaluating the membership value of bpm in NHR you get the following graph.

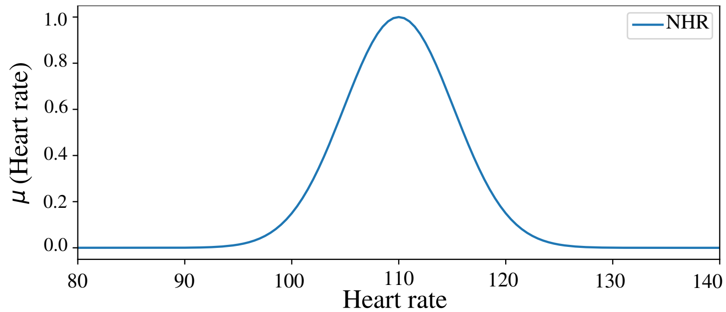


Figure 4.7: bpm membership.

The same is done with the error in VSNE, SNE and ZEE.

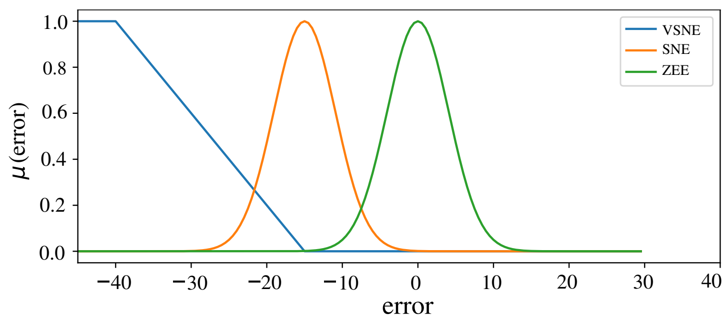


Figure 4.8: Error membership.

The minimum function is used to evaluate the rules, this means that depending on the rule, each point of the bpm vectors is compared against error to select the minimum value between them. Following rules are apply for this particular case:

```
i=1
While i<length(bpm):
    Rule_1(i) = min(VSNE(i), NHR(i))
    VSV_1(i) = Rule_1(i)
    Rule_2(i) = min(ZEE(i), NHR(i))
    VSV_2(i) = Rule_2(i)
    Rule_3(i) = min(SNE(i), NHR(i))
    SV(i) = Rule_3(i)
    i++
```

The values of VSV_1, VSV_2 and SV are presented in Figure 4.9. The above procedure is applied to the 25 rules of the Table 4.5.

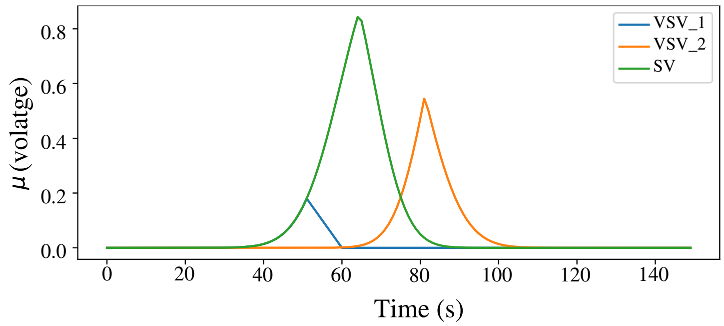


Figure 4.9: Voltage inference.

As can be seen from each fuzzy set of the voltage is more than one, in total 6 of VSV, 4 of SV, 5 of ZEV, 4 of BV and 6 of VBV. There is only one fuzzy set of each group is used the maximum operation between each fuzzy set of the same name.

```
1: VSV_{max} = max(VSV_1,VSV_2,...,VSV_6)
2: SV_{max}  = max(SV_1,SV_2,...,SV_4)
3: ZEV_{max} = max(ZEV_1,ZEV_2,...,ZEV_5)
4: BV_{max}  = max(BV_1,BV_2,...,BV_4)
5: VBV_{max} = max(VBV_1,VBV_2,...,VBV_6)
```

4.2.4 Defuzzification

There are 5 values of 5 different voltage membership functions at the same instant of time. However, a membership function must be selected per instant of time, making use of defuzzification by the centroid method that is described in the following equation.

$$y_0 = \frac{\sum y[\mu(y)]}{\sum \mu(y)} \tag{4.4}$$

Where y_0 represents an output value in a certain instant of time, y is a set of values of the output discourse universe and $\mu(y)$ represents a set of fuzzy values of the output.

Equation 4.4 can be expanded as follows:

$$\sum(\mu(y)) = ZEV_{max} + BV_{max} + VBV_{max} + VSV_{max} + SV_{max} \tag{4.5}$$

$$y_0 = \frac{y_1(VSV_{max}) + y_2(SV_{max}) + y_3(ZEV_{max}) + y_4(BV_{max}) + y_5(VBV_{max})}{\sum(\mu(y))} \tag{4.6}$$

Finally, the voltage value of y_0 is translated to a percentage of PWM pulse width in order to control the equipment with the microcontroller to be used, such conversion is achieved with the following three rule.

$$PPW = \frac{(V_{max})(y_0)}{100} \tag{4.7}$$

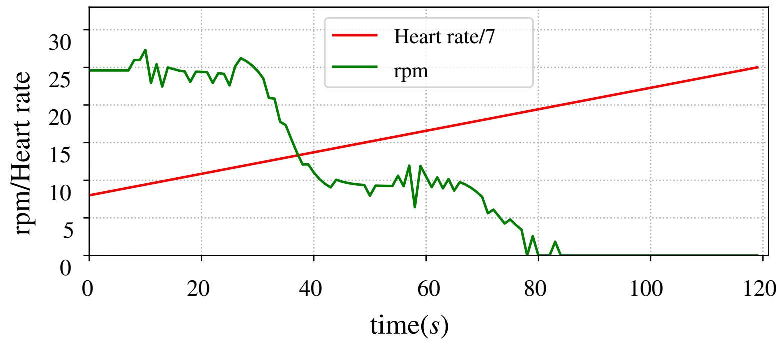
Where PPW is the percentage pulse width, V_{max} is the maximum voltage that the source can deliver (in the case of this investigation it is 12 V) and y_0 is the calculated voltage to be delivered by the fuzzy controller.

4.2.5 Results of the first proposed control

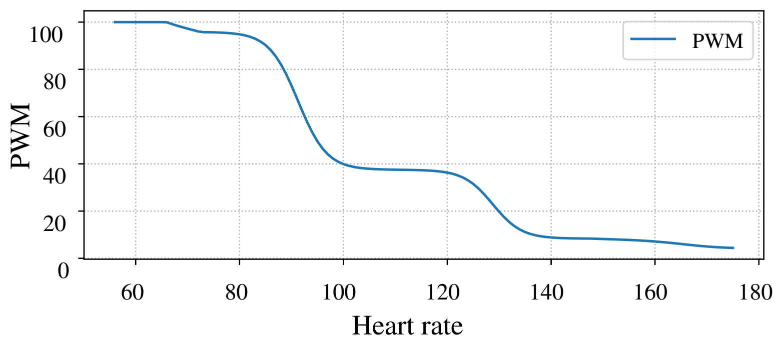
What do we expect from these tests?

- As explained in the table below, if the rider's heart rate is measured higher than the baseline, it is assumed that the patient is exhausted or stressed. Therefore the speed should be slowed down. In conclusion, the higher the heart rate increases, the lower the PWM control signal should be.
- Conversely, if the heart rate decreases, the PWM control signal should increase.
- The lower the measured *bpm*, the higher the speed.
- The higher the measured *bpm*, the lower the speed.
- The change between speeds should be smooth.

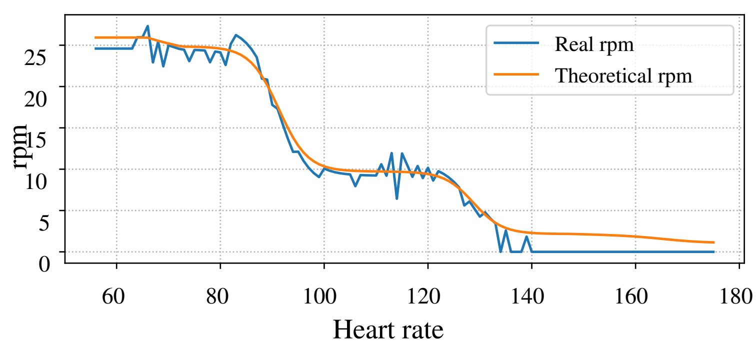
In test one, an increased heart rate is tested. The speed of the cycloergometer decreases as the heart rate increases. In Figure 4.10a it is shown how as the heart rate increases in a linear way over time, the speed of the cycloergometer decreases. Figure 4.10b describes how the control signal varies with the heart rate. Finally, in Figure 4.10c, it is observed that the speed changes in the desired way according to the heart rate.



(a)



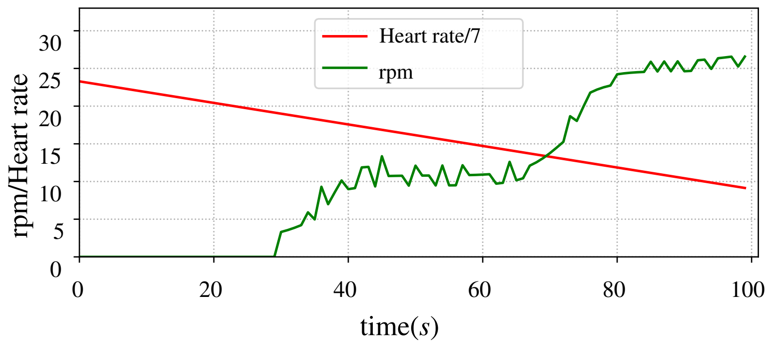
(b)



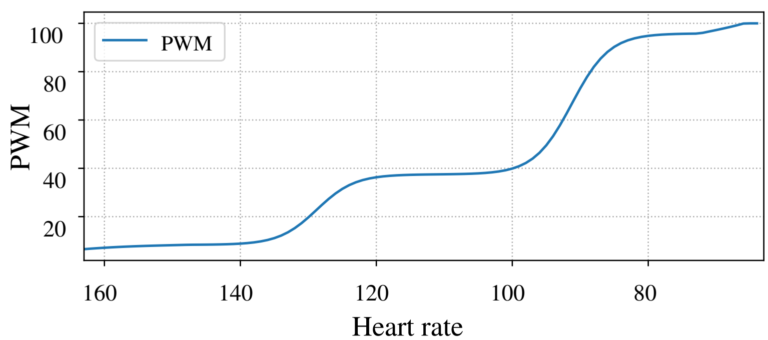
(c)

Figure 4.10: Results of Test 1: (a) Rpm behavior at increasing the heart rate, (b) PWM signal control, (c) Measured rpm vs real rpm.

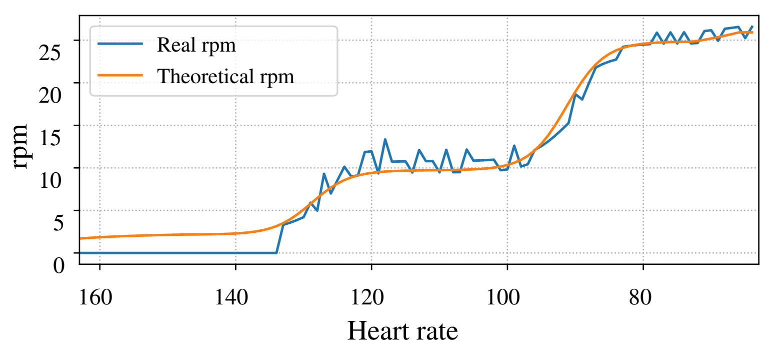
Test 2 is designed with a falling heart rate and, therefore, the speed increases. In Figure 4.11, it can be seen that the effect is achieved since the PWM control signal increases as well as the measured speed of the cycloergometer.



(a)



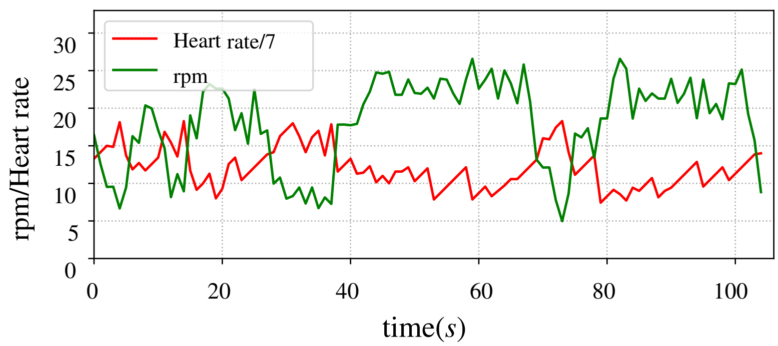
(b)



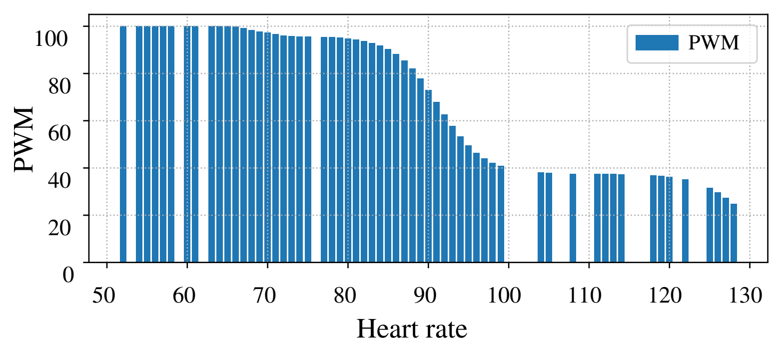
(c)

Figure 4.11: Results of Test 2: (a) Rpm behavior at decreasing the heart rate, (b) PWM signal control, (c) Measured rpm vs real rpm.

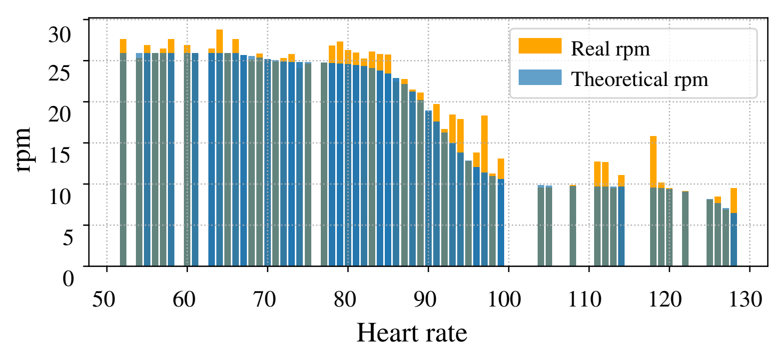
The third test is performed with a random heart rate to observe the behavior of the controller. In Figure 4.15a, the change is observed in both bpm and rpm. When there is a relatively sharp change in bpm the speed changes as desired. In Figures 4.15b and 4.15c, it is observed that each ordered measurement of heart rate corresponds to a speed, it is found that the lower bpm have higher speeds and the higher bpm have lower speeds.



(a)



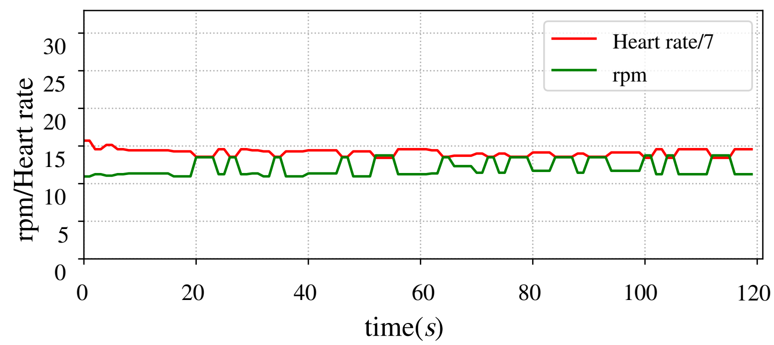
(b)



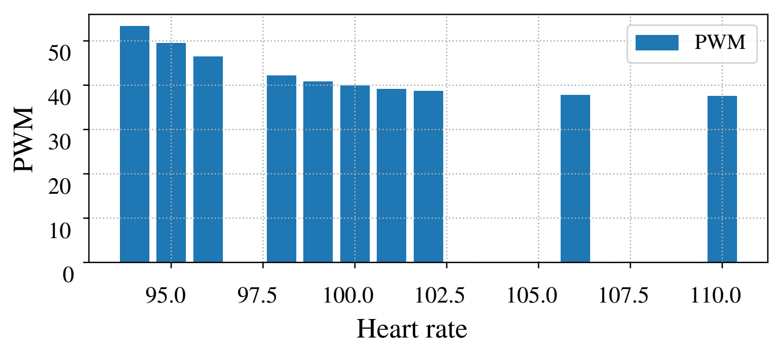
(c)

Figure 4.12: Results of Test 3: (a) Rpm behavior at decreasing the heart rate, (b) PWM signal control, (c) Measured rpm vs real rpm.

