Master Thesis

DEVELOPMENT OF A SOCIALLY ASSISTIVE HUMAN-ROBOT INTERFACE FOR CARDIAC REHABILITATION

Jonathan Alejandro Casas Bocanegra

Supervisor:

Prof. Dr. Carlos Andrés Cifuentes García

Co-supervisor:

Prof. Dr. Marcela Múnera

A thesis submitted in fulfilment of the requirements for the degree of Master in Electronic Engineering

May 2019

"It doesn't matter how beautiful your theory is

it doesn't matter how smart you are

if it doesn't agree with experiment, its wrong

in that simple statement

is the key of science"

Richard Feynman

Acknowledgements

This thesis has been possible thanks to the support and continuous mentoring of my advisors Prof. Dr. Carlos Cifuentes and Prof. Dr. Marcela Múnera. They closely followed the development of my work and were always available to provide all the guidance and advise.

I would also like to thank Fundación Cardioinfantil-Instituto de Cardiología for opening the doors to our research and allowed me to perform the experiments and have access to the patients.

To the Royal Academy of Engineering with the funding of the project Human-Robot Interaction Strategies for Rehabilitation based on Socially Assistive Robotics (IAPP51637) and Colciencias with the SORCAR project (grant 813-2017) that financed the work developed in this thesis.

Special thanks to the Cognitive Systems and Robotics lab at Plymouth University lead by Prof. Tony Belpaeme for receiving me and allowing me to carry out some activities of my thesis at their university.

Furthermore, to the research team for their support on the experiments, writing and editing of this manuscript.

Now, I would like to thank specially to:

Nathalia, without her support and encouragement throughout this whole process, this work would not have been possible.

Abstract

According to the world health organization, cardiovascular diseases (CVD's) are a major cause of death worldwide, taking the lives of 17.9 million people every year. Cardiac Rehabilitation (CR) programmes are dedicated to approach this problematic and reduce mortality due to the presence of a second event. However, the main problematic regarding these programmes is associated to the low adherence and attendance to the therapies, causing a major public health issue that generates high health care expenditures. In this context, different approaches have been considered to motivate people to attend the therapies and continue with the treatment.

Socially Assistive Robotics (SAR) has been gaining significant attention in multiple health care applications by providing assistance through social interaction rather than physical interaction. Social robots have provided support, motivation, and monitoring in areas such as stroke rehabilitation, patients with dementia, physical rehabilitation, and autism. These interventions have reported promising results, showing that patients feel more engaged and motivated to continue the therapeutic treatments. These findings are encouraging to explore the effect of SAR in CR.

This master thesis presents the development and validation of a socially assistive human-robot interface for CR. This interface integrates a Human-Computer interface (HCi) designed to perceive the environment and allow the interaction with the user and the therapy context. In conjunction with the HCi, the system integrates a social robotic platform, which is programmed to socially interact with the user, providing monitoring and motivation, according to the information generated by the HCi.

In order to evaluate the effect that the SAR system produces in CR patients, this thesis conducted a series of experimental studies. First, a longitudinal study was carried out with a group of six patients divided in 2 groups (control and intervention) aiming to compare the effect of the robot-therapy against conventional therapy. Furthermore, an acceptance and perception study was conducted for a

group of 28 patients and 15 clinicians to evaluate their opinions, experience, and expectations with the system. Results demonstrate significant potential in the incorporation of social robotic companions in CR, where patients that interacted with the robot showed improvement of their physiological condition (i.e., reduction of resting hearth rate and increasing of the recovery capability after exercise) compared to the baseline. Moreover, patients that interacted with the robot felt motivated and encouraged to continue the treatment, and clinicians perceive the system as an useful tool to support their tasks and provide a better assistance. Demonstrating that SAR holds promising potential to be a feasible approach that enhances CR effects and help improving the quality of life of cardiac patients.

Keywords: Socially Assistive Robotics, Human-Robot Interaction, Social Interaction, Cardiac Rehabilitation, Robot-Therapy.

Glossary

AMI Acute Myocardial Infarction.

AR Assistive Robotics.

BPM Beats Per Minute.

BS Borg Scale for qualitative assessment of exertion perception during physical activity.

CR Cardiac Rehabilitation.

CVD Cardiovascular Disease.

EAM e-commerce Acceptance Model.

FCI-IC Fundación Cardioinfantil-Instituto de Cardiología.

FSM Finite State Machine.

GUI Graphical User Interface.

HCi Human Computer interface.

HR Heart Rate.

HRI Human-Robot Interaction.

IMU Inertial Measurement Unit.

LDD Leg Difference Distance.

LRF Laser Ranger Finder.

MWW Mann Whitney-Wilcoxon test.

NCD Noncommunicable Disease.

PCI Percutaneous Coronary Intervention.

POP Post-Operatory Procedure.

RT Response Time.

RTM Robot Therapy Model.

SAR Socially Assistive Robotics.

SARI Socially Assisive Robot Interface.

SIR Socially Interactive Robotics.

SORCAR In spanish *Evaluación del impacto de la intervención de un robot social en las respuestas cardiovasculares de lospacientes del programa de Rehabilitación Cardiaca de la Fundación Cardioinfantil-Instituto de Cardiología*.

TAM Technology Acceptance Model.

UTAUT Unified Theory of Acceptance and Use of Technology.

WHO World Health Organization.

List of Tables

List of Figures

Contents

Chapter 1

Introduction

This work focuses on the development of a Human-Robot interface (HRI) for Cardiac Rehabilitation (CR). The integration of a humanoid robot together with a Human-Computer interface (HCi) is addressed to provide monitoring and motivation to patients trough social interaction during therapy sessions. Additionally, This thesis presents the validation of the HRI, as well as results of the experimental studies carried out to assess effects, in terms of physiological evolution and perception of patients which attend the outpatient phase of the CR programme at Fundación Cardio Infantil-Instituto de Cardiología (FCI-IC) in Bogota, Colombia. Likewise, results regarding acceptance and perception of clinicians associated to CR at FCI-IC are presented. This Chapter introduces the context that motivated the realization of this work and the research goals. Finally, the main contributions, publications and structure of this document are presented.

1.1 Motivation

Cardiovascular diseases (CVDs) are known as disorders of the heart and blood vessels that include coronary heart disease, cerebrovascular disease, rheumatic heart

disease and other conditions [1]. These diseases are refereed to conditions that involve narrowed or blocked vessels and can lead to heart attack, stroke and heart failure [2]. Two groups of CVDs are considered: (1) CVDs caused due to atherosclerosis, such as ischaemic heart disease or coronary heart disease (heart attack), cerebrovascular disease (stroke), and diseases of the aorta and arteries that include hypertension and peripheral vascular disease. (2) CVDs caused due to a different condition, including congenital or rheumatic heart disease, as well as, cardiomyopathies and cardiac arrhythmias [3]. Among these groups, 70% of the CVDs are caused due to atherosclerosis [1, 3].

CVDs take the lives of 17.9 million people every year, an estimated of 31% of all deaths worldwide [4] and it is predicted that CVDs will increase to 23.3 million for 2030 [5]. This problematic impacts multiple aspects in our society: A study presented in 2017 estimated for the European Union a cost of 111 billion associated to CVD's, representing the 8% of total health care expenditures [6]. This situation not only affects economically but also in terms of quality of life, where 20% of patients that suffered a CVD event present prevalence of depression [7].

According to the World Health Organization (WHO), more than 75% of all deaths caused by CVDs occur in low-income and middle-income countries [1]. This situation is reflected in Colombia, where the panorama is not different: the main cause of death (66% of all deaths in Colombia) reported in 2008 is due to a noncommunicable disease (NCD), which includes CVD, cancer, diabetes, among others. Within this group, CVD was found to be the first cause of death (28%) [8]. Furthermore, reports from the Pan American Health Organization indicate that in 2010, 24% of male population and 27% of female population of all premature deaths were caused by some CVD [9]. Moreover, as the life expectancy in Colombia increases, going from 50 to 72 years-old in the last 50 years, the population, where the CVDs are more prevalent (older than 60 years), will increase in the same manner. This fact

will continue presenting an steady increase in the CVD mortality in the country [8].

There are multiple risk factors that trigger these diseases: *behavioural risk factors* (e.g., tobacco use, physical inactivity, unhealthy diet and harmful use of alcohol), and *metabolic risk factors* (e.g. raised blood pressure, raised blood sugar, cholesterol and obesity). It has been found strong evidence demonstrating that these risk factors have a significant influence in the existence of atherosclerosis, which is the main cause of the CVDs [3]. In Colombia, different studies show high prevalence of behavioural risk factors such as tobacco use, alcohol and physical inactivity [8].