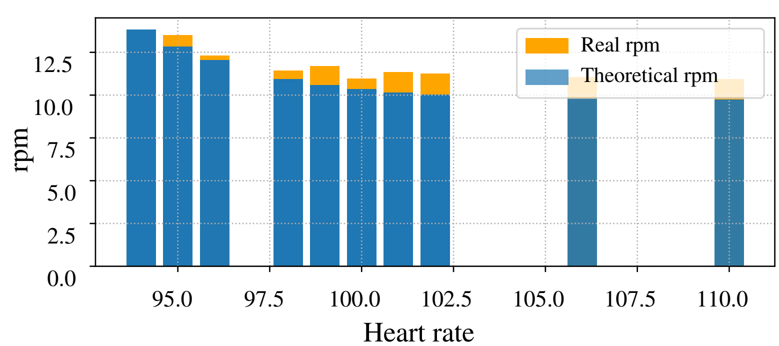
The fourth test is performed by directly measuring the heart rate through the oximeter, in order to observe the behavior of the controller based on a real measurement. It is observed in the Figure 4.13a that the heart rate does not vary considerably but even so it is observed that the controller responds to these small changes. In the Figures 4.13b and 4.13c it describes how the highest bpm have the lowest speeds and vice versa, thus achieving the general objective.



(a)



(b)



(c)

Figure 4.13: Results of Test 4: (a) Rpm behavior at decreasing the heart rate, (b) PWM signal control, (c) Measured rpm vs real rpm.

4.3 PID control test

It was decided to make a PID controller, to observe that the controller was not ideal for this project, or if we could obtain a control response similar to that of the fuzzy controller. Figure 4.14 shows the diagram describing the controller.

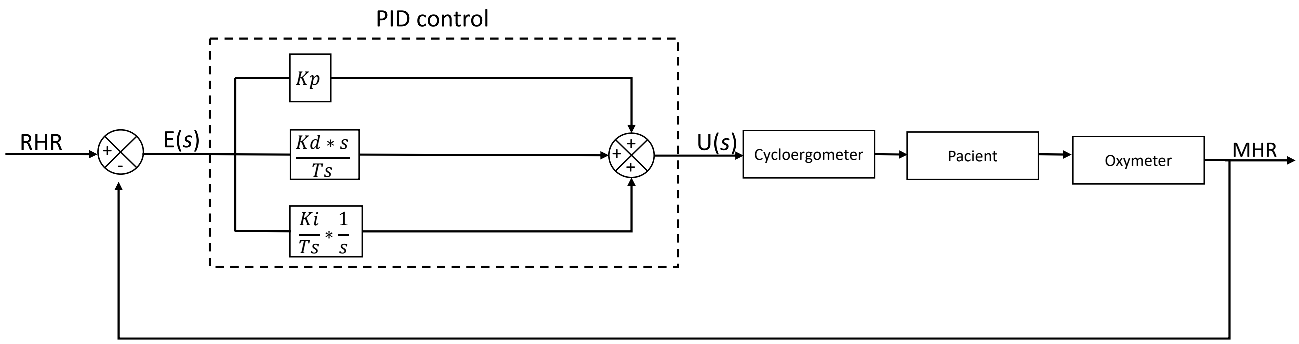
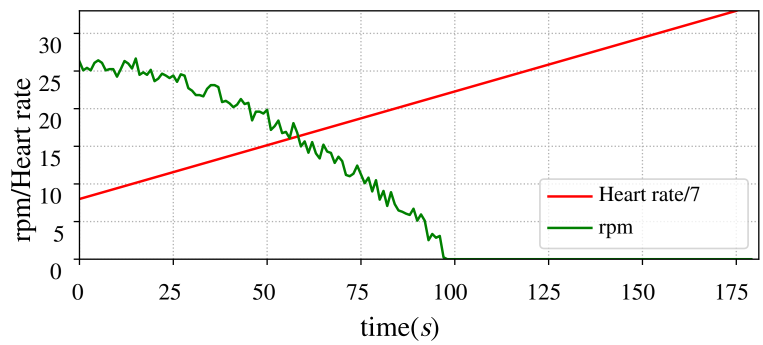


Figure 4.14: PID control

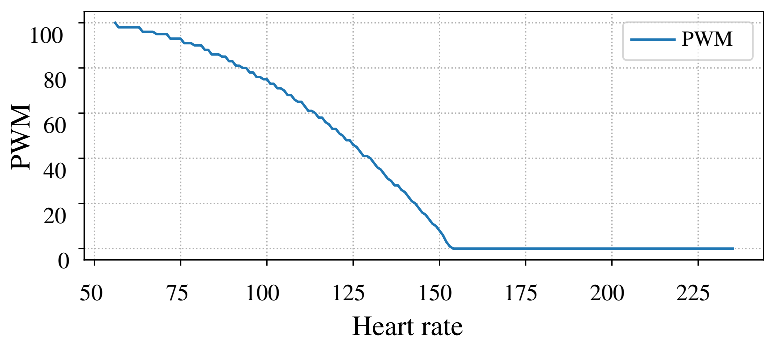
Where:
Kp: proportional gain.
Kd: derivative gain.
Ki: integral gain.
Ts: sampling time.
s: Laplace domain-independent variable.

4.3.1 Results of the PID control

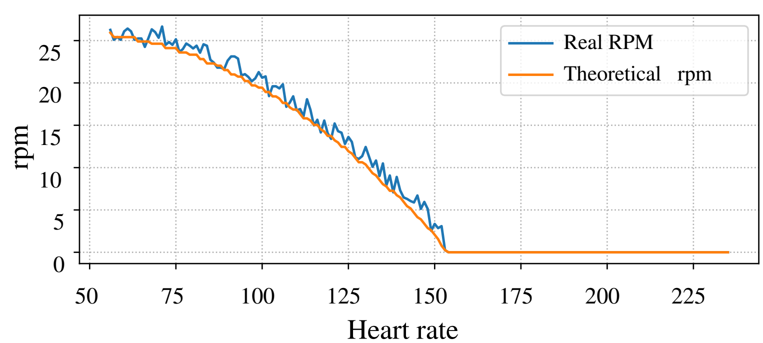
After having performed several tests and tunings to the controller, the gains and the sampling time have the following values: $Kp = 0.65$ $Ki = 0.030$ $Kd = 0.035$ $Ts = 1$(s)
Results similar to those in section 4.2.5 are expected from these tests.
In test 1 figure 4.15 it can be seen how the speed decreases as the heart rate increases; This is the expected result; however, it should be noted that the change is more abrupt than with the fuzzy controller.



(a)



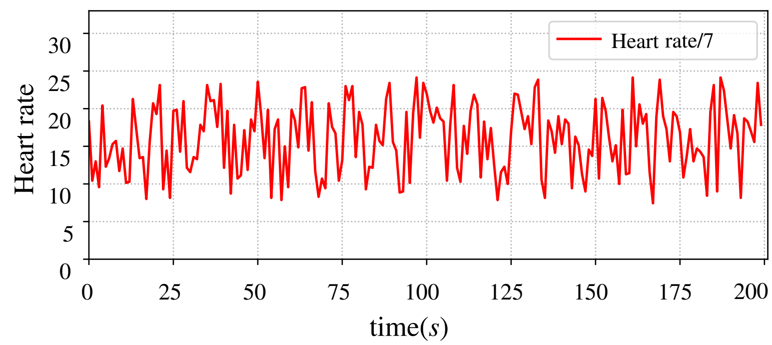
(b)



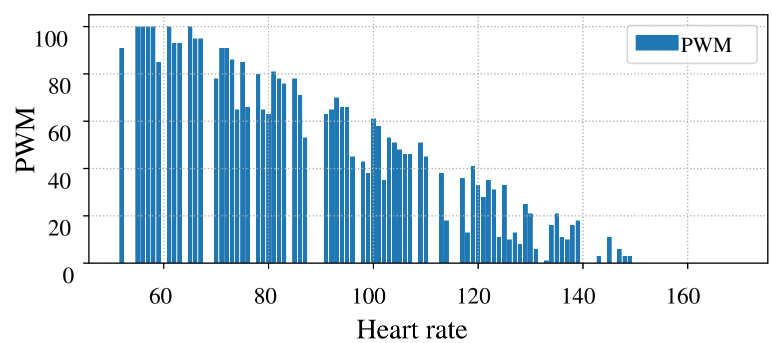
(c)

Figure 4.15: Results of Test 4: (a) Rpm behavior at increaing the heart rate, (b) PWM signal control, (c) Measured rpm vs real rpm.

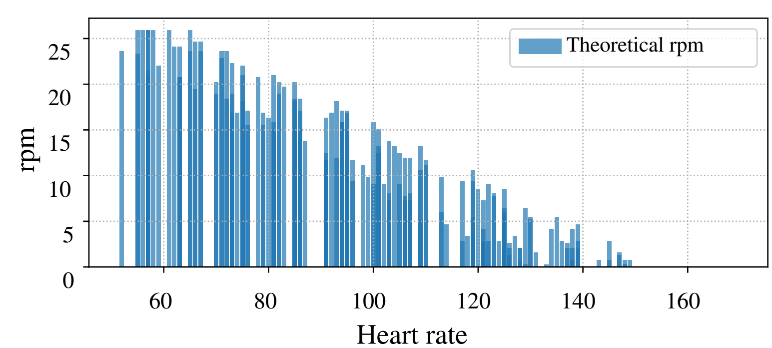
Test 2 has a random heart rate and is a clear example of why a PID controller is not suitable for this type of project. Observing the figure 4.16 you can notice how the velocities are too dispersed in some points there are higher velocities when they should be lower. In conclusion, when faced with unexpected changes in the independent variable, the PID controller cannot adapt to these changes.



(a)



(b)



(c)

Figure 4.16: Results of Test 4: (a) Rpm behavior at increaing the heart rate, (b) PWM signal control, (c) Measured rpm vs real rpm.

4.4 Automation of membership functions

Why modify or vary the membership functions?
The justification for adjusting the membership functions is that not everyone who can use the equipment is in the same state of health, so the range in which your heart rate works depends on the individual. [61, 62, 63]. For example, the *normal* heart rate of a person with obesity may not be the same as that of a person in good health; the obese person may have a daily heart rate of 100

bpm while the lean person may have a daily heart rate of 70 bpm. The same happens with age; a 70-year-old man could have a *big* heart rate of 110 *bpm* while a 25-year-old could have a heart rate of up to 125 *bpm*.
The following patient parameters are taken into account for the modification of functions:

- Age.
- Exercise intensity.
- Weight.
- Height.
- If suffer from diabetes.
- If suffer from hypertension.
- if have any pain.

First necessary to obtain the key points of the membership functions, which are obtained employing the equation (4.8), only this time will vary both the exercise intensity and the age.

$$bpm = [(220 - age - 100)(E.I)] + 100 \tag{4.8}$$

It has been decided to divide the key points into 8; 5 correspond to the functions on the x-axis, and three correspond to the width of the Gaussian functions; in figure 4.17 can see a graphical description of these points.

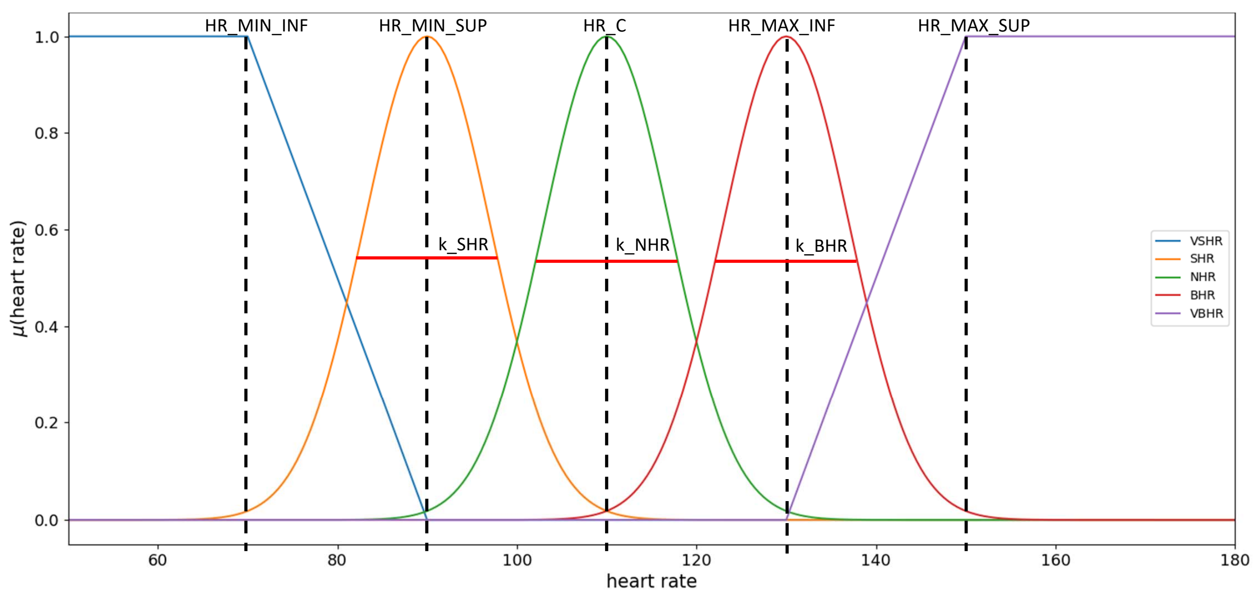


Figure 4.17: Membership functions key points.

To get the points HR_MAX_INF and HR_MAX_SUP, we calculate the midpoint between these two points, which is decided to call HR_MAX_MID; this point is calculated with the form bpm.

$$HR\_MAX\_MID = bpm = [(220 - age - 100)(E.I)] + 100 \tag{4.9}$$

To obtain HR_MAX_INF and HR_MAX_SUP, perform the following arithmetic operation.

$$HR\_MAX\_SUP = HR\_MAX\_MID + 8 \tag{4.10}$$

$$HR\_MAX\_INF = HR\_MAX\_MID - 12 \tag{4.11}$$

For the next points, perform the folloqing arithmetic operations

$$HR\_MIN\_INF = \frac{HR\_MAX\_INF + HR\_MAX\_SUP}{4} \tag{4.12}$$

$$HR\_MIN\_SUP = HR\_MIN\_INF + 20 \tag{4.13}$$

$$HR\_C = \frac{HR\_MIN\_INF + HR\_MAX\_SUP}{2} \tag{4.14}$$

It has been decided to leave the default widths of the Gaussian functions as follows:

$k\_SHR = 0.01$ corresponds to SHR
$k\_NHR = 0.01$ corresponds to NHR
$k\_BHR = 0.01$ corresponds to BHR

These key points only vary with age and exercise intensity so that two people of the same age and exercise intensity will share the standard membership functions. The following parameters are taken into account to change the functions on the x-axis and the width of the Gaussian functions:

- BMI (Body Mass Index).
- If has diabetes.
- If has hipertension.

The BMI equation is as follows [64]:

$$BMI = \frac{weight}{height^2} \tag{4.15}$$

Based on the BMI division, it has been decided to divide the BMI ranges into five WL (weight levels).

- $WL = -1$ means underweight.
- $WL = 0$ means normal weight.
- $WL = 1$ means overweight.
- $WL = 2$ means obesity.
- $WL = 3$ means morbidly obese.

The relationship between WL and BMI is described in the table 4.6.

Table 4.6: Relationship between BMI ranges and WL

Range BMI	WL
to 18.5	-1
18.5-24.9	0
24.9-29.9	1
29.9-49.9	2
$to49.9$	3

The following algorithm is described to modify the standard membership functions. First, two arrays are proposed for the modification of the x-axis and the width.

$$HR\_Rs = [0, 0, 0, 0, 0] \tag{4.16}$$

$$Ks = [1, 1, 1] \tag{4.17}$$

If the patient has diabetes then:

$$\begin{gathered} HR\_Rs = HR\_Rs + 2 \\ HR\_Rs[3] = HR\_Rs[3] + 3 \\ Ks[1] = Ks[1] * 0.7 \\ Ks[2] = Ks[2] * 0.85 \end{gathered}$$

If the patient has hypertension then:

$$\begin{gathered} HR\_Rs[2] = HR\_Rs[2] + 5 \\ HR\_Rs[3] = HR\_Rs[3] - 1 \\ HR\_Rs[4] = HR\_Rs[4] + 3 \\ Ks[0] = Ks[0] * 0.9 \\ Ks[1] = Ks[1] * 0.55 \\ Ks[2] = Ks[2] * 0.75 \end{gathered}$$

If $WL = -1$ then:

$$\begin{gathered} HR\_Rs[0] = HR\_Rs[0] + 3 \\ HR\_Rs[1] = HR\_Rs[1] - 5 \\ HR\_Rs[2] = HR\_Rs[2] - 5 \\ HR\_Rs[3] = HR\_Rs[3] - 5 \\ HR\_Rs[4] = HR\_Rs[4] - 3 \\ Ks[0] = Ks[0] * 0.9 \\ Ks[1] = Ks[1] * 0.5 \end{gathered}$$

If $WL = 1$ then:

$$HR\_Rs[3] = HR\_Rs[3] - 5$$
$$HR\_Rs[4] = HR\_Rs[4] - 7$$
$$Ks[1] = Ks[1] * .75$$

If $WL = 2$ then:

$$HR\_Rs[2] = HR\_Rs[2] + 1$$
$$HR\_Rs[3] = HR\_Rs[3] - 3$$
$$HR\_Rs[4] = HR\_Rs[4] - 10$$
$$Ks[1] = Ks[1] * .65$$
$$Ks[2] = Ks[2] * .85$$

If $WL = 3$ then:

$$HR\_Rs[2] = HR\_Rs[2] + 3$$
$$HR\_Rs[3] = HR\_Rs[3] - 3$$
$$HR\_Rs[4] = HR\_Rs[4] - 15$$
$$Ks[1] = Ks[1] * 0.5$$
$$Ks[2] = Ks[2] * 0.8$$

Finally, the variation arrays are added to the standard membership functions.

$$HR\_MIN\_INF = HR\_MIN\_INF + HR\_Rs[0] \tag{4.18}$$

$$HR\_MIN\_SUP = HR\_MIN\_SUP + HR\_Rs[1] \tag{4.19}$$

$$HR\_C = HR\_C + HR\_Rs[2] \tag{4.20}$$

$$HR\_MAX\_INF = HR\_MAX\_INF + HR\_Rs[3] \tag{4.21}$$

$$HR\_MAX\_SUP = HR\_MAX\_SUP + HR\_Rs[4] \tag{4.22}$$

$$K\_SHR = K\_SHR * Ks[0] \tag{4.23}$$

$$K\_NHR = K\_NHR * Ks[1] \tag{4.24}$$

$$K\_BHR = K\_BHR * Ks[2] \tag{4.25}$$

Suppose the patient has some pain that prevents him/her from moving the legs considerably fast. Then the maximum limit of the PWM duty cycle is set to 60%. For last an RHR will always be needed, so it has also been decided to calculate it by means of the following rule of three.

$$RHR = \frac{EI * 110}{60} \tag{4.26}$$

4.5 Graphical user interface

To create the user interface, we decided to use MIT app inventor, a web application that allows the design of mobile android applications.

The main screen described in the figure 4.18 shows four buttons; the first one *Dispositivos BT* is to connect to the HC-05 module, the connection is better shown in the figure 4.19.Notice that when connecting to the HC-05, the message displayed to the user changes from *Esperando conexión* to *Conectado*.

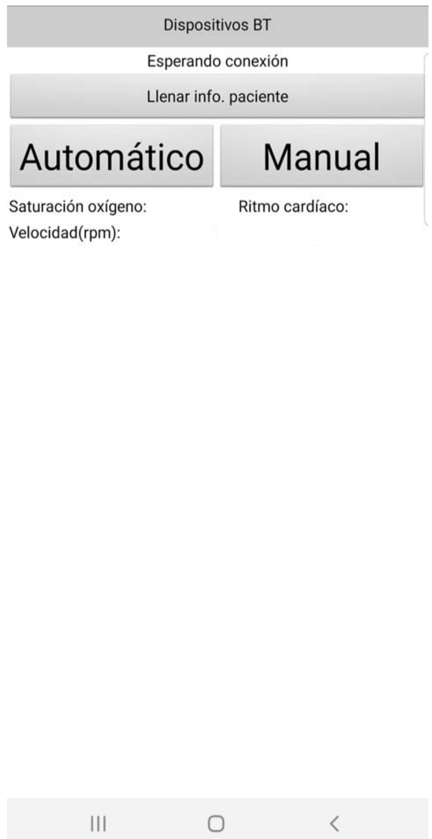


Figure 4.18: Main screen of the Graphical interface.

The next button described in figure 4.20 is to display a form that the user can fill out if he/she wants to save the patient's information or set an automatic mode. The last two buttons are for toggling between automatic and manual mode. Note in figure 4.21 that if the automatic mode is desired, the form must be filled in.

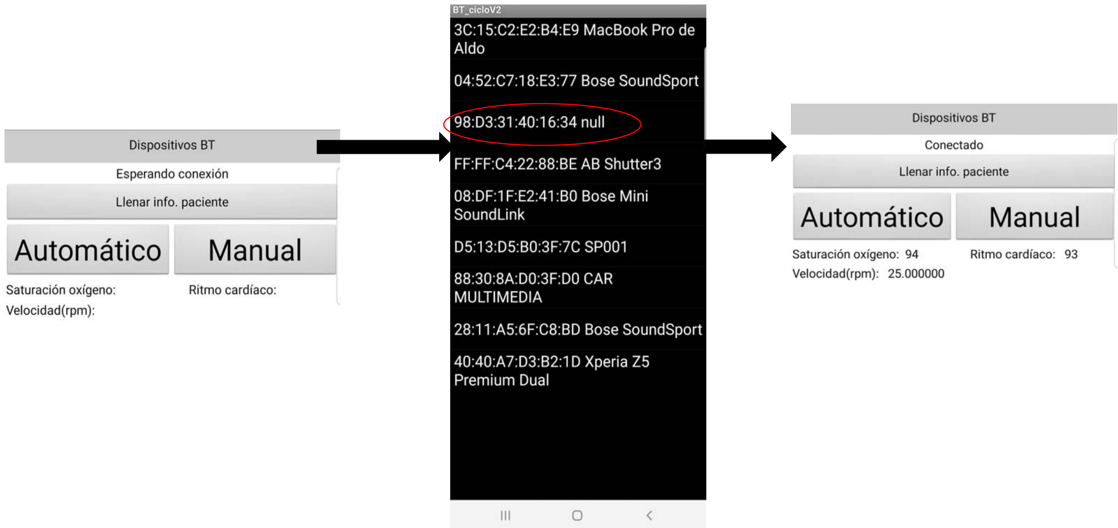


Figure 4.19: Bluetooth connection.

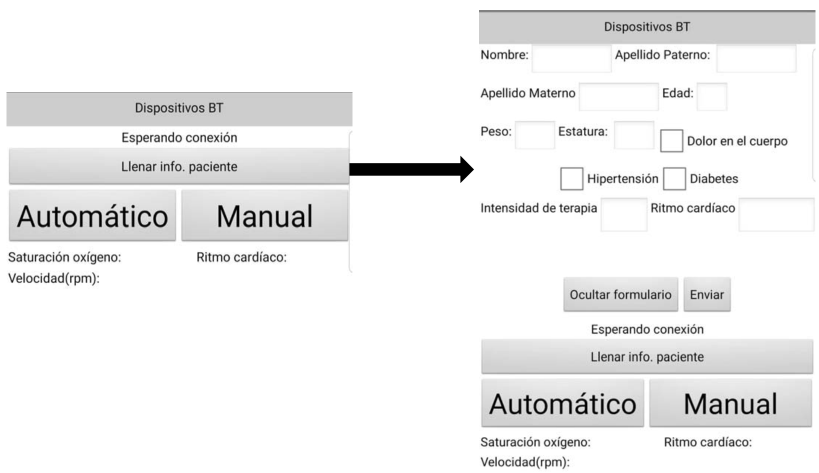


Figure 4.20: Form to fill in patient's information.

As described in figure 4.22 if there is a patient already added, the user of the application has the option to decide to add a new patient or to continue with the same one but with some parameter changed, for example, he/she has decided to change the therapy intensity.

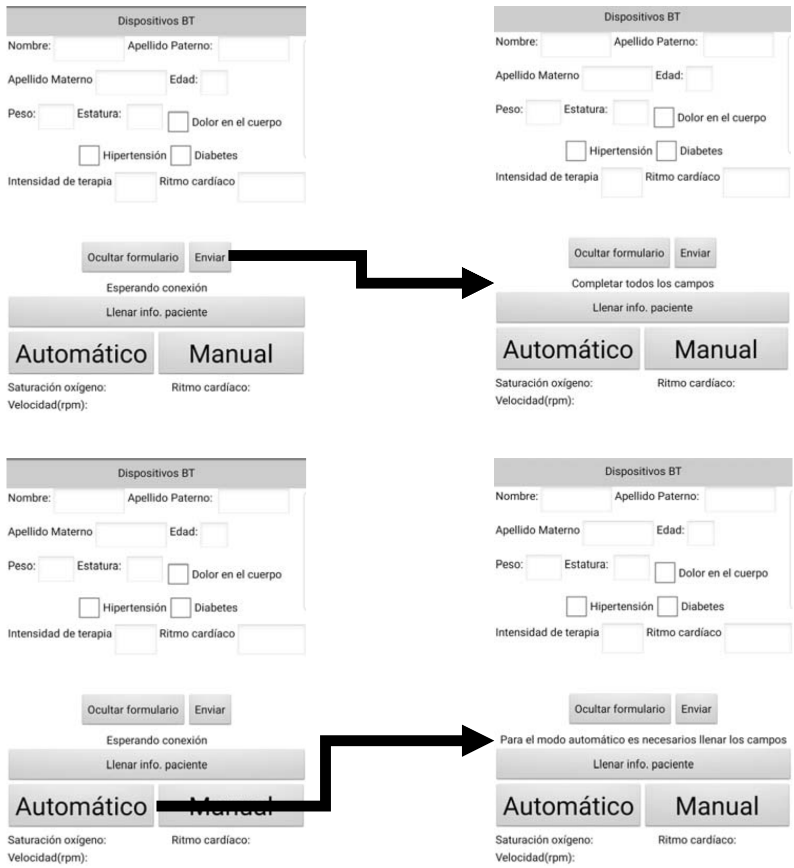


Figure 4.21: Cases where the form is not completed.

Figure 4.22: Case where there is a previous patient.

All-time, it measures and displays the heart rate, oxygen saturation, and speed at which the cyclergometer is running. Finally, the figure 4.23 shows how the screen is displayed when the manual mode is selected; in this mode, the speed can be increased or decreased by 5%.

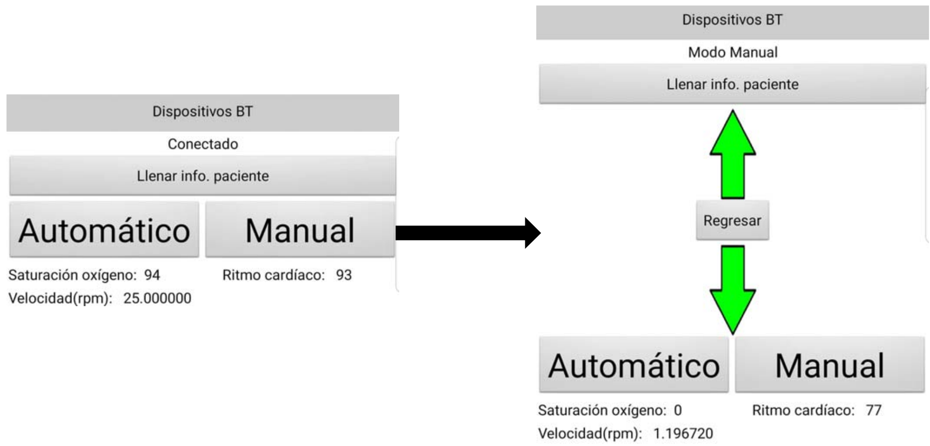


Figure 4.23: Manual mode.

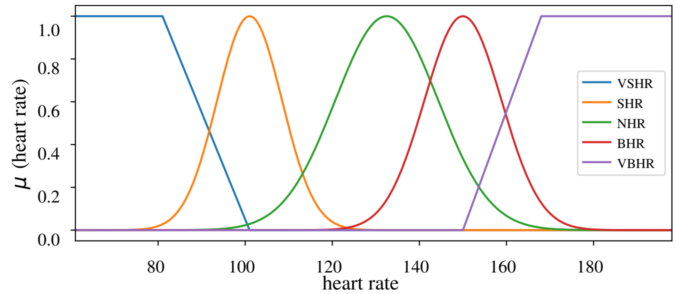
4.5.1 Test with GUI and automated functions

This subsection will show the results of implementing the automated membership functions; the automatic membership functions and their control and heart rate signals will be shown. The tests were implemented using simulated or virtual persons; all the parameters of these persons were filled in using the user interface.

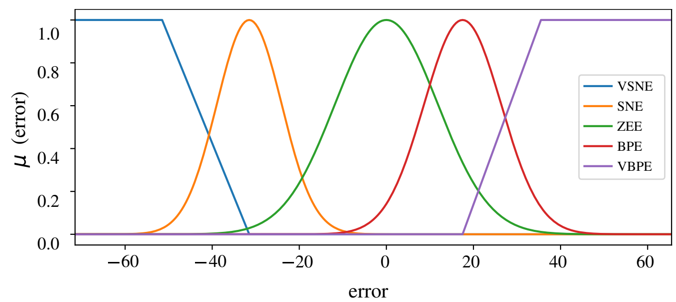
The test A simulates a person with the following parameters:

- Age: 40 years old.
- EI: 80%;
- Heigh: 1.80 m.
- Weight: 115 Kg.
- Hypertension: Yes.
- Diabetes: No.
- Pain: No.

Note in figure 4.10a how the NHR is wider because the person is overweight and how the BHR function is closer because his high heart rate starts earlier than usual due to hypertension. The figure 4.25 shows the results of the control signal when a rising heart rate is implemented; see how the PWM signal decreases smoothly while increasing the *bpm*. Figure 4.26 shows results but with a random heart rate, while figure **??** shows results with an actual measurement using the oximeter.

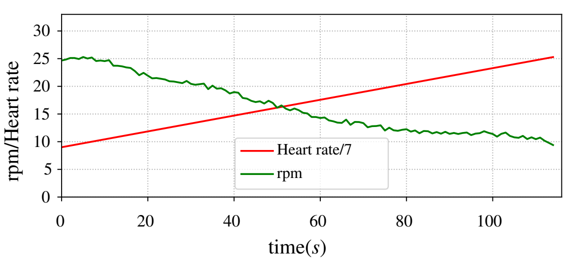


(a)

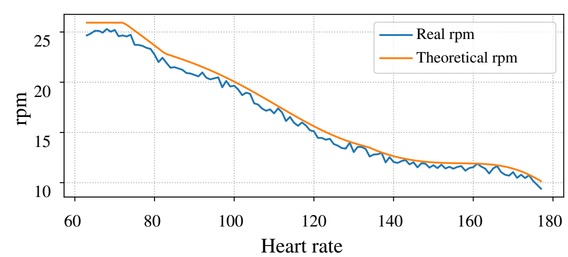


(b)

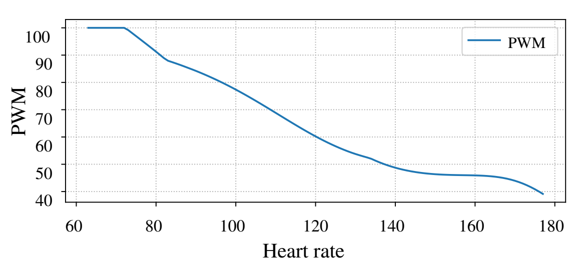
Figure 4.24: membership functions automatization : (a) heart rate. (b) error.



(a)

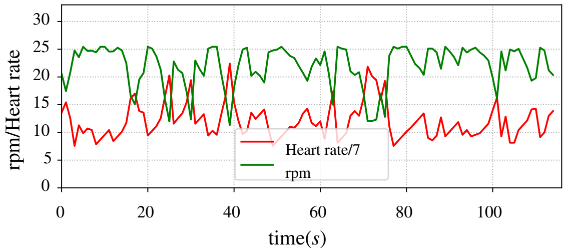


(b)

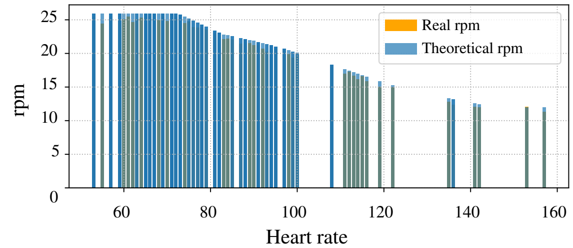


(c)

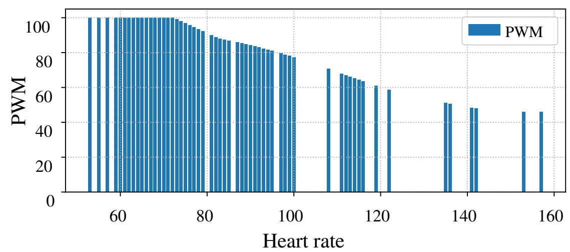
Figure 4.25: Results of Test A1 with automatization (a) increasing heart rate (b) theoretical rpm vs real rpm, (c) PWM control signal.



(a)

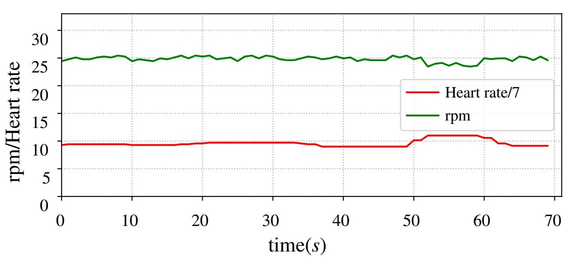


(b)

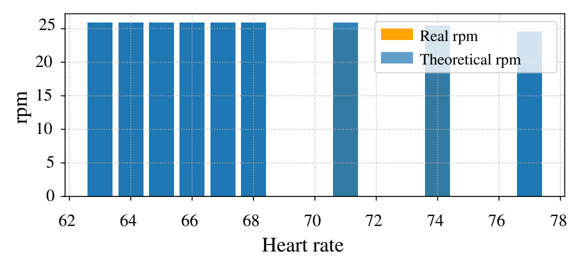


(c)

Figure 4.26: Results of Test A2 with automatization (a) random heart rate (b) theoretical rpm vs real rpm, (c) PWM control signal.



(a)



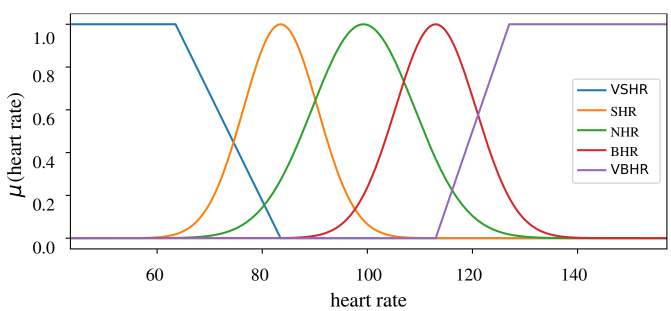
(b)

Figure 4.27 Results of Test A3 with automatization (a) real heart rate (b) theoretical rpm vs real rpm, (c) PWM control signal.