According to the WHO, three main strategies need to be approached, in order to address this problematic. (1) *Surveillance:* it is necessary to map and monitor the epidemic of CVDs, aiming to understand its development and propose solutions. (2) *Prevention:* is mostly related to the reduction of the exposure to risk factors. (3) *Management:* that must be dedicated to the provision of equitable health care for people with CVDs [3]. Regarding to *prevention*, it is estimated that the reduction of the most critical risk factors (tobacco, physical inactivity and alcohol) could prevent up to 70% of ischemic heart diseases and increase the life expectancy of the population [8]. This has been evidenced in the high-income countries, where in the last decades the cardiovascular mortality rate has reduced. This reduction has been attributed to prevention, treatment interventions and adequate health care after the cardiovascular events.

Cardiac Rehabilitation (CR) programmes are dedicated to approach this problematic. These programmes are designed to prevent CVDs or to treat a patient after the cardiovascular event. CR usually covers different areas, such as nutrition, physical exercise and health education. However, despite the importance of attending the whole CR therapy, the adherence associated to the programme does not reach a desirable level, since it is a long-term intervention. Different studies in many countries have found that the adherence to CR programmes is not higher than

50% [10–12]. Additionally, a study showed that people at high cardiovascular risk have demonstrated a high prevalence of unhealthy lifestyles, increasing risk factors and inadequate use of drug therapies to achieve blood pressure and lipid goals [13]. Most recently, a survey of coronary patients showed that after a median time of 1.35 years after their cardiovascular event, 48.6% of patients who were smoking at the time of their event persisted in smoking and little or no physical activity was reported in nearly two thirds of interviewees [13]. Due to this fact, taking action to promote, encourage and stimulate people to enhance their physical condition and adopt healthy habits by attending to CR programs is a priority.

The adherence has been studied for different rehabilitation programmes finding that patients feel more likely to adhere to exercises when they were satisfied with their physiotherapist and received encouragement from them [14]. Additionally, patients have shown better results, when they perceived that physiotherapists supervised their exercises and felt that the physiotherapist appreciated what was expected from them as patients [14]. Another study related to the adherence predictors in CR programmes has found that the most relevant predictor was the physician's endorsement and their attitude towards the programme [15]. Based on this evidence, it is clear the role that the continuous monitoring and encouragement of the medical staff plays in the success, in terms of adherence and performance, of patients attending to the rehabilitation therapies. Therefore, considering that conventional CR programmes are carried out with a group of patients monitored by therapists and physiatrists [16], this work focuses on the development of an assistive tool, based on Socially Assistive Robotics (SAR), that supports the work carried out by clinicians and aims to offer a more personalized service to the patients, trough continuous monitoring, motivation and companionship within the CR therapies.

1.2 Background

This thesis is developed in the context of the project Human-Robot Interaction Strategies for Rehabilitation based on Socially Assistive Robotics (IAPP51637) funded by the Royal Academy of Engineering and theSORCAR project (in spanish *Evaluación del impacto de la intervención de un robot social en las respuestas cardiovasculares de los pacientes del programa de Rehabilitación Cardiaca de la Fundación Cardioinfantil-Instituto de Cardiología*, grant 813-2017), leaded by FCI-IC and the Colombian School of Engineering Julio Garavito (ECIJG), and funded by Colciencias (Administrative Department of Science, Technology and Innovation).

The SORCAR project seeks to assess the impact on the chronotropic, pressor and adherence response in patients attending to CR programmes, when estimulated and monitored by a social humanoid robot during the rehabilitation session. This project is carried out in the CR center at FCI-IC in Bogotá, Colombia (see Fig, 1.1). The main approach that is evaluated withing the project is the incorporation of socially assistive robots into conventional rehabilitation programmes. In this case, as a first stage of the project, an intervention in the Phase II of the CR programme is carried out and the development of this thesis contributes to this stage.

Furthermore, later stages of the project seek to extend the functionalities and capabilities of SAR systems, such as the development of advanced sensing strategies that allow the implementation of robust and reliable measuring devices useful in clinical scenarios. Likewise, this project focuses on the development and validation of interaction strategies applied in clinical scenarios. In this regard, the implementation of more natural interfaces for robots that communicate with patients through social behaviours is explored.

Figure 1.1: Fundación Cardioinfantil-Instituto de Cardiología (FCI-IC). Clinic where the SORCAR project is carried out.

1.3 Objectives

The primary objective of this thesis is to develop a HRI based on Socially Assistive Robotics (SAR) for cardiac rehabilitation, to provide monitoring and motivation within the phase II of the programme at FCI-IC. Beyond the general goal, there are specific objectives presented below.

- To perform the observation of a conventional therapy, in order to identify relevant measurement parameters associated to the therapy performance, their acquisition and processing strategies.

- To design a multimodal HRI that allows synchronous acquisition and on-line processing of physiological parameters, as well as to provide monitoring and motivation during the therapy.

- To perform an evaluation study, in order to validate the system's performance and user's perception involving patients and clinicians.

1.4 Contributions

The key contributions of this work are the development of a HRI for CR and the experimental validation of the robot-based therapy in a real clinical scenario. There are a series of technical and scientific contributions described below.

1. Design and implementation of a multimodal sensor interface for CR therapy monitoring. This system was evaluated under laboratory conditions and in the clinical context.

2. Design and implementation of a software architecture for the integration of a sensor-interface and a social robotic agent.

3. Development of a Protocol for the qualitative evaluation of user's perception, regarding the interaction with social robotic agents and technology in general.

4. Copyright registration of the software developed for the Robot-Therapy application in CR

1.5 Publications

The work presented in this thesis has been subject of the following scientific publications

1. (Conference Proceeding) Lara, Juan S., Jonathan Casas, Andres Aguirre, Marcela Munera, Monica Rincon-Roncancio, Bahar Irfan, Emmanuel Senft, Tony Belpaeme, and Carlos A. Cifuentes. "Human-robot sensor interface for cardiac rehabilitation." In 2017 International Conference on Rehabilitation Robotics (ICORR), pp. 1013-1018. IEEE, 2017.

2. (Conference Proceeding) Casas, Jonathan, Bahar Irfan, Emmanuel Senft, Luisa Gutiérrez, Monica Rincon-Roncancio, Marcela Munera, Tony Belpaeme, and Carlos A. Cifuentes. “Social assistive robot for cardiac rehabilitation: A pilot study with patients with angioplasty." In Companion of the 2018 ACM/IEEE International Conference on Human-Robot Interaction, pp. 79-80. ACM, 2018. *Awarded with the 2nd place of the best Late Breaking Report at HRI18 Conference*

3. (Conference Proceeding) Casas, Jonathan, Nathalia Céspedes Gomez, Emmanuel Senft, Bahar Irfan, Luisa F. Gutiérrez, Mónica Rincón, Marcela Múnera, Tony Belpaeme, and Carlos A. Cifuentes. “Architecture for a Social Assistive Robot in Cardiac Rehabilitation." In 2018 IEEE 2nd Colombian Conference on Robotics and Automation (CCRA), pp. 1-6. IEEE, 2018.

4. (Journal Article - under review) Casas, Jonathan, Emmanuel Senft, Luisa F. Gutiérrez, Mónica Rincón, Marcela Múnera, Tony Belpaeme, and Carlos A. Cifuentes. “Social Assistive Robots: Assessing the Impact of a Training Assistant Robot in Cardiac Rehabilitation"

5. (Book Chapter - in Press) Casas, Jonathan, Nathalia Céspedes Gomez, Marcela Múnera and Carlos A. Cifuentes. “Human-Robot Interaction for Rehabilitation Scenarios" published in Control Systems Design of Bio-Robotics and Bio-mechatronic with Advanced Applications, Elsevier.

1.6 Organization

This Master Thesis document is structured as follows:

Chapter 2 presents the current state of the cardiac rehabilitation service, describing the phases, components and features of conventional programmes and the

specific programme at FCI-IC. Additionally, this chapter presents the results of the observations carried out in the clinic.

Chapter 3 introduces the context of socially assistive robotics, going from a general approach in rehabilitation up to the applications in the CR context. This chapter also presents the Robot-Therapy Model (RTM) developed for the HRI system.