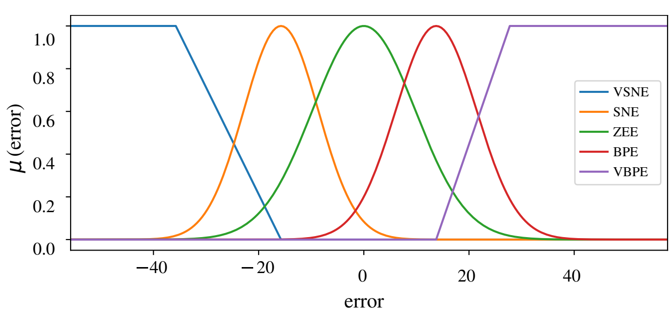
Test B simulates a person with the following parameters:

- Age: 70 years old.
- EI: 50%.
- Height: 1.68 m.
- Weight: 75 Kg.
- Hypertension: No.
- Diabetes: Yes.
- Pain: Yes.

Looking at the figure 4.28, you can see how the Gaussian functions are closer together than in the figure 4.24 and also that the NHR function has a greater width than BHR and SHR. See in figure 4.29 that the desired change is realized as the heart rate increases. In figure 4.30 it can be seen how equally in random low heart rates, high velocities are obtained while in high heart rates, low speeds are obtained. The last test shown in figure 4.31 shows the desired behavior of the velocity at an actual heart rate.

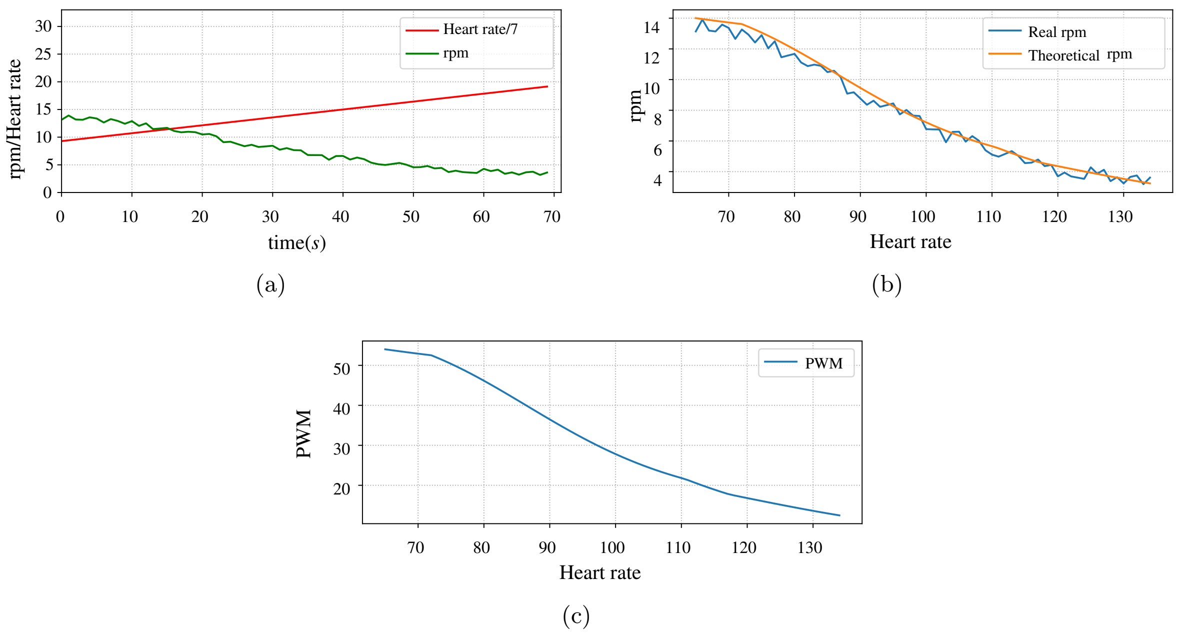


(a)



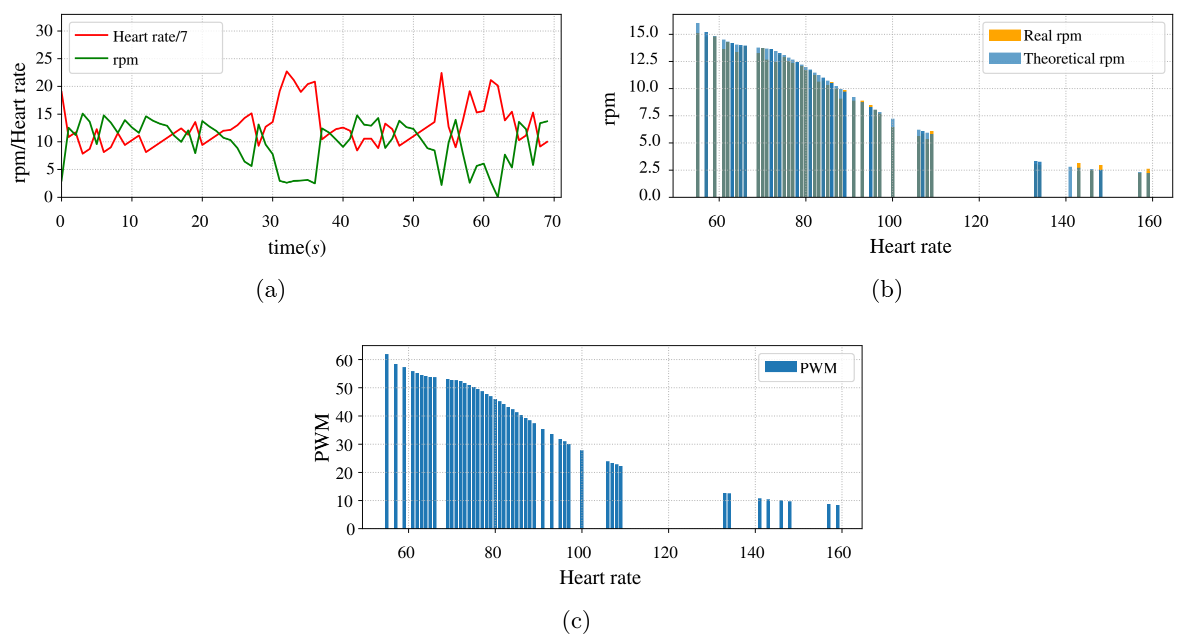
(b)

Figure 4.28: membership functions automatization : (a) heart rate. (b) error.



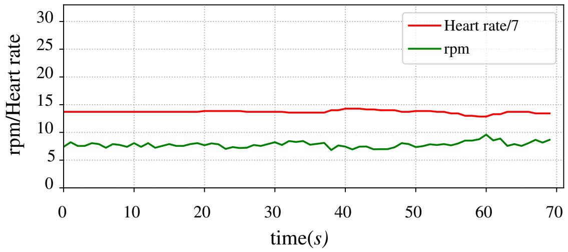
(a) (b) (c)

Figure 4.29: Results of Test B1 with automatization (a) increasing heart rate (b) theoretical rpm vs real rpm, (c) PWM control signal.

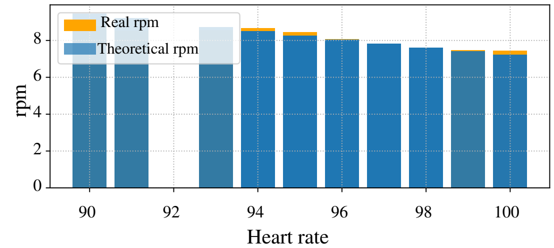


(a) (b) (c)

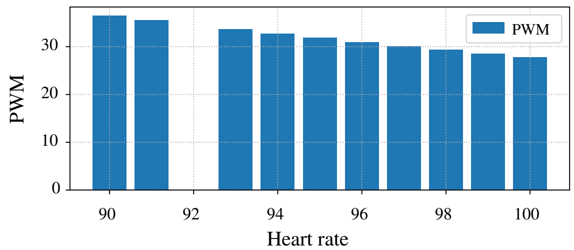
Figure 4.30: Results of Test B2 with automatization (a) random heart rate (b) theoretical rpm vs real rpm, (c) PWM control signal.



(a)



(b)



(c)

Figure 4.31: Results of Test B3 with automatization (a) real heart rate (b) theoretical rpm vs real rpm, (c) PWM control signal.

Finally, figure 4.32 shows a simulated young person with a better state of health than the previous tests; the parameters are as follows:

- Age: 20 years old.
- EI: 60%.
- Height: 1.75 m.
- Weight: 90 Kg.
- Hypertension: No.
- Diabetes: No.
- Pain: No.

It should be noted in the figure 4.32 how the functions are more symmetrical, they are not so close together, and their width has not been modified; this is because the person's parameters indicate a good state of health. In figure 4.33 notice how the control curve is maintained in specific heart rate ranges due to the settings that have been made in the membership functions. In figure 4.34 it is equally noticeable that the objective is met with a random heart rate signal, and the same happens with 4.35 with a heart rate extracted from the oximeter.

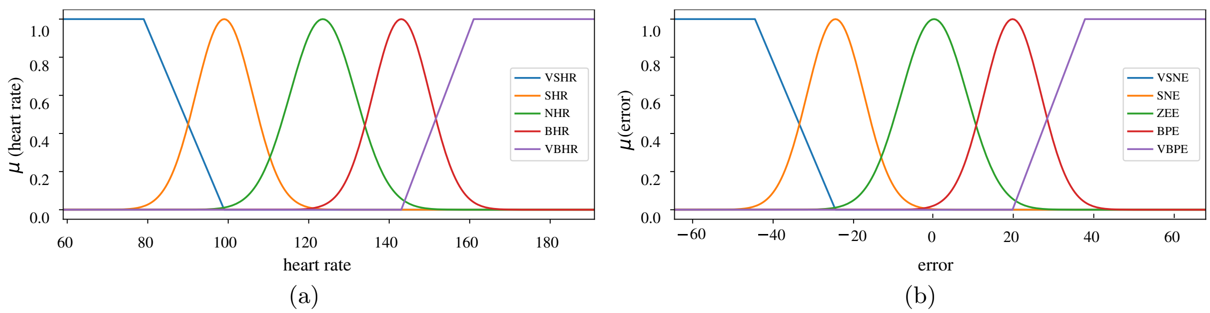


Figure 4.32: membership functions automatization : (a) heart rate (b) error.

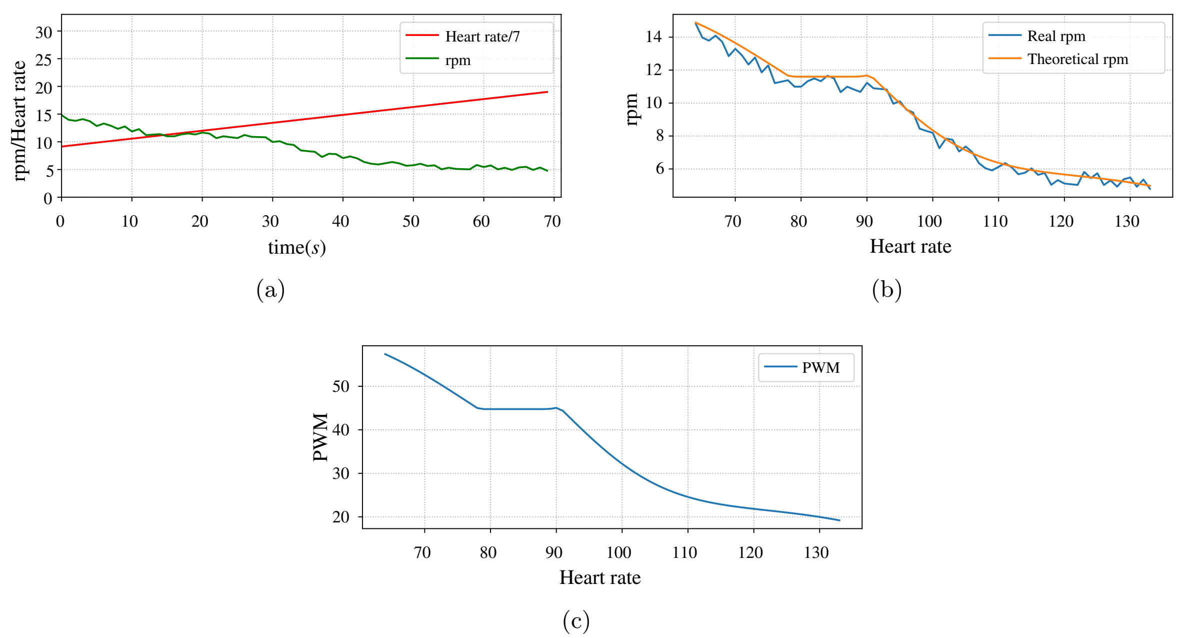


Figure 4.33: Results of Test C1 with automatization (a) increasing heart rate (b) theoretical rpm vs real rpm, (c) PWM control signal.

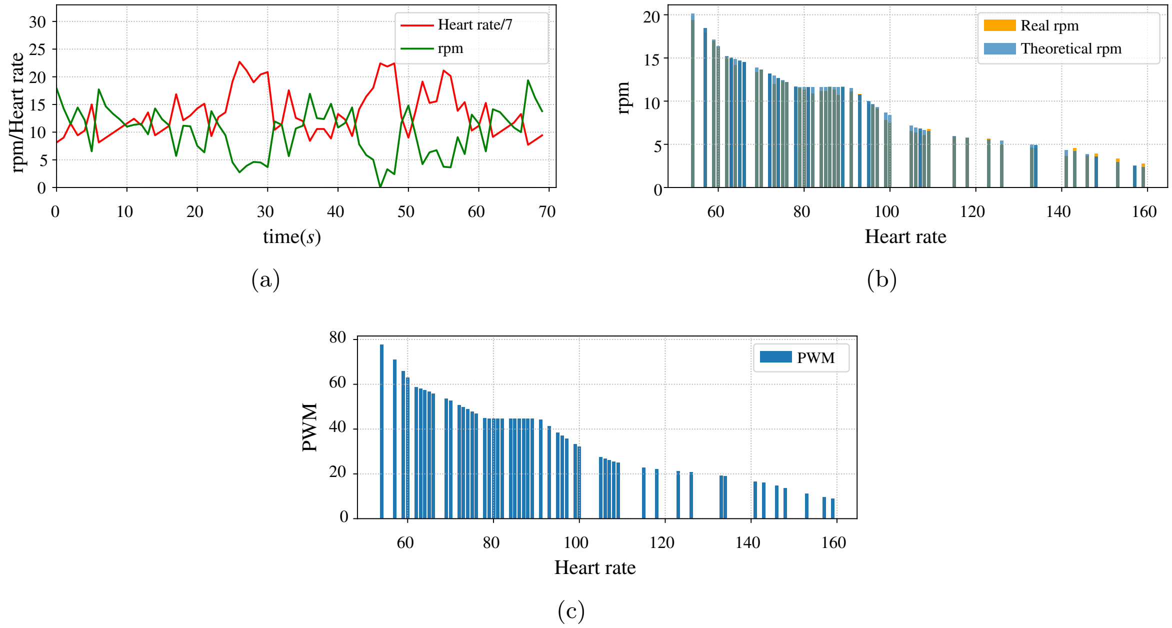


Figure 4.34: Results of Test C2 with automatization (a) random heart rate (b) theoretical rpm vs real rpm, (c) PWM control signal.

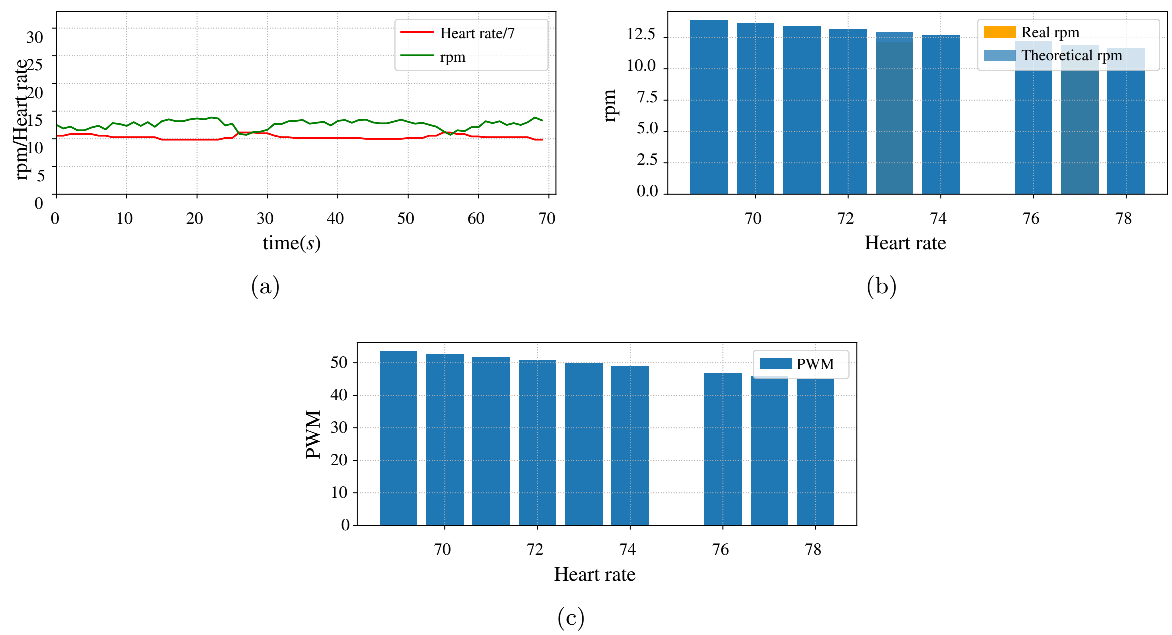


Figure 4.35: Results of Test C3 with automatization (a) real heart rate (b) theoretical rpm vs real rpm, (c) PWM control signal.

4.6 PCB board design

For transportation and ease of use purposes, a PCB board was designed to connect the purchased materials. In figure 4.36 you can see the electrical schematic of the PCB while figure 4.37 shows the PCB layout that will go on the board.

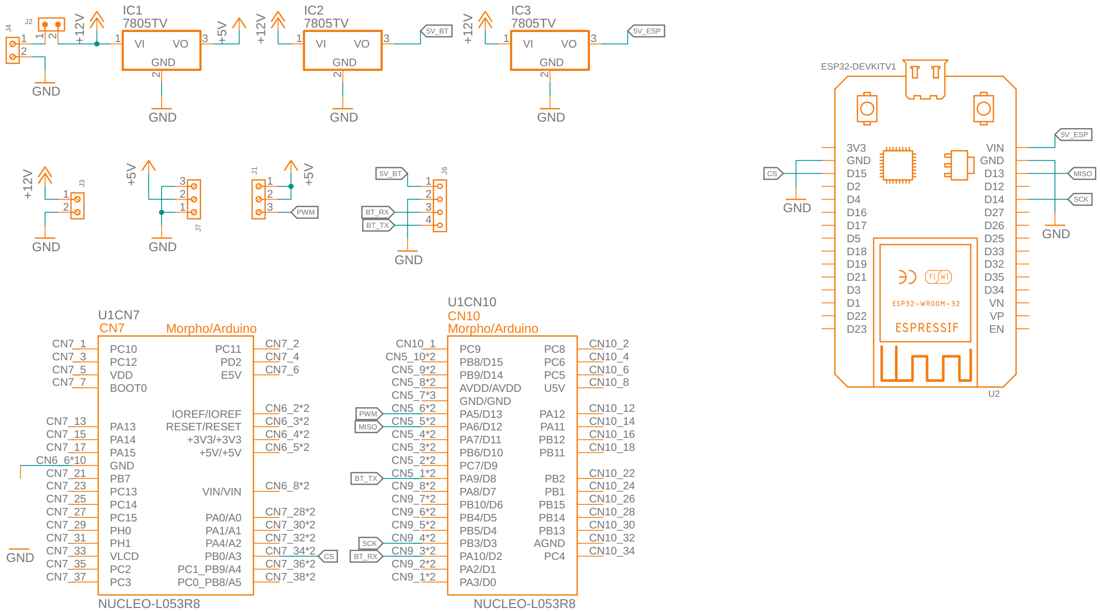


Figure 4.36: Schematic.

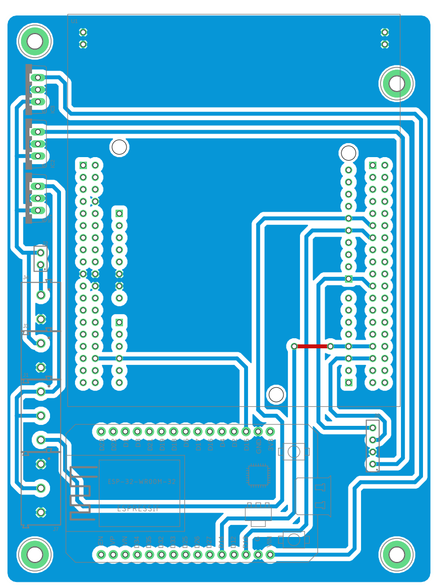
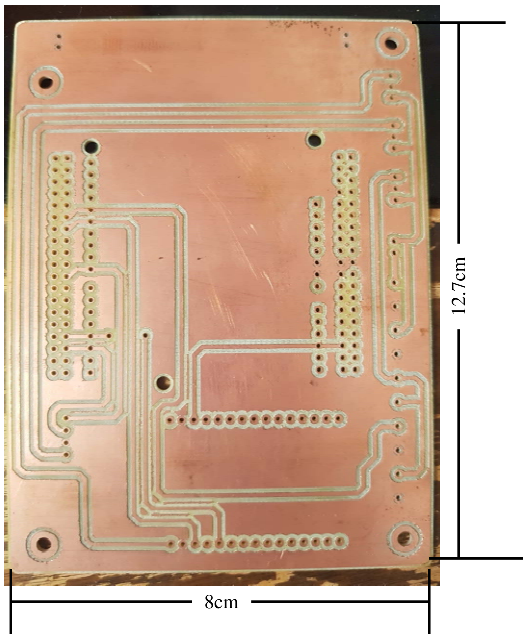
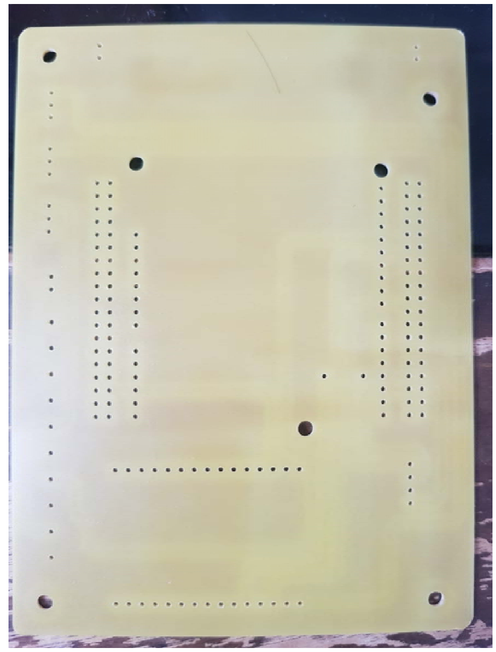


Figure 4.37: PCB layout.

The copper part of the PCB board can be seen in the figure 4.38a, while the region where the materials are placed can be seen in the figure 4.38b.



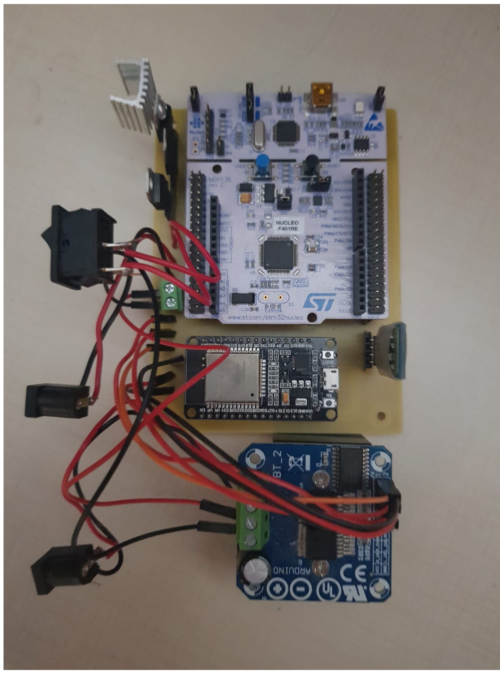
(a)



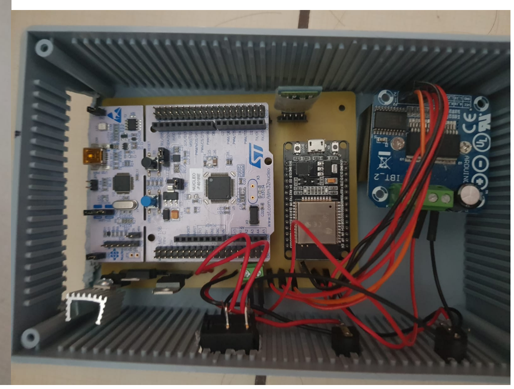
(b)

Figure 4.38: PCB: (a) PCB copper. (b) PCB upper.

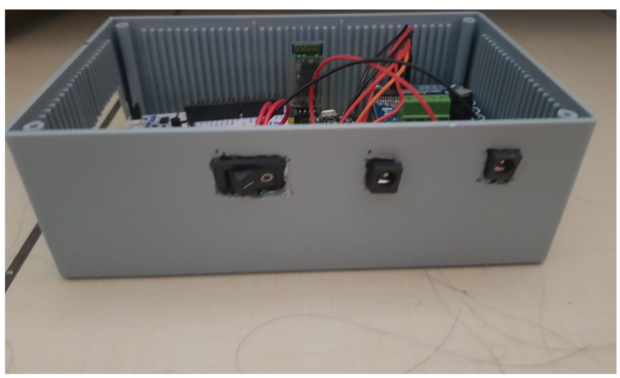
Figure 4.39 shows the PCB board already joined with materials and a box for handling and better transport.



(a)



(b)



(c)

Figure 4.39: PCB board with materials(a) real heart rate (b) PCB in a box viewed from above, (c) PCB in a box side view.

4.7 Letter of consent

As part of the ethical work of this project, a letter of consent is provided to the participants of the tests, where the steps to follow as well as security measures are detailed, in the figures 4.40 and A.14 you can see the format of this letter in english and in the annexes section the signed letters are attached. Note that in the appendix section the signed letters are in spanish because the participants are Mexican.

DD/MM/2021

LETTER OF INFORMED CONSENT

Dear Sir/Madam: You have been invited to participate in this research project. The study will be conducted in the company of a physical therapist and the project author Sergio Aldo Lechuga Ensastiga, who will be responsible for monitoring the session at all times. If you decide to participate in the study, it is important that you consider the following information. Feel free to ask any questions that are not clear to you. The purpose of this study is to determine the effectiveness and satisfaction of the cycloergometer equipment.

Indicate health status:

Age: _____ Weight: ______ Height: ______ Gender: M/F BMI: ____________

Do you suffer from hypertension or any other heart-related condition?

Yes	No

Other?
Specify:____
____
____

Do you suffer from diabetes?

Yes	No

Why do you need therapy sessions?

____
____
____

Do you feel any pain when trying to move your legs?

Yes	No

Yes? Percentage of pain 0-100%: ___

Any other pain that would prevent you from participating in the study or that we should take into consideration?

Yes	No

¿Sí?
Specify:____
____
____

Any other physical or health conditions that you feel should be reported?

Yes	No

¿Sí?
Specify:____

Figure 4.40: Letter of consent page 1.

____

____

Procedures and possible risks:

1. You will lie on your back and will be helped to place your legs on the pedals of the equipment.
2. The corresponding bio-potential sensors will be placed.
3. Before turning on the equipment, you will be asked if you feel any discomfort or pain. If so, an assessment will be made as to whether you can continue.
4. Se encenderá el equipo y con ello empezará la sesión terapéutica.
5. During the course of the session, you will feel the speed of the cycloergometer increasing and decreasing.
6. If during the session you feel any discomfort or pain, inform the attendants and the equipment will be adjusted or the session will be stopped.
7. If a major irregularity in your heart rate is observed, the test will be stopped and will be evaluated to continue on another date.
8. During the session your bio-signals will be monitored.
9. Any external risk that may arise is important to follow the instructions of the expert who accompanies us.
10. At the end of your session, you will leave the equipment as instructed by the physiotherapist.
11. You will be given a satisfaction survey to evaluate the effectiveness of the equipment.

Confidentiality: All information you provide for the study will be kept strictly confidential, will be used only by the project research team, and will not be available for any other purpose. You will be identified with a number and not your name. The results of this study will be published for scientific purposes, but will be presented in such a way that you cannot be identified.

PARTICIPANT:

____

Signature

____

Name and signature of investigator or person obtaining consent:

Name: Sergio Aldo Lechuga Ensastiga

Date/time:

____

Signature:

____

Figure 4.41: Letter of consent page 2.

4.8 Likert survey

A Likert survey was applied to each participant, in table 4.7 shows the questions and answers used for the Likert survey.

Table 4.7: Likert survey Questions and answers.

Statement/ Question	Strongly disagree	Disagree	Undecided	Agree	Strongly agree
1. The automatic gear shift was just right.					
2. Did you find any of the parts of the device uncomfortable?					
3. At any time during therapy did you feel pain or discomfort?					
4. The way to measure their vital signs was comfortable.					
5. It is preferable to make speed changes automatically rather than manually.					
6. Today's session was relaxing.					
7. The apparatus and methods used today can meet your physiotherapeutic needs.					
8. Do you think that today's therapy could be helpful to you in your rehabilitation?					

4.8.1 Results and analysis

The survey was done to seven people who agreed to test the equipment and the instrumentation of the cycloergometer; this survey is based on eight questions and statements, which determine whether the instrumentation applied to the equipment is sufficient to meet physiotherapeutic needs.

For the analysis of the survey, we first calculated the conbranch alpha; this coefficient is calculated to determine if the survey is reliable or not; for this, the coefficient is compared against confidence intervals already established [65]; in the table 4.8, can see these intervals. For this analysis, an alpha of 0.68 was obtained, which within the reliability scale indicates that the survey applied is “Good.”

Table 4.8: Confidence intervals of conbranch’s alpha

Very low	**Low**	**moderate**	**Good**	**Very good**
0 to 0.2	0.2 to 0.4	0.4 to 0.6	0.6 to 0.8	0.8 to 1.0

With Cronbach’s alpha, it is clear that evaluating people’s perception of the equipment is generally well-received. However, the present work analyzes whether the control implemented in the cycloergometer can satisfy the patient’s therapeutic needs. Therefore, it is essential to emphasize to the next questions/items:

1. The automatic gear shift was just right.

5. It is preferable to make speed changes automatically rather than manually.

7. The apparatus and methods used today can meet your physiotherapeutic needs.

8. Do you think that today’s therapy could be helpful to you in your rehabilitation?

In question 1, 71% of the test subjects are totally agree that the speed change was adequate. In comparison, 29% only agree; hence this question has a mean of 4.7, which means that 92% of the people believe that the speed change was adequate; therefore, it is concluded that the fuzzy control works correctly during speed changes. The statistics for this question are presented in the table 4.9.

Table 4.9: Question 1 statistics.

The automatic gear shift was just right.	
Mean	4.71
Standard deviation	0.49
Variance	0.23
Standard error of the mean	0.184

Question 5 has a mean of 4.5, which means that 90% of the test subjects prefer the automatic gear shift to the manual one. The statistics for question 5 are shown in the table 4.10.

Table 4.10: Question 5 statistics.

It is preferable to make speed changes automatically rather than manually.	
Mean	4.5
Standard deviation	0.79
Variance	0.61
Standard error of the mean	0.29

Question 7 has a mean of 4.8, which means that 96% of the test subjects subjects believe that the equipment and instrumentation used can meet physiotherapeutic needs. The statistics for question 7 are shown in the table 4.11.

Table 4.11: Question 7 statistics.

The apparatus and methods used today can meet your physiotherapeutic needs.	
Mean	4.85
Standard deviation	0.38
Variance	0.14
Standard error of the mean	0.14

Question 8 has a mean of 4.8, which means that 96% of the test subjects subjects believe that this project, can help in their rehabilitation. The statistics for question 8 are shown in the table 4.12.

Table 4.12: Question 8 statistics.

Do you think that today's therapy could be helpful to you in your rehabilitation?.	
Mean	4.8
Standard deviation	0.38
Variance	0.14
Standard error of the mean	0.14

The results of the questions measuring whether it is possible to meet physiotherapeutic needs can be seen in figure 4.42. As for questions two, three, four, and six, measure the comfort of using the device. Although the overall perception is good, only 85% strongly agree that all the equipment is not uncomfortable, 11.5% agree, and 3.5% disagree. This may be since to use the device; the person must be on the floor, resulting in something hard and uncomfortable for the person using it. The results of this question and the rest that measure comfort can be seen in the figure 4.43.

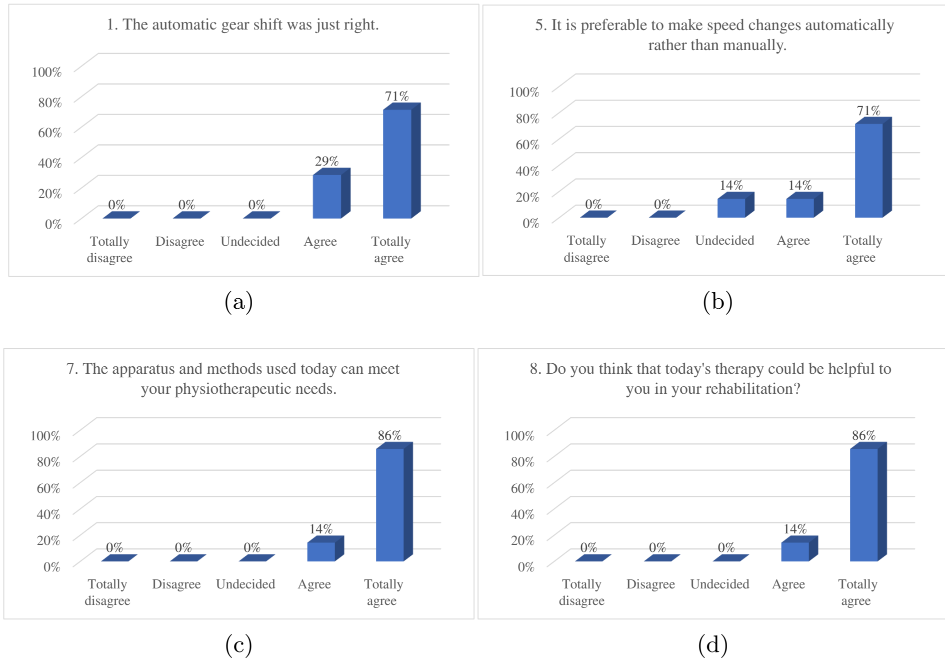


Figure 4.42: Questions that measure whether the control and methods are sufficient to meet the physiotherapist's needs.