Chapter 4 introduces the development of the HCi block considered in the RTM, which will provide to the robotic system the ability to interact with the user and the therapy environment. This chapter concludes with the validation of the HCi by means of a pilot study conducted under laboratory conditions.

Chapter 5 presents a detailed structure of the Socially Assistive Robot Interface (SARI) that will be integrated with the HCi, and describes each layer of the architecture that were implemented. Finally, the chapter concludes with the validation of the robot architecture, conducting a pilot study with a cardiac patient during the phase II of the CR.

Chapter 6 addresses the development of Human-Robot Interaction (HRI) experimental studies. Two studies are considered: (1) Quantitative study to evaluate the effect on the physiological conditions of the patients, and (2) Perception assessment that evaluates the expectations and acceptance of potential users of the system.

Chapter 7 presents the conclusions and recommendations for future work.

Chapter 2

Current State of the Cardiac Rehabilitation Service

2.1 Introduction

Cardiac Rehabilitation (CR) is a medically supervised program designed to improve cardiovascular health if experienced heart attack, heart failure, angioplasty or heart surgery [17]. CR is a combination of physical activity, psychological support and educational programmes, designed to improve patient's conditions. CR programmes are recognized as one of the most effective secondary prevention strategies to reduce the possibility of a CVD. Different studies demonstrate that exercise-based CR programmes provide important health benefits to cardiac patients, improving their quality of life, as well as reducing mortality and hospitalization rates [18].

In the last decades, it has been evidenced the effectiveness that CR programmes have in reducing mortality rates and acute myocardial infarction, in countries as Germany, where these rates have dropped from 118.4 to 63.7 per 100.000 population between 1980 and 2011 [19]. Similar results were found in [20], where exercise,

risk factors control and pharmaceutical therapy, have shown an improvement in their exercise capacity, as well as in their secondary prevention against cardiac diseases. [20]. Moreover, benefits from the CR therapy can be evidenced not only in terms of the physical condition, but also from the psychological perspective. It has been reported that patients attending to a CR programme showed an increment in the control over their illness, more confidence in the ability to change their habits, and decreasing anxiety and depression [21].

Although the benefits of CR are notable and the participation in such programmes is associated with improved prognosis for the patients [19, 22], the attendance and adherence to the programmes are significantly low. Among the factors that affect the attendance to the therapies, the most relevant are a lack of interest in rehabilitation, a reluctance to make lifestyle changes, and depression [20]. This situation requires urgent attention, since studies show that people who do not attend or abandon the programme, are more likely to develop associated diseases, such as diabetes, hypertension, and lower ventricular ejection fractions [19]; in contrast with people that attend to CR therapy, who exhibit a reduction of the cardiac mortality by approximately a 27% [20].

In this context, it is a priority to involve more people, that present cardiac vulnerabilities or risk factors associated to CVDs, in CR therapies, and encourage them to improve their physical condition, and reduce risk factors by adopting healthy habits. This chapter describes in detail the conventional structure of a CR programme, as well as the state of the service in Colombia. Finally, the results of the observations carried out at FCI-IC are presented as the starting point of the intervention in the clinic.

2.2 Cardiac Rehabilitation Programme

The structure and components of the CR programmes differ depending on the country and institution. However, they traditionally consist of three phases: inpatient, outpatient, and community maintenance. The Outpatient phases take place in a specialised centre or institution and are carefully performed under the supervision of health care providers with monitoring based on exercise tolerance test results [20]. The three phases are described below.

Phase I is considered as the impatient phase that occurs immediately after the cardiac event, and regularly has a duration of 7 to 10 days. In this phase the medical staff focuses on helping the patients to regain mobility and recover muscular tone. The goals of this phase include the assessment of mobility and its effect in the cardiovascular system, prescription of adequate exercises to improve cardiac fitness and education to reduce cardiovascular risks associated to the medical treatment [23].

Phase II is the first outpatient phase that begins immediately after the patient leaves the hospital and consists of a combination of physical exercise on a treadmill and an education programme oriented to prevention of risk factors, as well as adoption of healthy habits (e.g. controlling blood pressure, cholesterol, weight and stress management). This phase has an average duration of 3 months and is designed to provide a safe monitored environment for exercise [23]. The monitoring consist of measuring the patient's blood pressure, heart rate, and eventually heart and lungs sounds. Additionally, is also important to monitor the perceived exertion level (i.e. fatigue or effort during the exercise). This measurement is carried out with the Borg Scale (BS), which is a qualitative measurement that estimates the

perceived exertion of the patient (6 for low intensity and 20 for very high intensity) [16, 24].

As result from the phase II, the patient should be able to self-monitor its physiological parameters and exertion levels. This aspect will return the confidence to the patient to continue a normal life, being aware of its health condition and the healthy lifestyle that is required to prevent from a second cardiac event [25].

Finally, **Phase III** is considered as a long-term maintenance period, in which the objective is to provide reinforcement to the already-acquired routines in previous phases and to provide advice concerning secondary prevention. In this phase the patient can be prescribed with a tailored set of exercises that include flexibility, strengthening, and aerobic exercises. With the completion of this phase, the patient has increased its exercise tolerance and independence, and is ready to continue with the normal routine at home [25].

As can be observed, over the three phases it is involved a comprehensive rehabilitation that includes not only the prescription of exercises, but also an education programme covering the reduction of risk factors and adoption of healthy habits. These model of rehabilitation is recommended by different institutions, since it is the effective way to improve their quality of life and reduce secondary events [18].

2.3 CR Service in Colombia

In Colombia, the CVDs present a significant burden in the mortality and hospitalization rates. It is considered the first cause of death for the population older than 45 years [26]. Although cardiac pathologies are critical in the Colombian context, there is a limited amount of research and publications regarding this problematic [27]. In literature can be evidenced that the CR programmes started to

be implemented in the country between 1980 and 1985 [28]. Later, in 2000 was conformed the cardiovascular rehabilitation and prevention committee from the Colombian society of Cardiology and Cardiovascular surgery [28]. By 2008, the country counted with 39 CR programmes and were published the first approximations to the components and characteristics of the programmes. Subsequently, by the year 2010, the country counted with 44 CR programmes [28].

A later study performed in 2011, presented the distribution of institutions that offer a CR programme, finding that the leading city was Bogotá with 13 programmes; followed by Medellin with 6, Manizales with 5, and Cali with 3 [26]. Additionally, among the institutions differs also the type of service that is provided. In this study was found that all programmes contain the phase II. However, only 84% of the programmes offer the phase III and 70.5% offer the phase I [26]. These results put in evidence the limited coverage of CR programmes in the country.

Few studies have been reported showing the impact of CR programmes. In 2012, a study was conducted in Santander, Colombia, where it was evidenced the benefits that exercise-based CR rehabilitation generates, reducing mortality and hospitalization rates. However, it was also highlighted the high desertion rates, also supported by [28], estimating that less than 10 % of patients attend to the programmes. Additionally, low remission from the medical service (65,9% of patients are not remitted to the CR programmes) has been reported [29].

As stated in the objectives of this work, the study was developed at FCI-IC, institution that counts with a Cardiac Rehabilitation Unit. The next section describes the observations that were carried out for this programme, aiming to identify opportunities and requirements for the system.

2.4 Observations of the Conventional Therapy at FCI-IC

This study focuses on the design and development of a Socially Assistive Robotics (SAR) system into the phase II of the rehabilitation programme at FCI-IC. The phase II is considered since it is the initial outpatient phase, where patients have stabilized their cardiovascular system and are able to start performing physical activity on a treadmill. Similarly, in this phase there is a priority to reinforce the adoption of healthy habits and improve patients' physical condition which are aspects that are expected to be improved by the robotic system. It has been mentioned in previous sections the difference that CR programmes can present between institutions. Therefore, an observation phase was required in order to understand the therapy development, and based on those observations being able to identify opportunities, restrictions and limitations of the system.

From the observations, there are multiple aspects of interest for the design of the SAR system: (1) the Patient-Therapist interaction is one of the most important aspects to define the robot's behaviour. (2) The components of the therapy, namely the procedure that is carried out on each session that will provide information regarding the timing and structure of the intervention, (3) variables and parameters registered during the session in order to define the system storage requirements, and (4) risk factors associated with the activities or the physiological conditions of the patients that can be monitored or controlled by the system. The remainder of this section presents the results of the observations.