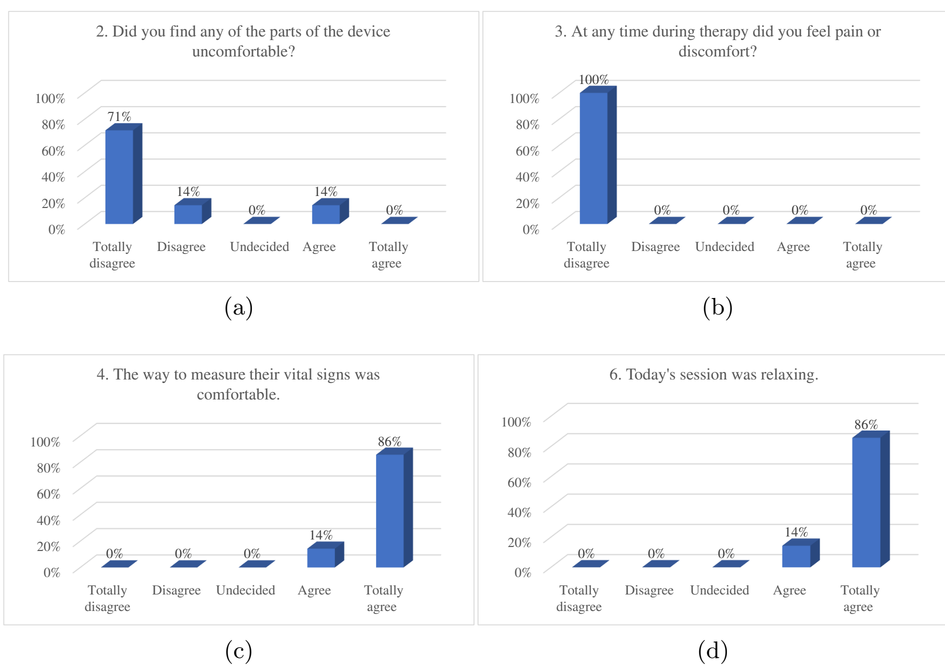


Figure 4.43: Questions that measure comfort in using the equipment.

Seven tests were performed on five people who gave their consent; for confidentiality reasons, the participants' faces are not shown. Figure 4.44 shows the first person, whose data are as follows:

- Age: 37 years old.
- EI: 75%.
- Height: 1.60 m.
- Weight: 62 Kg.
- Hypertension: No.
- Diabetes: No.
- Pain: No.

With this data, we obtain the membership functions for this person; these functions can be seen in the figure 4.45. Note how the VBHR functions are slightly closer together, all due to patient information.

Figure 4.44: Test person 1.

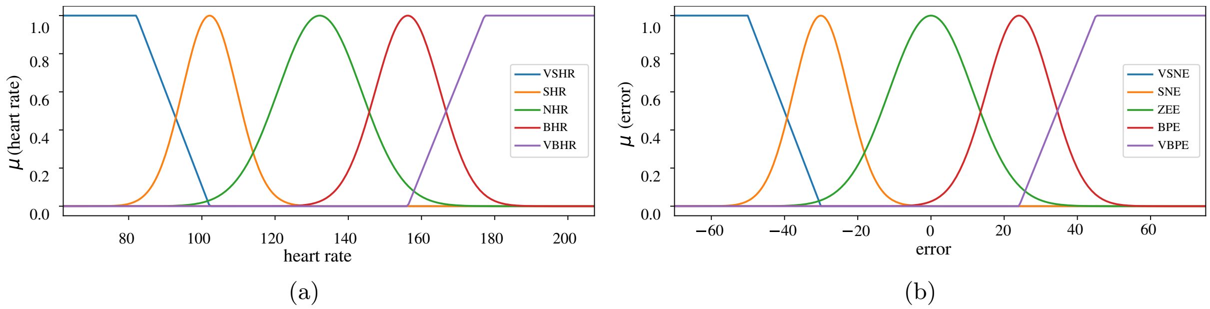


Figure 4.45: membership functions automatization : (a) heart rate (b) error.

In the figure 4.46, we can see the signals obtained and the control signals; in 4.46a we can observe that the person has a heart rate between 64 bpm and 98 bpm, values that correspond to the VSHR and SHR functions, due to the latter in 4.46b the PWM signal is observed to be almost at 100%, however if the hr increases the PWM decrease.

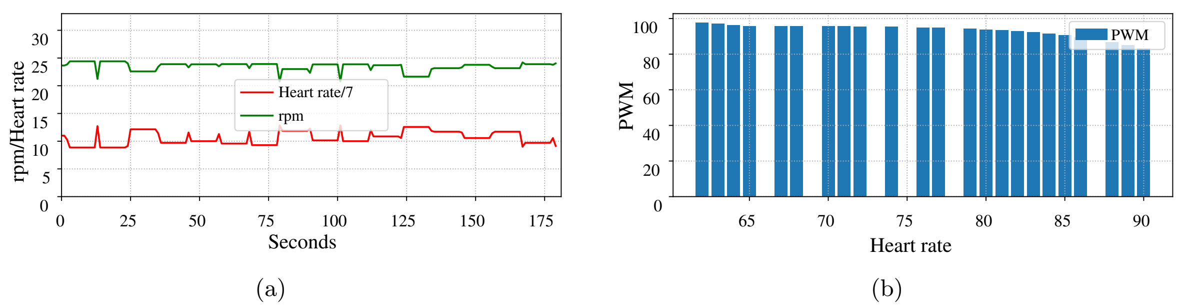


Figure 4.46: Results with patient 1: (a) heart rate vs theoretical rpm (b) PWM control signal.

The second test person can be seen in figure 4.47; its data are as follows:

- Age: 29 years old.
- EI: 80%.
- Height: 1.72 m.
- Weight: 75 Kg.
- Hypertension: No.
- Diabetes: No.
- Pain: No.

Figure 4.47: Test person 2.

In the figure 4.48 it can be seen its membership functions. Note how the NHR, BHR, and VBHR functions are closer due to the data provided.

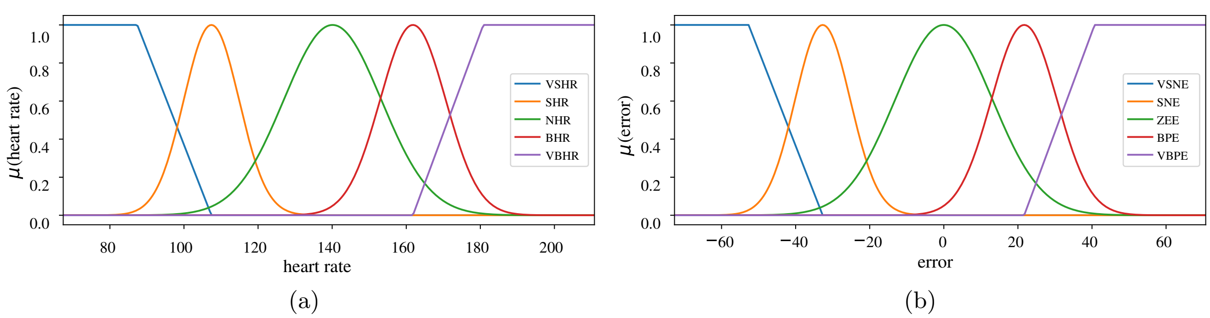
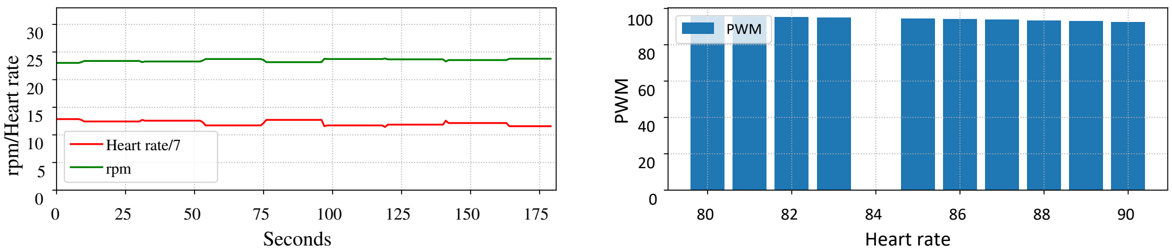


Figure 4.48: membership functions automatization : (a) heart rate (b) error.

In the figure 4.49a, it can be seen that his heart rate did not vary much during the session and that he was also at VSHR and SHR levels, so the control signal in 4.49b shows how it does not vary much from 98%. However, it should be noted that between the heart rate of 80 bpm and 90 bpm, there is a slight variation in the speed, so the control responds to trim or minor changes in heart rate.



(a) (b)

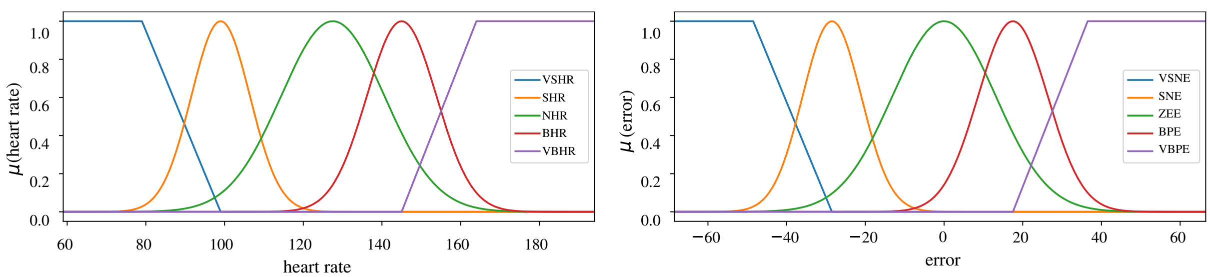
Figure 4.49: Results with patient 2: (a) heart rate vs theoretical rpm (b) PWM control signal.

The third test person can be seen in figure 4.50; its data are as follows:

- Age: 40 years old.
- EI: 70%.
- Height: 1.50 m.
- Weight: 60 Kg.
- Hypertension: No.
- Diabetes: No.
- Pain: No.

Figure 4.50: Test person 3.

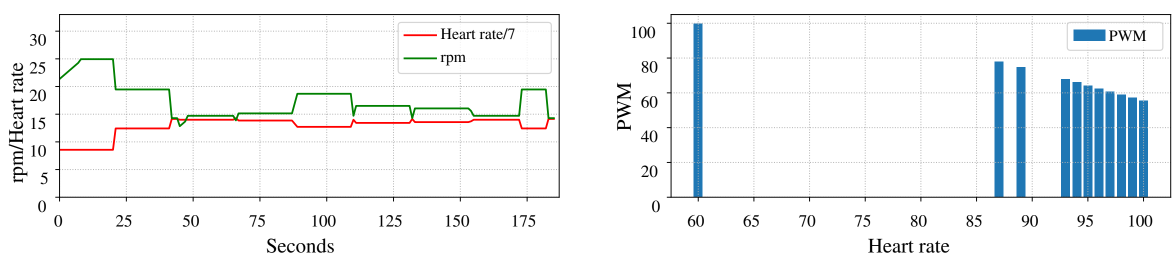
In 4.51 you can see its membership functions and notice how all the functions are now more to the left, with respect to the previous ones, which means that the membership functions are adapted to the person using.



(a) (b)

Figure 4.51: membership functions automatization : (a) heart rate (b) error.

It can be noticed by 4.52a that the patient at the beginning was relaxed, however as the test progressed, his heart rate increased, varying between 86 bpm and 100 bpm, these values together with the setting of membership functions, made the control signal in 4.52b to be between 75% and 58%. This indicates that the control signal adapts to the person's health conditions and heart rate



(a) (b)

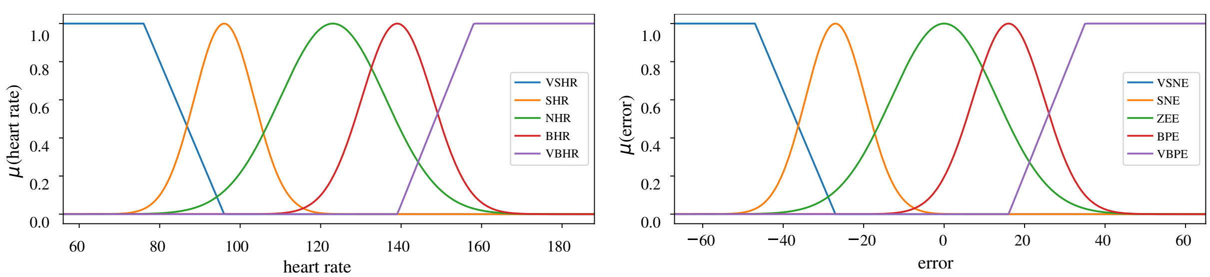
Figure 4.52: Results with patient 3: (a) heart rate vs theoretical rpm (b) PWM control signal.

The fourth test person can be seen in figure 4.53; its data are as follows:

- Age: 29 years old.
- EI: 55%.
- Height: 1.64 m.
- Weight: 77 Kg.
- Hypertension: No.
- Diabetes: No.
- Pain: No.

Figure 4.53: Test person 4.

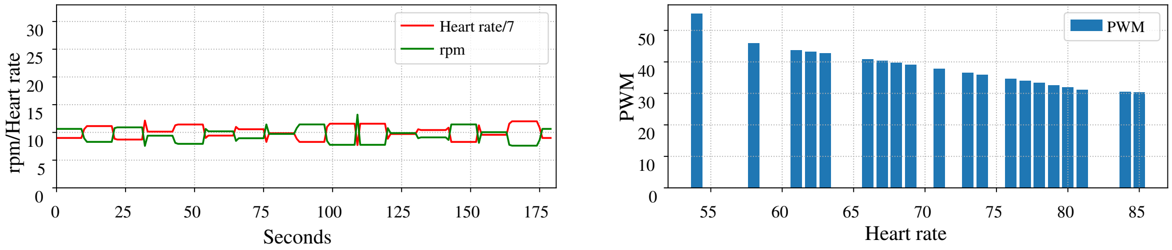
In the figure 4.54 it is slightly shifted to the left concerning the previous functions, again due to the health conditions of the person.



(a) (b)

Figure 4.54: membership functions automatization : (a) heart rate (b) error.

In 4.55a you can see the variation of your heart rate and speed in rpm. For 4.55b it can be noticed how the PWM control signal oscillates between 50% and 35% this is due to the readings of the heart rate, the membership functions and in this case especially to the EI, which in this case was 55%.



(a) (b)

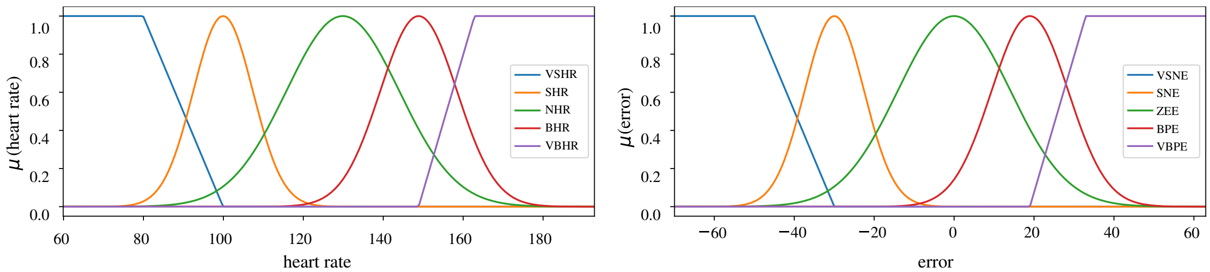
Figure 4.55: Results with patient 4: (a) heart rate vs theoretical rpm (b) PWM control signal.

The fifth test person can be seen in figure 4.56; its data are as follows:

- Age: 31 years old.
- EI: 65%.
- Height: 1.83 m.
- Weight: 125 Kg.
- Hypertension: No.
- Diabetes: No.
- Pain: No.

Figure 4.56: Test person 5.

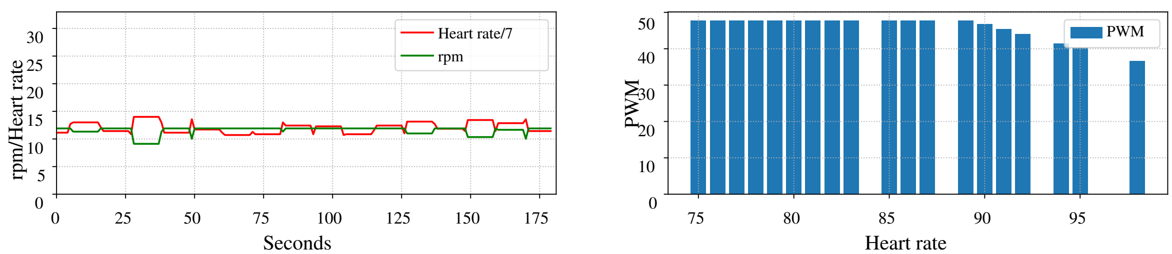
In 4.57 it can be seen that the NHR, BHR, and VBHR functions are closer together, that NHR and BHR are more open than the previous ones and that VBHR has a steeper slope than the previous ones.



(a) (b)

Figure 4.57: membership functions automatization : (a) heart rate (b) error.

We can notice in 4.58a that the speed in rpm varies as expected; increasing the heart rate decreases the speed and reducing the heart rate increases the speed. In 4.58b we can notice that due to the data read and provided by the patient, the PWM signal works between 50% and 45%.