2.4.1 CR Unit at FCI-IC

The rehabilitation services, located at FCI-IC in Bogotá, Colombia, counts with the CR and Physical rehabilitation unit. These services receive patients, aiming to improve their quality of life, functionality, physical endurance, to perform exercise, and reduce cardiovascular risk factors. The unit counts with an interdisciplinary group conformed by physiatrist, cardiologist, nurses, physiotherapists, and occupational therapists. The unit has provided rehabilitation services for the last 25 years, allowing patients to adapt their lifes to the new physical conditions and optimize their health state, basing their intervention on three elements: physical activity, continuous control and monitoring of medicament, and specific education provided by a diverse team of professionals [30].

(a) (b)

Figure 2.1: Heart team providing medical attention in Cardiac Rehabilitation at FCI-IC. (a) Therapist is manually measuring heart rate while physiatrist ask the patient about his state. (b) Therapist is manually measuring the blood pressure, while physiatrists registers the values in the spreadsheet.

Staff: The rehabilitation service counts with 10 specialized doctors (physiatrist and cardiologist) that work together with a group of nurses and therapists to pro-

vide assistance and monitoring during the session. The *Heart team* is conformed by a multidisciplinary group of one physiatrist and three nurses/therapists that assist each CR session. Fig. 2.1 illustrates conventional assistance during the therapy, where physiological parameters and health status are controlled.

Patients: The unit provides attention to patients that present cardiovascular conditions or have underwent therapeutic procedures that involve:

- Post-coronary myocardial infarction
- Surgical myocardial revascularization
- Angioplasty or stent placement
- Postoperative valvular change
- Aortic aneurysm correction
- Congenital cardiopaty correction (adults and children), acute ischemic cardiopathology.
- Heart failure
- Heart transplant
- Neurocardiogenic syncope (adults and children)
- Peripheral vascular disease
- Chronic lung or heart disease
- Patients at high risk for coronary heart disease
- Patients with implants (pacemakers, defibrillators)

Infrastructure: This unit counts with 9 treadmills and 10 static bikes available for patients that attend the sessions of the phase II and III of the CR programme (See Fig. 2.2). The facility operates from Monday to Friday, starting at 7:30 until 17:30 and each session is programmed to have a duration of 1.5 hours, providing attention for an average of 620 consultants/month as well as 1450 inpatient sessions/month and 3200 outpatient sessions/month. The schedule of the facility is designed to receive patients from different groups at specific time slots (e.g. phase II, phase III, spirometry patients that present heart failure and geriatric patients).

Figure 2.2: Cardiac Rehabilitation Unit at FCI-IC. The figure illustrates four main areas of the CR unit: (a) the treadmill and (c) static bike zone, where patients perform physical activity, (d) the physiatrist desktop where the paperwork and parameters of the session are recorded, (b) and the meeting zone, where the secondary prevention and education conferences take place.

As the study focuses on deploying the intervention in the phase II, next section describes the scheme of a conventional therapy.

2.4.2 Phase II CR Therapy

During the observations of a conventional therapy session for the phase II, at FCI-IC, different aspects were identified. First, the stages of each therapy session were

observed as well as the variables that are measured on each stage. Table 2.1 summarizes the variables that are registered and monitored on each stage. These variables are below detailed in the five stages identified.

Table 2.1: Measured Variables in CR session at FCI-IC

	Variable	Unit
Pre-Exercise Varibles	Initial resting HR	bpm
	Weight	kg
	Initial blood pressure	mmHg
Exercise Variables	Speed	mph*
	HR	bpm
	Treadmill inclination	degrees
	Borg scale	
Pos-Exercise Variables	Final HR	bpm
	Final blood pressure	mmHg

*treadmills provide speed in mph

Initial Parameters Measurement: In this stage the *pre-exercise* variables are measured (see Table 2.1). The *initial HR* is considered as the heart rate level, measured in beats per minute (BPM), that patients present without performing any physical activity. This variable ranges from 60 to 80 BPM in healthy adult patients and can reach 100 BPM in sedentary individuals [31]. The *Weight* (in kg) is measured aiming to control overweight, as it is associated to cardiovascular problems that can affect the patient's health condition [32]. Finally, *initial blood pressure* is measured as well, since increments in this variable are associated with an increased risk of cardiovascular events [33].

Currently, this information is manually registered by the physicians on paper sheets for each patient. Once all the parameters have been measured and registered, patients can start with the therapy.

Warming Up: Considering that patients attending CR therapies present delicate healthy conditions, it is a priority for the medical staff to guarantee their safety. For this reason the Warming-up stage is vital to prepare patient's to perform physical

exercise. This is performed by means of low-intensity exercises that produce an improvement in aerobic capacity reducing risk [34]. Hence, patients start to walk and carry out stretching exercises during 10 to 15 minutes before starting the physical activity on the treadmill.

Physical Activity: Once the patients have performed the warm-up, they are ready to start the physical activity carried out on treadmill. As illustrated in Table 2.1, in this stage there are mainly four variables that are controlled during the exercise. The *speed*, measured in miles per hour (mph) as the predefined unit of the treadmill, is configured at the beginning of the exercise according to the patient's health condition and evolution during the therapy. The *inclination*, measured in degrees, is configured on the treadmill to adjust the slope of the band and increase the exercise intensity to demand a greater effort from the patient. As the patient's physical conditions show improvement along the sessions, the intensity is increased (i.e., the speed and inclination are increased).

Furthermore, the *heart team* supervises the exertion that patients present during exercising; this is done by means of the HR developed during the activity and the *Borg Scale* (BS). The BS is a qualitative scale to estimate the exertion perceived by the patient, and ranges from 6 to 20, indicating 6 for low intensity and 20 for very high intensity [16]. Fig. 2.3 illustrates the scale indications that are available in the CR unit at FCI-IC. As shown in the figure, the scale is divided in four categories that indicate very low intensity in a range of 6 to 9 (Fig. 2.3(a)), low to some strong intensity are grouped from 10 to 13 (Fig. 2.3(b)), high to very high intensity is considered among 14 and 17 (Fig. 2.3(c)), and finally very high intensity until intolerable intensity is considered in the range of 18 to 20 (Fig. 2.3(d)). In the case of the CR therapy carried out at the clinic, the medical staff control the exercise activity in order to not overcome the second group (i.e., 10 to 13). If a patient reports a value greater than 13, the exercise intensity is reduced.

The BS is requested by the health professional around each 5 to 7 minutes. This stage has a duration that ranges from 15 minutes up to 20 minutes. Once this stage has finished, patients step out of the treadmill and perform the cool-down activity.

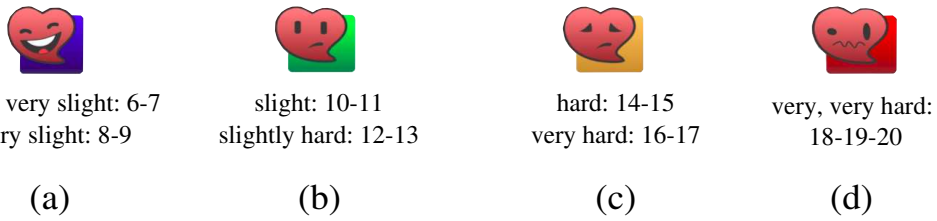


Figure 2.3: Informative poster regarding the Borg Scale in the CR unit at FCI-IC. (a) Indicate slight intensity perceived by the user, (b) indicates slightly hard intensity, (c) hard, to very hard exercise intensity, and (d) intolerable intensity.

Cool-down: Due to the physical activity that has been performed, the cardiovascular system of the patients responds by increasing the HR and blood pressure [31]. These parameters remains elevated before slowly recovering that reaches the resting level again. Following a training programme such as the CR therapy during a continuous period of time, the time it takes for the HR to reach the resting state is reduced. This metric is an appropriate reference to assess the effect of the therapy on the physical condition [35]. Aiming to allow the patients to recover from the exercise, they perform stretching exercises normally in a period of 10 to 15 minutes.

Final Parameters Measurement: Once the cool-down concludes, patients are asked to take a sit and measure the final parameters shown in Table 2.1 (*final HR* and *final blood pressure*). As was mentioned before, these parameters tend to increase during the exercise, and are measured again at the end to control how they return to the resting condition. Following a training programme of more than 10 weeks, a patient can experience a reduction of approximately 10 BPM on its resting HR [31].

With the purpose of providing a comprehensive CR programme, the *heart team* led

by a physiatrist, complement the physical training with education and reduction of risk factors. Life-styles such as smoking, intake of saturated fat, and lack of physical exercise are prone to generate risk factors such as hypertension and hyperlipidaemia that lead to coronary heart disease [36]. The knowledge of health risks generates a precondition for change, and if patients are not educated about unhealthy habits, they have no reason to change their lifestyle [37]. Therefore, education regarding self-management and control over their health is a core component of the CR programme. This is achieved by means of talks and conferences that address different topics related to the conditions previously mentioned. Once the measurement and the intervention of the physiatrist conclude, the session is finished.

2.4.3 Risks Associated to the Therapy

From the observations, there were identified two main risks that are associated to the development of the therapy: (1) The first risk is associated with the patient's cardiac activity. As this kind of patients can present cardiac alterations, such as arrhythmias (i.e., an irregular heartbeat that leads to fast or slow heartbeat, premature contraction or fibrillation [38]), this could generate an emergency at any time. For this reason, the medical staff must ensure a regular monitoring of patients' state, in order to be able to act preventively. (2) The second risk is related to the patient's previous experience in performing physical activity on a treadmill. According to its experience and physical condition, it is possible to present dizziness, that is caused when the patient starts looking at his/her feet. In this case, it is recommended to look at a fixed point in front to reduce this risk that can cause falling from the machine and be exposed to injuries.

2.4.4 Design Criteria

According to the description of the programme developed at the FCI-IC, observations and requirements of the system, as well as improvement opportunities have been identified.

Table 2.2: Requirements for the SAR System

	Variable	Feature
Variables	Spatiotemporal	Speed (mph) Cadence (Hz) Step length (m)
	Physiological	Heart Rate (BPM) Blood pressure (mmHg)
	Exercise Intensity	Treadmill inclination (degrees) Borg scale
Interactivity	Graphical User Interface	Visual interaction Posture correction
	Social Robot	Social interaction Monitoring Motivation
Follow-up	Database	Events recording Parameters recording

Requirements:

From the observations, there are requirements that the system must accomplish. As presented in Table 2.2, these requirements have been classified in three main groups described below.

Variables that are required to be measured by the system. These are mainly three types, namely *spatiotemporal*, *physiological*, and *exercise intensity* variables. *Spatiotemporal* variables are meant to measure speed (mph) of the band, cadence (Hz) which is the step frequency of the patient (amount of steps per second) and

step length (m) which refers to the distance between legs on each step during exercise. The measurement of these variables was requested by the clinicians at the CR unit to monitor patient's movement. Additionally, the measurement of the cadence and step length will be used to determine the speed (this will be introduced in chapter 4). *Physiological* variables are considered to control the physical condition of the patients by means of the heart rate and blood pressure. Finally, *exercise intensity* is monitored by means of the Borg Scale and configured with the treadmill inclination.

Interactivity will be provided by means of a *Graphical User Interface* that allows visual interaction and provide posture corrections to avoid risk during the session. Similarly, a *social robot* must be integrated to provide a more natural and social interaction with the system, as well as to monitor and motivate patients during exercise.

Follow-up The third requirement is associated to the data management and follow-up of the programme. Hence, a *database* must be included to provide a record of the events generated on each session, as well as to record each parameter of the sessions to allow the clinical staff to perform analysis on the patient's evolution.

Opportunities:

During the observation phase, there was a significant number of aspects that can be improved with the proposed intervention. The most relevant is the continuous monitoring. As the health professionals have to handle a group of 15-25 patients, it is extremely difficult to provide continuous supervising of their parameters. For this reason, they are limited to ask and check eventually patient's vital signs and performance. Fig. 2.4 illustrates a conventional therapy at FCI-IC with 17 patients

and the therapist standing in the middle indicating the exercises in the warm-up stage, evidencing the high volume of patients that the cardiac team must handle. According to this, the first requirement was established as an on-line measurement. By implementing this feature, it is expected to reduce risk factors associated to the sudden increasing of the heart rate during the session. Moreover, according to the second risk factor identified in the therapy, by means of a continuous measurement, it is feasible to provide appropriate posture correction and feedback during the exercise, hence reducing the possibility of presenting dizziness or falling from the treadmill.

Figure 2.4: Conventional cardiac group volume in CR at FCI-IC. The figure illustrates the CR group performing exercises of the warm-up stage. The therapists standing in the middle, indicates the exercises that patients should follow.

This chapter explored the current context of CR therapies, their structure, components, and service coverage in Colombia. Furthermore, the results of the observations carried out at FCI-IC, as well as, the requirements and opportunities derived from this observation were discussed. As the clinical environment has been studied and the requirements and opportunities are identified, next chapter focuses on the Socially Assistive Robotics (SAR) approach. Where the benefits of this

technology in different applications are evidenced as well as the illustration of the robot-therapy model that will be adopted is presented.

Chapter 3

Socially Assistive Robotics for Rehabilitation Scenarios

3.1 Introduction

Socially Assistive Robotics (SAR) can be defined as the intersection of Assistive Robotics (AR) and Socially Interactive Robotics (SIR). AR is the robotic field that addresses the assistance of people with disabilities. This assistance is provided by means of physical interaction (i.e., generate physical contact for example devices that assist mobility such as exoskeletons or smart walkers) [39]. On the other hand, SIR is the area focused on the development of robots able to perceive human social behaviour, such as emotions, and present similar communicative skills using natural cues (e.g., gaze or gestures). These robots are conceived under the assumption that humans prefer to interact with machines similarly as they do with other people. Hence, SIR can be applied in a range of applications (research platforms, educational tools, and therapeutic devices) [40,41]. In this context, SAR combines both fields, as it is focused on assistance (the main objective of AR) implementing robots that exhibit social behaviour an interact socially with the users, which is

the main approach of SIR. However, unlike SIR, the scope of SAR is limited to the applications on rehabilitation, assistance, and healthcare scenarios [39].

Aiming to contextualize the application developed in this work and highlight the potential that this field exhibits in rehabilitation scenarios, this chapter presents the state of the art regarding the social robotic platforms, their features and classification. Furthermore, similar studies in related fields and their outcomes are discussed, followed by the description of the system proposed in this work. However, previous to this, a brief description of what social interaction is, and the aspects that are important to develop social robotic agents are addressed in the next section.

3.2 Social Interactions

Social interaction is regarded as a dynamic sequence of social actions between individuals, or a group of them. As a product of their interaction individuals modify their actions and reactions. Humans interact socially in a wide range of multimodal communication channels [42]. Among these channels, there are two types of social interaction that are of interest when designing social robots: (1) verbal communication which is considered as an exchange of established symbols that can be spoken or written [43]. (2) Nonverbal communication can be manifested by gaze, gestures and expressions that communicate a particular message [42]. Based on these two social interaction types, the main taxonomy of SAR is structured. Hence, a social robot must exhibit properties such as emotion, dialog, personality, embodiment, and perception [39].

In this context, a social robot that contains the social communication skills previously described, is able to interact with humans in social environments. Therefore, the conditions open the possibility for the incorporation of such robotic agents

in therapeutic or assistance environments, where humans can communicate and interact intuitively with the device. This potential will be evidence in the next sections.

3.3 Social Robotic Agents

The main role of social robotic agents or social robots, is to act as companions or assistants in specific tasks that involve the achievement of a goal under certain conditions. In rehabilitation and healthcare environments, social robots are regarded as training assistants, coaches or motivator agents that help improving patient's performance or increasing engagement during the therapy. With this in consideration, social robots are required to contain a series of features that allow them to interact in an effective way, providing adaptability and flexibility to human environments. As these agents are designed to interact socially with humans, they must exhibit human-like behaviours and their appearance and functionality must be structured in such a way that humans can interpret and be familiarized with [40].

3.3.1 Physical Embodiment

As aforementioned, one considerable property that enables an effective social interaction is the *physical embodiment*. This feature allows the robot to perceive and experience the physical world. Hence, it will be able to interact with humans and engage with their activities in a more natural and intuitive way [44]. The *embodiment* is a term considered to refer to the fact that intelligence cannot be limited to exist in the form of an abstract algorithm, but requires a physical instantiation or body [45, 46]. Different studies have demonstrated the effect and benefits that embodiment attributes to the robotic platforms over other types of social agents,

such as virtual agents and screen-based avatars (i.e., an icon or figure representing a particular person or character) (see Fig. 3.1).