(a) (b)

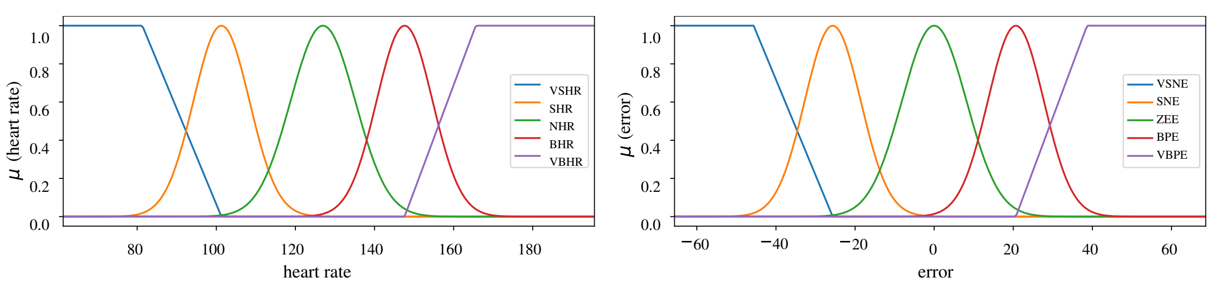
Figure 4.58: Results with patient 5: (a) heart rate vs theoretical rpm (b) PWM control signal.

The sixth test person can be seen in figure 4.59; its data are as follows:

- Age: 44 years old.
- EI: 85%.
- Height: 1.65 m.
- Weight: 71 Kg.
- Hypertension: No.
- Diabetes: No.
- Pain: No.

Figure 4.59: Test person 6.

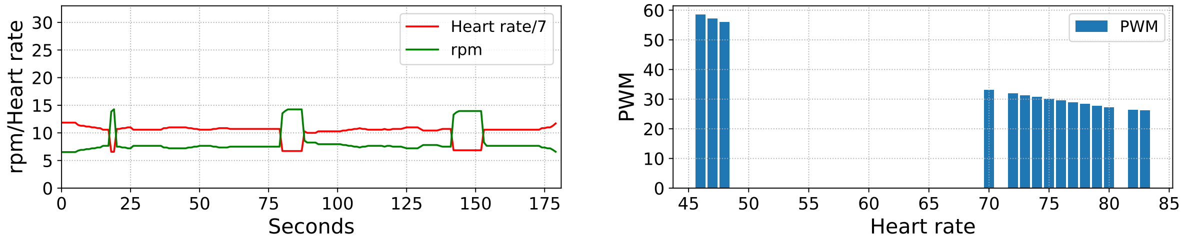
In 4.60 it is noticeable that their membership functions tend to be more standard functions than the previous ones, this due to their health status; however, it can be observed that due to their age and the intensity of exercise used in the session, their maximum heart rate changes.



(a) (b)

Figure 4.60: membership functions automatization : (a) heart rate (b) error.

We can notice in 4.61a that the speed in rpm varies as expected; increasing the heart rate decreases the speed and reducing the heart rate increases the speed. In 4.61b Note that no heart rates between 50 and 69 bps were recorded during the session; however, where it was recorded, the controller gives a desired PWM output.



(a) (b)

Figure 4.61: Results with patient 5: (a) heart rate vs theoretical rpm (b) PWM control signal.

The seventh test person can be seen in figure 4.62; its data are as follows:

- Age: 68 years old.
- EI: 90%.
- Height: 1.60 m.
- Weight: 68 Kg.
- Hypertension: No.
- Diabetes: No.
- Pain: Yes.

Figure 4.62: Test person 7.

In 4.63 It is observed that their membership functions are more standard, so that these functions depend on the exercise intensity.

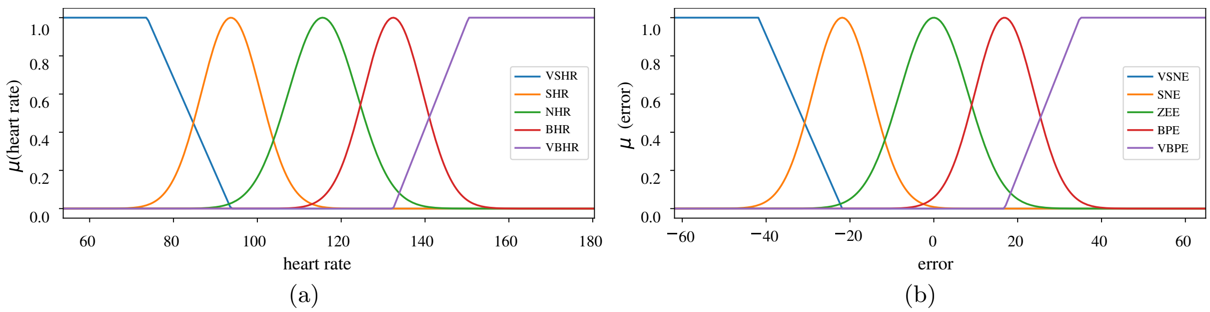


Figure 4.63: membership functions automatization : (a) heart rate (b) error.

Before starting the test and with the consent of the physiotherapist, the patient was asked from 1 to 10 how much pain he felt and if this was an impediment to doing the test; according to the same patient, his pain was very little, barely a nuisance. Therefore, one part of the test was not taken into account if she had pain; the other part was taken into account. In the figure we 4.64 can observe that her heart rate was a constant 63 *bpm* throughout the session, so the speed of the cycloergometer was 24 rpm, which corresponds to 91% of the maximum achievable speed. This was until after the 72nd second, it was decided to add the variable of pain, where the rate was reduced to 65% of the maximum speed.

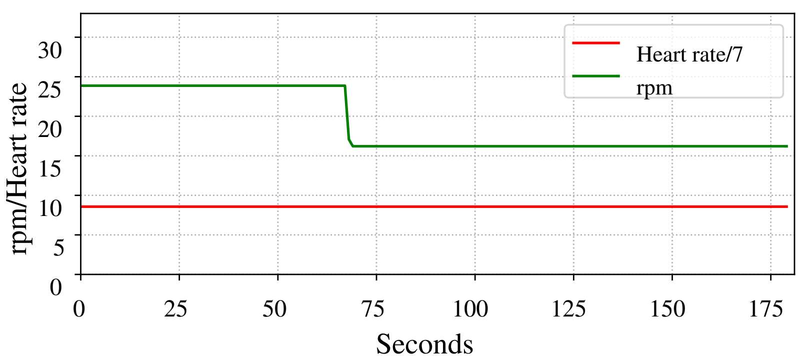


Figure 4.64: Results with patient 7: heart rate vs theoretical rpm.

CHAPTER 5

Conclusions and future works

For this work, we managed to implement a flexible methodology that allows correcting or improving previous steps; a significant part of it is based on testing, and each ends satisfactorily. In earlier works as [22, 23, 25] it had been proposed to acquire biosignals for the classification of diseases or ailments of a person, the improvement in this work against the previous ones is that not only an indirect category is being made, but from that classification, the control of the cycloergometer is achieved.

The first tests show that the first proposed fuzzy control manages to vary the speed of the cycleergometer according to the heart rate of the patient; this is best observed in the tests where the heart rate was random because, despite abrupt changes in the bio-signal, the speed only increases when the heart rate is low and decreases when the heart rate is high.

It was confirmed what they said in the investigations of [21, 32], that the PID control was not the most suitable to work in this type of system. Empirically, the following values were obtained for the gains: $Kp = 0.65$ $Ki = 0.030$ $Kd = 0.035$ various combinations of gains and increase and decrease of each of them were tested and although the latter gains produced acceptable control for absolute values, it can be shown that the PID control does not work correctly with non-absolute variables that belong to a human language, such as heart rate. This can be seen in the figure 4.16 where a rhythm value has several PWM speeds, and it is not congruent as in the figure 4.15c that for a heart rate value only had a single PWM value.

The tests to check the behavior of the automation of the membership functions demonstrate the flexibility of the project. Each person has their membership functions. Those functions adapt to them according to their state of health; likewise, the control charts of these tests reflect that the fuzzy control adjusts and works correctly to the changes that different membership functions may have.

In terms of patient testing, the fuzzy control yielded the desired PWM output for each patient depending on the membership functions of each patient, which again shows the flexibility and adaptability of the device. At the same time, the Likert survey shows that all patients think that the project could be beneficial in their rehabilitation.

The scientific contribution of this project is in its flexibility and availability to adapt to other equipment, not only therapeutic but also sports; for example, this control can be adapted to a treadmill, a bicycle, or strength equipment in both legs and arms. Also, the contribution lies in the fact that there is not such a vast state of the art on the subject of fuzzy controllers for therapeutic equipment, this work does not replace previous work. Still, it does contribute to the research and the topics reviewed in the project.

Regarding the ergonomics of the equipment, from the analysis of the surveys, it is concluded that the equipment, in general terms, is perceived as comfortable for the realization of the therapy; however, after talking with the patients and the physiotherapist, they mentioned that it would be nice and an improvement for the user if there was something softer for the back and head.

5.1 Future works

As already mentioned, this project can be transported to control other sports and therapeutic equipment. There is also the great option of changing the biosignals that manage the equipment; for example, it could be stress, muscle movement, or breathing rate instead of a heart rate. To apply such changes, you would probably add a signal processing stage; however, the fuzzy algorithm will not change too much.

One major innovation that could be achieved is to replace the stm32 MCU with an FPGA. In this project, several measurement processes, data transmission, timers, and interrupts are performed. This means that resources are consumed or shared; with an FPGA, most functions would be parallel, and the resources would be individual.

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Appendix

01

07/10/2021

CARTA DE CONSENTIMIENTO INFORMADO

Estimado(a) Señor/Señora: Usted ha sido invitado a participar en el presente proyecto de investigación, El estudio se realizará en compañía de un fisioterapeuta, y del autor del proyecto Sergio Aldo Lechuga Ensastiga, los cuales serán responsables de estar monitoreando la sesión en todo momento que dure. Si usted decide participar en el estudio, es importante que considere la siguiente información. Siéntase libre de preguntar cualquier asunto que no le quede claro. El propósito del presente estudio es determinar la efectividad y satisfacción del equipo denominado cicloergómetro.

Indicar estado de salud:

Edad: 37 Peso: 62 Altura: 1.60 Sexo: M/F IMC: 24.7

¿Sufre de hipertensión o algún otro padecimiento relacionado al corazón?

Si No

¿Otra?

Especifique:____

¿Sufre de diabetes?

Si No

¿Razón por la cual necesita de sesiones de terapía?

¿Siente algún dolor al intentar mover las piernas?

Si No

¿Sí? Porcentaje de dolor 0-100%: ___

¿Algún otro dolor que le impida participar en el estudio o que debamos tener a consideración?

Si No

¿Sí?

Especifique:____

¿Alguna otra condición física o de salud que crea que deba ser informado?

Si No

¿Sí?

Especifique:____

Figure A.1: Letter of consent of patient one page 1.

01

Procedimientos y posibles riesgos:

1. Se acostará boca arriba y se le ayudará a colocar sus piernas en los pedales del equipo.
2. Se colocarán los sensores bio-potenciales correspondientes.
3. Antes de encender el equipo se le preguntará si siente alguna molestia o dolor. Si es así se evaluará si se puede continuar.
4. Se encenderá el equipo y con ello empezará la sesión terapéutica.
5. Durante el transcurso de la sesión usted sentirá como la velocidad del cicloergómetro aumenta y disminuye.
6. Si durante la sesión siente molestia o dolor informe a los encargados y se ajustará el equipo o se detendrá la sesión.
7. Si se observa una irregularidad mayor en su ritmo cardíaco se detendrá la prueba y se evaluará continuar en otra fecha.
8. Durante la sesión se monitorearán sus bio-señales.
9. Cualquier riesgo externo que pueda surgir es importante seguir las indicaciones del experto que nos acompañe.
10. Al finalizar su sesión usted dejara el equipo conforme le indique el fisioterapeuta.
11. Se le otorgara una encuesta de satisfacción para evaluar la efectividad del equipo.

Confidencialidad: Toda la información que Usted nos proporcione para el estudio será de carácter estrictamente confidencial, será utilizada únicamente por el equipo de investigación del proyecto y no estará disponible para ningún otro propósito. Usted quedará identificado(a) con un número y no con su nombre. Los resultados de este estudio serán publicados con fines científicos, pero se presentarán de tal manera que no podrá ser identificado(a).

Fecha/hora:
11:20, 10 07 2021

Firma

Nombre y firma del investigador o persona que obtiene el consentimiento:

Nombre: Sergio Aldo Lechuga Ensastiga

Firma:

Figure A.2: Letter of consent of pacient one page 2.

04

07/10/2021

CARTA DE CONSENTIMIENTO INFORMADO

Estimado(a) Señor/Señora: Usted ha sido invitado a participar en el presente proyecto de investigación, El estudio se realizará en compañía de un fisioterapeuta, y del autor del proyecto Sergio Aldo Lechuga Ensastiga, los cuales serán responsables de estar monitoreando la sesión en todo momento que dure. Si usted decide participar en el estudio, es importante que considere la siguiente información. Siéntase libre de preguntar cualquier asunto que no le quede claro. El propósito del presente estudio es determinar la efectividad y satisfacción del equipo denominado cicloergómetro.

Indicar estado de salud:

Edad: 29 Peso: 75 Altura: 1.72 Sexo: M/F IMC: 25.35

¿Sufre de hipertensión o algún otro padecimiento relacionado al corazón?

Si	No

¿Otra?

Especifique:________________________________

¿Sufre de diabetes?

Si	No

¿Razón por la cual necesita de sesiones de terapía?

Dolores en la ciatica

¿Siente algún dolor al intentar mover las piernas?

Si	No

¿Sí? Porcentaje de dolor 0-100%: ___

¿Algún otro dolor que le impida participar en el estudio o que debamos tener a consideración?

Si	No

¿Sí?

Especifique:________________________________

¿Alguna otra condición física o de salud que crea que deba ser informado?

Si	No

¿Sí?

Especifique:________________________________

Figure A.3: Letter of consent of patient two page 1.

02

Procedimientos y posibles riesgos:

1. Se acostará boca arriba y se le ayudará a colocar sus piernas en los pedales del equipo.
2. Se colocarán los sensores bio-potenciales correspondientes.
3. Antes de encender el equipo se le preguntará si siente alguna molestia o dolor. Si es así se evaluará si se puede continuar.
4. Se encenderá el equipo y con ello empezará la sesión terapéutica.
5. Durante el transcurso de la sesión usted sentirá como la velocidad del cicloergómetro aumenta y disminuye.
6. Si durante la sesión siente molestia o dolor informe a los encargados y se ajustará el equipo o se detendrá la sesión.
7. Si se observa una irregularidad mayor en su ritmo cardíaco se detendrá la prueba y se evaluará continuar en otra fecha.
8. Durante la sesión se monitorearán sus bio-señales.
9. Cualquier riesgo externo que pueda surgir es importante seguir las indicaciones del experto que nos acompañe.
10. Al finalizar su sesión usted dejara el equipo conforme le indique el fisioterapeuta.
11. Se le otorgara una encuesta de satisfacción para evaluar la efectividad del equipo.

Confidencialidad: Toda la información que Usted nos proporcione para el estudio será de carácter estrictamente confidencial, será utilizada únicamente por el equipo de investigación del proyecto y no estará disponible para ningún otro propósito. Usted quedará identificado(a) con un número y no con su nombre. Los resultados de este estudio serán publicados con fines científicos, pero se presentarán de tal manera que no podrá ser identificado(a).

Fecha/hora:
7/10/2021 11:52.

Firma

Nombre y firma del investigador o persona que obtiene el consentimiento:

Nombre: Sergio Aldo Lechuga Ensastiga

Firma:

Figure A.4: Letter of consent of patient two page 2.

03

07/10/2021

CARTA DE CONSENTIMIENTO INFORMADO

Estimado(a) Señor/Señora: Usted ha sido invitado a participar en el presente proyecto de investigación, El estudio se realizará en compañía de un fisioterapeuta, y del autor del proyecto Sergio Aldo Lechuga Ensastiga, los cuales serán responsables de estar monitoreando la sesión en todo momento que dure. Si usted decide participar en el estudio, es importante que considere la siguiente información. Siéntase libre de preguntar cualquier asunto que no le quede claro. El propósito del presente estudio es determinar la efectividad y satisfacción del equipo denominado cicloergómetro.

Indicar estado de salud:

Edad: 40 Peso: ~~1.50~~ 62 Altura: 1.50 Sexo: M/F IMC: 27.55

¿Sufre de hipertensión o algún otro padecimiento relacionado al corazón?

Si	No

¿Otra?

Especifique:____

¿Sufre de diabetes?

Si	No

¿Razón por la cual necesita de sesiones de terapía?

recomendaciones medicas debido a varices y a sedentarismo

¿Siente algún dolor al intentar mover las piernas?

Si	No

¿Sí? Porcentaje de dolor 0-100%: ___

¿Algún otro dolor que le impida participar en el estudio o que debamos tener a consideración?

Si	No

¿Sí?

Especifique:____

¿Alguna otra condición física o de salud que crea que deba ser informado?

Si	No

¿Sí?

Especifique:____

Figure A.5: Letter of consent of patient three page 1.

03

Procedimientos y posibles riesgos:

1. Se acostará boca arriba y se le ayudará a colocar sus piernas en los pedales del equipo.
2. Se colocarán los sensores bio-potenciales correspondientes.
3. Antes de encender el equipo se le preguntará si siente alguna molestia o dolor. Si es así se evaluará si se puede continuar.
4. Se encenderá el equipo y con ello empezará la sesión terapéutica.
5. Durante el transcurso de la sesión usted sentirá como la velocidad del cicloergómetro aumenta y disminuye.
6. Si durante la sesión siente molestia o dolor informe a los encargados y se ajustará el equipo o se detendrá la sesión.
7. Si se observa una irregularidad mayor en su ritmo cardíaco se detendrá la prueba y se evaluará continuar en otra fecha.
8. Durante la sesión se monitorearán sus bio-señales.
9. Cualquier riesgo externo que pueda surgir es importante seguir las indicaciones del experto que nos acompañe.
10. Al finalizar su sesión usted dejara el equipo conforme le indique el fisioterapeuta.
11. Se le otorgara una encuesta de satisfacción para evaluar la efectividad del equipo.