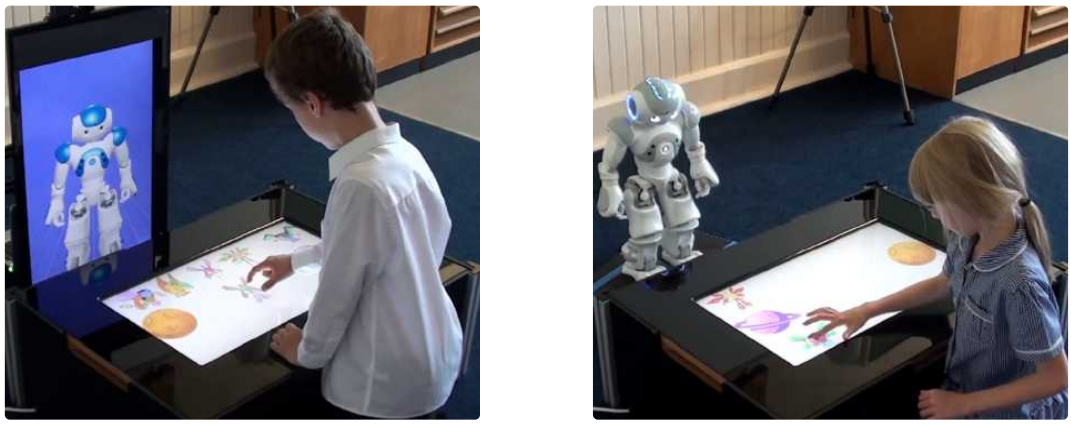


Figure 3.1: Comparison study. (a) child interacting with virtual agents (b) child interacting with social robot. Image taken from Kennedy *et al* [47].

Kennedy *et al* [47] presented a study finding that physical robots would exhibit more advantages over virtual robots. However, they stated that it is unclear whether the real robot improves task performance, or distracts from a task. Moreover, a long-term study, carried out with children in school and hospital facilities, showed that children respond better to a robot which adapts its behavior to the young user. Likewise, this study found that the robot, as a physical embodied agent, receives more attention than an on-screen avatar does [48]. Experimental data suggested that physically embodied interactions are favored over virtual ones and that the first one can make a difference in a task-oriented setting [44]. Additionally, Powers *et al* tested different hypotheses about the social impact of a robot agent in which results showed that a robot would have more social impact than a computer agent [49]. In this study, the robots did not have more social influence on health behavior than the agents did, but robots were more engaging.

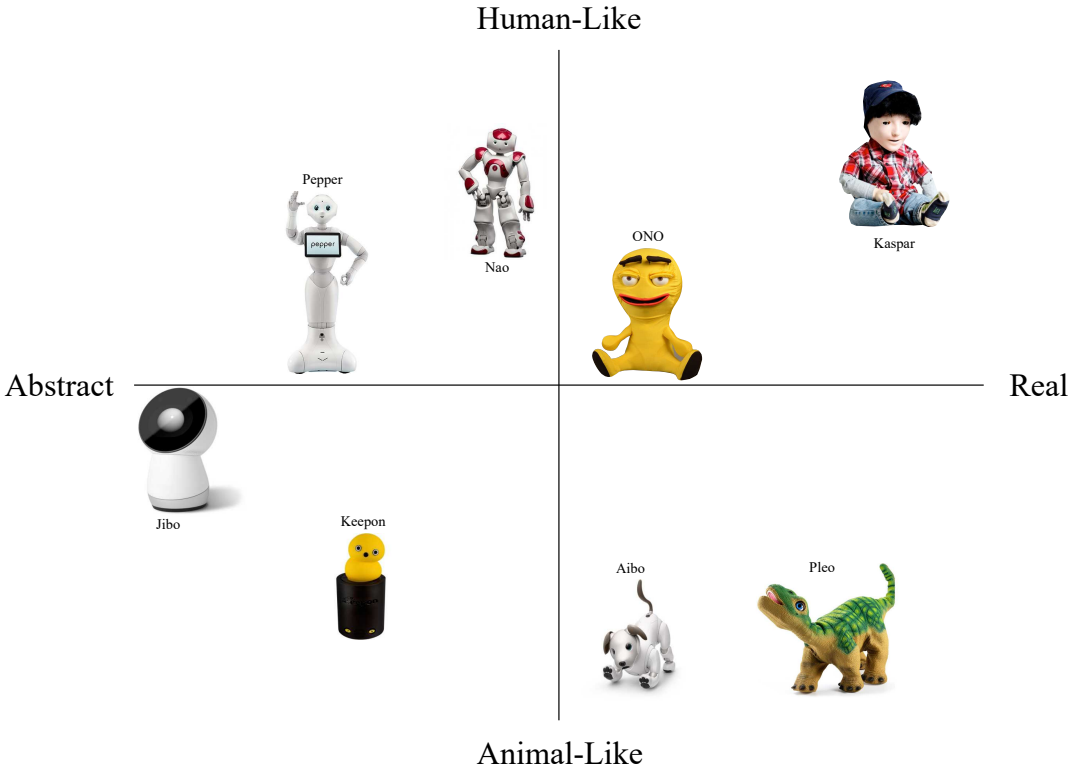


Figure 3.2: Socially Assistive Robots classification. In this chapter we consider two main categories: *Real/Abstract* referring to their similarity to living beings and *Human/Animal* referring to their similarity with humans or in contrast their similarity with animals.

Social Robots Classification

Although all social robots are embodied (have a physical body that allow them to interact with the world), the degree of interaction may vary depending on their capabilities. Hence, a robot with more motor and sensor skills will present more capabilities to interact with the environment as it can establish more relationships with the world. Currently, there is a wide spectrum in the design features that social robots have. In this chapter, it is considered the classification of social robots in two main categories: (1) *Real-Abstract*, which indicates the degree of similarity that the platform has with the nature (i.e. how similar the robot is to a living being), unlike the abstract design. (2) *Animal-Human* appearance describes their similarity to a human being or an animal creature. Fig. 3.2 illustrates some robots that are conventionally used. As can be observed, these platforms vary in

their shape and appearance.

As shown in Fig. 3.2, Jibo is placed at the most abstract side of the graph since it does not exhibit any bio-inspired appearance. However, it has the ability to socially interact with human users using verbal and nonverbal communication [50]. In the same way, Keepon present similarities with Jibo regarding their physical appearance. However, it is located closer to the animal-like robots, as it counts with eyes that present similarities with natural creatures [51]. Animal-like robots such as Aibo [52] and Pleo [53] present high similarities with natural creatures, in addition, their range of movements and functionalities resemble a natural behaviour. Finally, human-like robots such as Pepper [54], Nao [55], Ono [56], and Kaspar [57] exhibit anthropomorphic features such as arms, head, and eyes. However, they differ in their appearance, where Pepper and Nao look more synthetic (i.e., plastic), while Ono tends to be more realistic and Kaspar can be considered as one of the most realistic and anthropomorphic social robot.

Robotic Platform Configurations

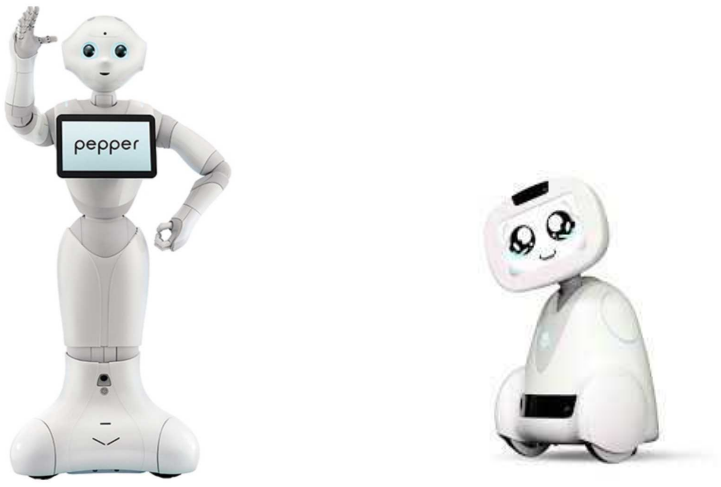
All these platforms can be regarded as social robotic agents. However, their functionalities and field of applications can diverge, as each robot can be suitable for a specific task and a specific degree of interaction depending on their configuration and degrees of freedom. As every day more robotic platforms are designed, the application spectrum of SAR is expanding in a similar way, covering multiple areas in healthcare and rehabilitation scenarios. This section describes tree types of social robots configurations and the scenarios in which each of them are commonly used.

Table-Top Robots: This kind of robots are usually placed on tables to interact with people and in most cases do not count with locomotion to perform any displacement. Fig. 3.3 illustrates some examples of table-top social platforms. The

(a) (b) (c)

Figure 3.3: Table-Top social robots. (a) Ono robot, (b) Kaspar robot. (c) Keepon robot

robot Ono (Fig.3.3(a)) is an open-source social robot that has been mainly tested for children with autism due to its facial expressions. However, it presents a limited mobility of its body [56]. The major feature of this platform is the ability to express emotions, as it counts with several degrees of freedom on its face. Similarly, Kaspar (Fig.3.3(b)) is a child-sized humanoid robot designed as a social companion to improve the lives of children with autism and other communication difficulties [57]. Finally, Keepon (Fig.3.3(c)) has been used in clinical and research environments to observe and study the development of social behaviours in children [51].



(a) (b)

Figure 3.4: Wheeled social robots. (a) Robot Pepper .(b) Robot Buddy.

Wheeled Robots: are robots that count with a wheel base that allow them to move freely in different spaces. This feature in combination with social behaviors provide them a greater degree of interaction as they are able to share the same spaces with humans and interact in a more natural way. Two examples of these robotic platforms are illustrated in Fig. 3.4. Pepper (Fig. 3.4(a)) is a robotic platform with a high degree of impact due to its mobility, shape and size in social interactions. It has been created in order to communicate with its users in the most natural and intuitive way possible through gestures and voice [54]. Buddy (Fig. 3.4(b)) is a friendly companion robot designed for entertainment and education. This robot has the ability to interact with humans in home-based scenarios, where the robot is able to recognize all family members and provide assistance and companionship in their daily life [58].

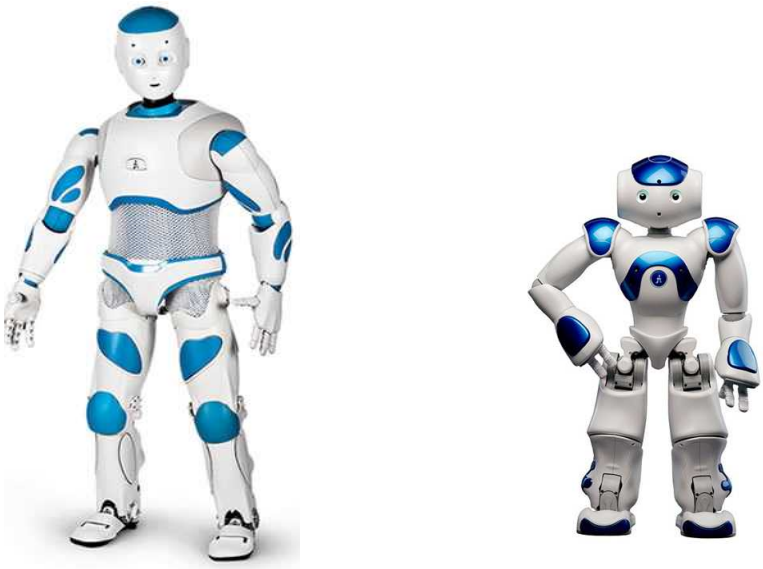


Figure 3.5: Humanoid social robots. (a) Robot Romeo. (b) Robot Nao.

Humanoid Robots: Are robotic platforms whose physical appearance is similar to humans. In other words, they have arms and legs and can move with the same locomotion as humans do. Although robots in other categories can have similarities

with humans such as Pepper (Fig. 3.4(a)) or Kaspar (Fig. 3.3(b)), the classification of humanoid robots was considered according to their anthropomorphism and humam-like movement capabilities. Fig. 3.5 illustrates two examples of humanoid robots that are commonly known in rehabilitation and assistance contexts. Romeo (Fig. 3.5(a)) is a robotic platform that was designed to assist people with movement impairments and limited autonomy to carry out displacements [59]. The project that involved the development of Romeo aims to evaluate the ability of the robot to create and maintain social bonds with people trough cognitive processes. Furthermore, the Nao robot (Fig. 3.5(b)) is a humanoid robot that has been widely used in different scenarios that involve human-robot interaction due to its social capabilities [55]. This platform counts with several features such as artificial vision, speech and different sensors that allow the robot to recognise the environment. Due to its physical appearance, this platform is ideal for rehabilitation and training scenarios, since it can recreate human-like movements, which is useful when demonstrating exercises and providing appropriate instructions. Therefore, for the purpose of this work the Nao robot was the platform incorporated to the system to carry out the study.

(a) (b) (c)

Figure 3.6: mobile social robots. (a) Social Robot Clara [60]. (b) Mobile social robot, image taken from [61], (c) Social assistive robot for physical exercising [62].

Mobile Social Robots This category comprises social robots that have been built on top of a robotic mobile platform. Platforms of these characteristics have been incorporated in research exploring different rehabilitation scenarios. Fig. 3.6(a), illustrates the robot CLARA, that was designed to play the role of a therapy assistant. As depicted in the figure, the robot comprises a mobile platform that allows the robot to move around the room. A camera and a screen are also installed to provide social presence and recognize the patient. On the screen there is a real therapist video displayed to interact with the patient and provide instructions to patients [60]. Similarly, Fig. 3.6(b) illustrates a similar robot that implements a mobile platform, a Laser Range Finder (LRF) to navigate, and a camera to detect the patient and guide the therapies [61]. Similarly, Fig 3.6(c) illustrates a mobile robot with an anthropomorphic torso designed to assist physical exercise for elderly patients [62].

Once the main features and classifications of social robotic platforms has been described, the next section presents a detailed overview of the applications and the relevant findings associated to this research.

3.4 SAR in Rehabilitation

SAR was initially explored in cardiovascular therapies with the development of CLARA, a hands-off physical therapy assistant which its aim was to reduce the effects of nursing shortages, provide motivation and aid patients through the rehabilitation exercises as spirometry therapies. With this study, researchers found high expectations over the robot's usefulness and an average overall satisfaction of the population about 80% [60](see Fig 3.7). Furthermore, SAR has been used in several applications focused in elderly care [63], dementia and mental health treatments [64–66], physical and post stroke rehabilitation [67], among many others.

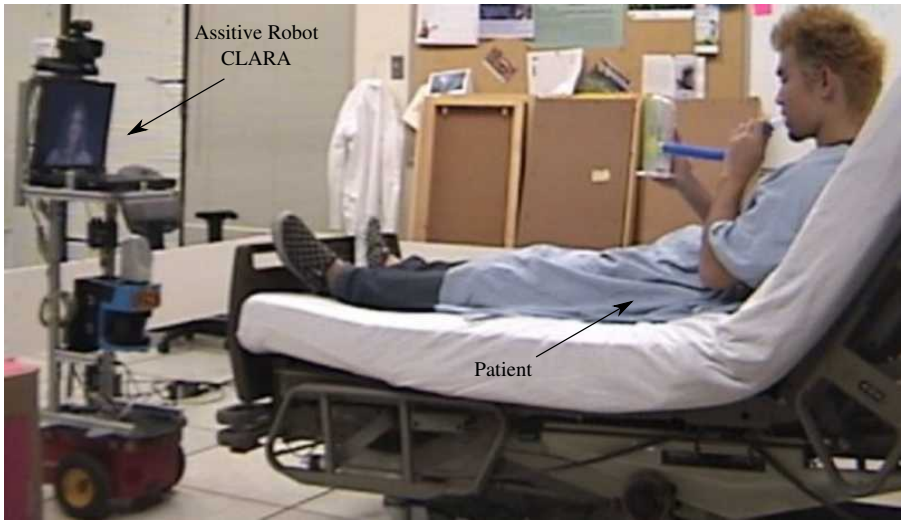


Figure 3.7: Spirometry therapy scenario assistive by social robot CLARA. Image taken from Kang *et al* [60]

3.4.1 Elderly Care

Elderly care is the service that provides assistance to older adults that present disabilities or chronic issues. This service can be provided at home or geriatric centres. Among basic assistance that is provided, it is included basic medical care monitoring of vital signs, medication administering, exercise, and provision of emotional support. The main objective of this service is to provide independence and control over their illness in a familiar environment [68].

Within elderly care services, robots as PARO (see Fig. 3.8) are used in therapeutic scenarios, in order to achieve social-exchanges and encourage patients during exercises [66, 69]. The study opens interesting perspectives about the use of robots as non-pharmacological therapeutic aid, and it has been found that Paro was able to support the complexity of a clinical scenario in a flexible way allowing patient's engagement and socio-relational exchanges. Also, effects as the improvement of communication, cognitive skills [70] and reduction of anxiety [71] in elderly population have been observed demonstrating positive attitudes towards social robots.