Confidencialidad: Toda la información que Usted nos proporcione para el estudio será de carácter estrictamente confidencial, será utilizada únicamente por el equipo de investigación del proyecto y no estará disponible para ningún otro propósito. Usted quedará identificado(a) con un número y no con su nombre. Los resultados de este estudio serán publicados con fines científicos, pero se presentarán de tal manera que no podrá ser identificado(a).

Fecha/hora:

Firma

Nombre y firma del investigador o persona que obtiene el consentimiento:

Nombre: Sergio Aldo Lechuga Ensastiga

Firma:

Figure A.6: Letter of consent of patient three page 2.

04

07/10/2021

CARTA DE CONSENTIMIENTO INFORMADO

Estimado(a) Señor/Señora: Usted ha sido invitado a participar en el presente proyecto de investigación, El estudio se realizará en compañía de un fisioterapeuta, y del autor del proyecto Sergio Aldo Lechuga Ensastiga, los cuales serán responsables de estar monitoreando la sesión en todo momento que dure. Si usted decide participar en el estudio, es importante que considere la siguiente información. Siéntase libre de preguntar cualquier asunto que no le quede claro. El propósito del presente estudio es determinar la efectividad y satisfacción del equipo denominado cicloergómetro.

Indicar estado de salud:

Edad: 29 Peso: 77 Altura: 1.64 Sexo: M/F IMC: 28.62

¿Sufre de hipertensión o algún otro padecimiento relacionado al corazón?

Si	No

¿Otra?

Especifique:____

¿Sufre de diabetes?

Si	No

¿Razón por la cual necesita de sesiones de terapia?

Dolor en rodillas debido a deporte

¿Siente algún dolor al intentar mover las piernas?

Si	No

¿Sí? Porcentaje de dolor 0-100%: ___

¿Algún otro dolor que le impida participar en el estudio o que debamos tener a consideración?

Si	No

¿Sí?

Especifique:____

¿Alguna otra condición física o de salud que crea que deba ser informado?

Si	No

¿Sí?

Especifique:____

Figure A.7: Letter of consent of patient four page 1.

04

Procedimientos y posibles riesgos:

1. Se acostará boca arriba y se le ayudará a colocar sus piernas en los pedales del equipo.
2. Se colocarán los sensores bio-potenciales correspondientes.
3. Antes de encender el equipo se le preguntará si siente alguna molestia o dolor. Si es así se evaluará si se puede continuar.
4. Se encenderá el equipo y con ello empezará la sesión terapéutica.
5. Durante el transcurso de la sesión usted sentirá como la velocidad del cicloergómetro aumenta y disminuye.
6. Si durante la sesión siente molestia o dolor informe a los encargados y se ajustará el equipo o se detendrá la sesión.
7. Si se observa una irregularidad mayor en su ritmo cardíaco se detendrá la prueba y se evaluará continuar en otra fecha.
8. Durante la sesión se monitorearán sus bio-señales.
9. Cualquier riesgo externo que pueda surgir es importante seguir las indicaciones del experto que nos acompañe.
10. Al finalizar su sesión usted dejara el equipo conforme le indique el fisioterapeuta.
11. Se le otorgara una encuesta de satisfacción para evaluar la efectividad del equipo.

Confidencialidad: Toda la información que Usted nos proporcione para el estudio será de carácter estrictamente confidencial, será utilizada únicamente por el equipo de investigación del proyecto y no estará disponible para ningún otro propósito. Usted quedará identificado(a) con un número y no con su nombre. Los resultados de este estudio serán publicados con fines científicos, pero se presentarán de tal manera que no podrá ser identificado(a).

Fecha/hora:
10:45 7/10/21

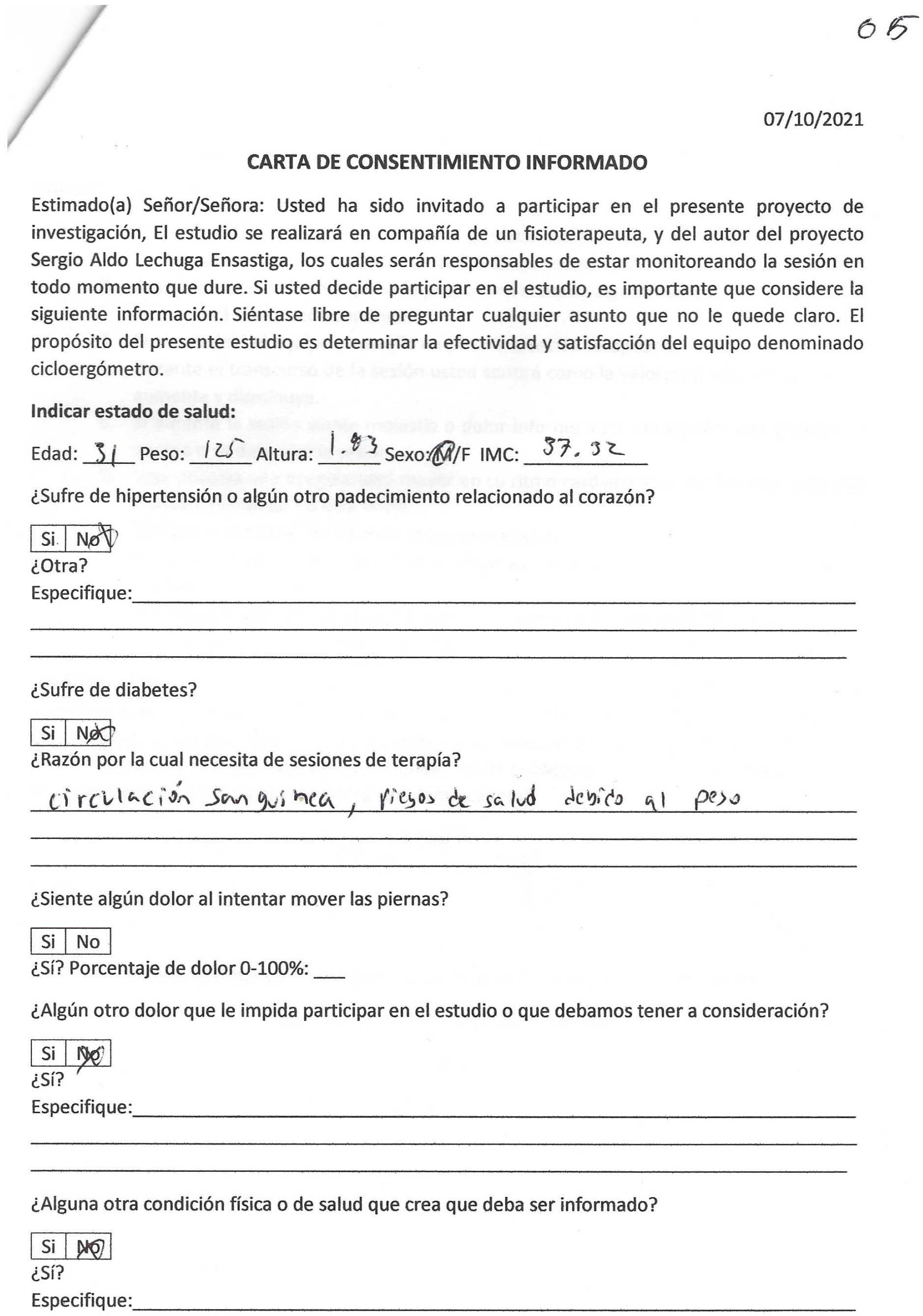
Firma

Nombre y firma del investigador o persona que obtiene el consentimiento:

Nombre: Sergio Aldo Lechuga Ensastiga

Firma:

Figure A.8: Letter of consent of patient four page 2.



05

07/10/2021

CARTA DE CONSENTIMIENTO INFORMADO

Estimado(a) Señor/Señora: Usted ha sido invitado a participar en el presente proyecto de investigación, El estudio se realizará en compañía de un fisioterapeuta, y del autor del proyecto Sergio Aldo Lechuga Ensastiga, los cuales serán responsables de estar monitoreando la sesión en todo momento que dure. Si usted decide participar en el estudio, es importante que considere la siguiente información. Siéntase libre de preguntar cualquier asunto que no le quede claro. El propósito del presente estudio es determinar la efectividad y satisfacción del equipo denominado cicloergómetro.

Indicar estado de salud:

Edad: 31 Peso: 125 Altura: 1.83 Sexo: M/F IMC: 37.32

¿Sufre de hipertensión o algún otro padecimiento relacionado al corazón?

Si | No

¿Otra?

Especifique:

¿Sufre de diabetes?

Si | No

¿Razón por la cual necesita de sesiones de terapía?

circulación sanguinea, riesgos de salud debido al peso

¿Siente algún dolor al intentar mover las piernas?

Si | No

¿Sí? Porcentaje de dolor 0-100%: ___

¿Algún otro dolor que le impida participar en el estudio o que debamos tener a consideración?

Si | No

¿Sí?

Especifique:

¿Alguna otra condición física o de salud que crea que deba ser informado?

Si | No

¿Sí?

Especifique:

Figure A.9: Letter of consent of patient five page 1.

05

Procedimientos y posibles riesgos:

1. Se acostará boca arriba y se le ayudará a colocar sus piernas en los pedales del equipo.
2. Se colocarán los sensores bio-potenciales correspondientes.
3. Antes de encender el equipo se le preguntará si siente alguna molestia o dolor. Si es así se evaluará si se puede continuar.
4. Se encenderá el equipo y con ello empezará la sesión terapéutica.
5. Durante el transcurso de la sesión usted sentirá como la velocidad del cicloergómetro aumenta y disminuye.
6. Si durante la sesión siente molestia o dolor informe a los encargados y se ajustará el equipo o se detendrá la sesión.
7. Si se observa una irregularidad mayor en su ritmo cardíaco se detendrá la prueba y se evaluará continuar en otra fecha.
8. Durante la sesión se monitorearán sus bio-señales.
9. Cualquier riesgo externo que pueda surgir es importante seguir las indicaciones del experto que nos acompañe.
10. Al finalizar su sesión usted dejara el equipo conforme le indique el fisioterapeuta.
11. Se le otorgara una encuesta de satisfacción para evaluar la efectividad del equipo.

Confidencialidad: Toda la información que Usted nos proporcione para el estudio será de carácter estrictamente confidencial, será utilizada únicamente por el equipo de investigación del proyecto y no estará disponible para ningún otro propósito. Usted quedará identificado(a) con un número y no con su nombre. Los resultados de este estudio serán publicados con fines científicos, pero se presentarán de tal manera que no podrá ser identificado(a).

Fecha/hora:
07-octubre-2021

Firma

Nombre y firma del investigador o persona que obtiene el consentimiento:

Nombre: Sergio Aldo Lechuga Ensastiga

Firma:

Figure A.10: Letter of consent of patient five page 2.

07/10/2021

CARTA DE CONSENTIMIENTO INFORMADO

Estimado(a) Señor/Señora: Usted ha sido invitado a participar en el presente proyecto de investigación, El estudio se realizará en compañía de un fisioterapeuta, y del autor del proyecto Sergio Aldo Lechuga Ensastiga, los cuales serán responsables de estar monitoreando la sesión en todo momento que dure. Si usted decide participar en el estudio, es importante que considere la siguiente información. Siéntase libre de preguntar cualquier asunto que no le quede claro. El propósito del presente estudio es determinar la efectividad y satisfacción del equipo denominado cicloergómetro.

Indicar estado de salud:

Edad: 44 Peso: 71 Altura: 1.65 Sexo: M/F IMC: 26.1

¿Sufre de hipertensión o algún otro padecimiento relacionado al corazón?

Si	No

¿Otra?

Especifique:____

¿Sufre de diabetes?

Si	No

¿Razón por la cual necesita de sesiones de terapia?

Recuperación de datos cirugía

¿Siente algún dolor al intentar mover las piernas?

Si	~~No~~

¿Sí? Porcentaje de dolor 0-100%: 0

¿Algún otro dolor que le impida participar en el estudio o que debamos tener a consideración?

Si	No

¿Sí?

Especifique:____

¿Alguna otra condición física o de salud que crea que deba ser informado?

Si	No

¿Sí?

Especifique:____

Figure A.11: Letter of consent of patient six page 1.

Procedimientos y posibles riesgos:

1. Se acostará boca arriba y se le ayudará a colocar sus piernas en los pedales del equipo.
2. Se colocarán los sensores bio-potenciales correspondientes.
3. Antes de encender el equipo se le preguntará si siente alguna molestia o dolor. Si es así se evaluará si se puede continuar.
4. Se encenderá el equipo y con ello empezará la sesión terapéutica.
5. Durante el transcurso de la sesión usted sentirá como la velocidad del cicloergómetro aumenta y disminuye.
6. Si durante la sesión siente molestia o dolor informe a los encargados y se ajustará el equipo o se detendrá la sesión.
7. Si se observa una irregularidad mayor en su ritmo cardíaco se detendrá la prueba y se evaluará continuar en otra fecha.
8. Durante la sesión se monitorearán sus bio-señales.
9. Cualquier riesgo externo que pueda surgir es importante seguir las indicaciones del experto que nos acompañe.
10. Al finalizar su sesión usted dejara el equipo conforme le indique el fisioterapeuta.
11. Se le otorgara una encuesta de satisfacción para evaluar la efectividad del equipo.

Confidencialidad: Toda la información que Usted nos proporcione para el estudio será de carácter estrictamente confidencial, será utilizada únicamente por el equipo de investigación del proyecto y no estará disponible para ningún otro propósito. Usted quedará identificado(a) con un número y no con su nombre. Los resultados de este estudio serán publicados con fines científicos, pero se presentarán de tal manera que no podrá ser identificado(a).

Fecha/hora:

07/10/2021 5:02 pm

Firma:

Nombre y firma del investigador o persona que obtiene el consentimiento:

Nombre: Sergio Aldo Lechuga Ensastiga

Firma:

Figure A.12: Letter of consent of patient six page 2.

07

08/02/2022

CARTA DE CONSENTIMIENTO INFORMADO

Estimado(a) Señor/Señora: Usted ha sido invitado a participar en el presente proyecto de investigación, El estudio se realizará en compañía de un fisioterapeuta, y del autor del proyecto Sergio Aldo Lechuga Ensastiga, los cuales serán responsables de estar monitoreando la sesión en todo momento que dure. Si usted decide participar en el estudio, es importante que considere la siguiente información. Siéntase libre de preguntar cualquier asunto que no le quede claro. El propósito del presente estudio es determinar la efectividad y satisfacción del equipo denominado cicloergómetro.

Indicar estado de salud:

Edad: 66 Peso: 68 Altura: 1.60 Sexo: M/F IMC: 26.6

¿Sufre de hipertensión o algún otro padecimiento relacionado al corazón?

Si | ~~No~~

¿Otra?

Especifique:______

¿Sufre de diabetes?

Si | ~~No~~

¿Razón por la cual necesita de sesiones de terapia?

Movimiento de columna

¿Siente algún dolor al intentar mover las piernas?

~~Si~~ | No

¿Sí? Porcentaje de dolor 0-100%: 20%

¿Algún otro dolor que le impida participar en el estudio o que debamos tener a consideración?

Si | ~~No~~

¿Sí?

Especifique:______

¿Alguna otra condición física o de salud que crea que deba ser informado?

Si | ~~No~~

¿Sí?

Especifique:______

Figure A.13: Letter of consent of patient seven page 1.

Procedimientos y posibles riesgos:

1. Se acostará boca arriba y se le ayudará a colocar sus piernas en los pedales del equipo.
2. Se colocarán los sensores bio-potenciales correspondientes.
3. Antes de encender el equipo se le preguntará si siente alguna molestia o dolor. Si es así se evaluará si se puede continuar.
4. Se encenderá el equipo y con ello empezará la sesión terapéutica.
5. Durante el transcurso de la sesión usted sentirá como la velocidad del cicloergómetro aumenta y disminuye.
6. Si durante la sesión siente molestia o dolor informe a los encargados y se ajustará el equipo o se detendrá la sesión.
7. Si se observa una irregularidad mayor en su ritmo cardíaco se detendrá la prueba y se evaluará continuar en otra fecha.
8. Durante la sesión se monitorearán sus bio-señales.
9. Cualquier riesgo externo que pueda surgir es importante seguir las indicaciones del experto que nos acompañe.
10. Al finalizar su sesión usted dejara el equipo conforme le indique el fisioterapeuta.
11. Se le otorgara una encuesta de satisfacción para evaluar la efectividad del equipo.

Confidencialidad: Toda la información que Usted nos proporcione para el estudio será de carácter estrictamente confidencial, será utilizada únicamente por el equipo de investigación del proyecto y no estará disponible para ningún otro propósito. Usted quedará identificado(a) con un número y no con su nombre. Los resultados de este estudio serán publicados con fines científicos, pero se presentarán de tal manera que no podrá ser identificado(a).

Fecha/hora:
08/02/2022 5:32 pm

Firma

Nombre y firma del investigador o persona que obtiene el consentimiento:

Nombre: Sergio Aldo Lechuga Ensastiga

Firma:

Figure A.14: Letter of consent of patient seven page 2.