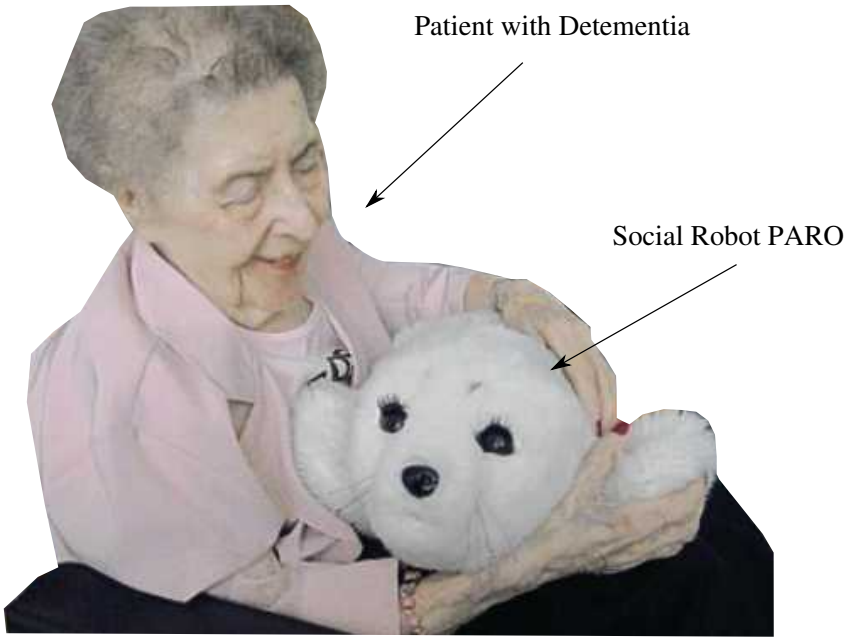


Figure 3.8: Elderly patient with dementia interacting with social robot PARO. Image taken from Calo *et al* [66]

3.4.2 Stroke Rehabilitation

The main goal of stroke rehabilitation is addressed to help patients to relearn the skills lost after the event. This programme helps improving quality of life and Independence. One of the most relevant components of the rehabilitation is associate to physical activities such as motor-skill exercises, mobility training, constraint-induced therapy to force the affected limbs to recover their function, and range-of-motion therapy that reduce muscle tension or spasticity [72].

This application has been widely approached by SAR. Where autonomous robots [67,73], and embodied agents [74] have been explored to monitor and supervise post-stroke survivors during gait training and upper-limb exercises (see Fig. 3.9). The studies showed a positive impact within the users on their willingness to perform prescribed rehabilitation, changes in the motor functioning and improvements in the average number of trials accomplished per minute.

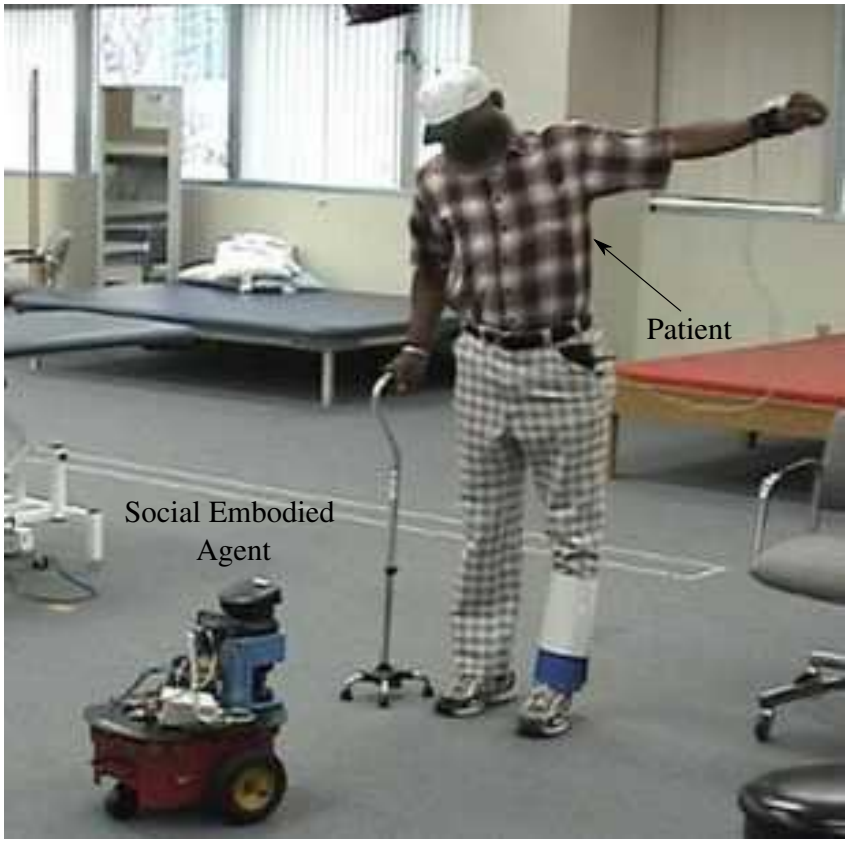


Figure 3.9: Post-stroke therapy assisted by social embodied agent. Image taken from Mataric *et al* [67]

3.4.3 Physical Rehabilitation & Coaching

Neurological disorders such spinal cord injury, cardiovascular disease, and conditions that generate neurological disorders, causing upper and lower limbs limitation, are approached by physical rehabilitation and coaching [75]. This defined as an active process to achieve a full recovery or if full recovery is not possible, reach optimal physical, mental and social potential to integrate people appropriately into society [76]. Physical rehabilitation focuses primarily on two aspects: restoring or improving patient's physiological performance, cardiovascular functioning, and aerobic capabilities during exercises. Furthermore, cognitive aspects that involve language, perception, motivation, attention, and memory are also essential to evaluate patient's performance throughout the rehabilitation [76, 77].

This application is an area of interest in social robotics as robots can be incorporated as companions to guide different kind of exercises and improve the adherence to these programmes by means of social interaction. As an example, Nao robots were implemented into conventional physiotherapy practices in order to guide several body movements [78], and in upper-limb exercises for patients with physical impairments, such as cerebral palsy and obstetric brachial plexus palsy [79]. Results have demonstrated an accurate monitoring of the therapies, and fluent interaction with the robot. Also, patients like to follow the exercises provided by the Nao and engage with the rehabilitation trying to perform the tasks [79]. In 2008, a long-term study showed the effects of human-robot interaction in coaching with the aim of reducing the rates of overweight and obesity. In this case, the robot asked patients their diet goals in terms of burning calories during the exercise and data related to the food consumed during the day. Similar applications have been reported on physical training for elderly people, where the social robot instructs patients with the exercises (see Fig. 3.10) [62]. The results showed that the participants assisted by the social robot were more interested in knowing the calories consumption and exercise performed than those who used other methods [80].

Adherence is an important factor to achieve exercise adoption, different studies have shown positive results regarding this factor. Gadde *et al*, evaluated in early stages an interactive personal robot trainer to monitor and increase exercise adherence in older adults [81]. The system was proved with 10 participants, showing initially a positive response and a favorable interaction. As a complementary application where robots are used to motivate and increase the adherence in long-term therapies and medical self-care, is diabetes mellitus treatments, where robots play the role of personal assistant in adult [82] and children [83] population. Showing, potential results within motivational aspects and treatment engagement.

Considering the context discussed above, and the potential that several studies have

Figure 3.10: Patient following physical exercise monitored by social robot. Image taken from Fasola *et al* [62]

demonstrated, this work focuses on the development of a Human-Robot Interface for cardiac rehabilitation based on SAR, incorporating the Nao robotic platform. The next section describes the model that was designed for the interaction with the user and the main components that contains the interface.

3.5 Proposal of a SAR system for CR

Chapter 2 introduced the requirements identified based on the observations of conventional therapy. As was specified in Table 2.2, these requirements were grouped in three categories (*variables* to measure, *interactivity*, and *follow-up*). Summarizing, the system must accomplish a continuous measuring and recording of variables, while providing visual interactivity (by means of a Graphical User interface (GUI)). These functionality, that comprises the *variables*, *follow-up*, and the GUI regarding the interactivity requirement, will be considered as the *Human-Computer interface (HCi)*. Similarly, the Interactivity requirements associated to social interaction, monitoring, and motivation, will be addressed by the *Social Robotic Agent*. Both

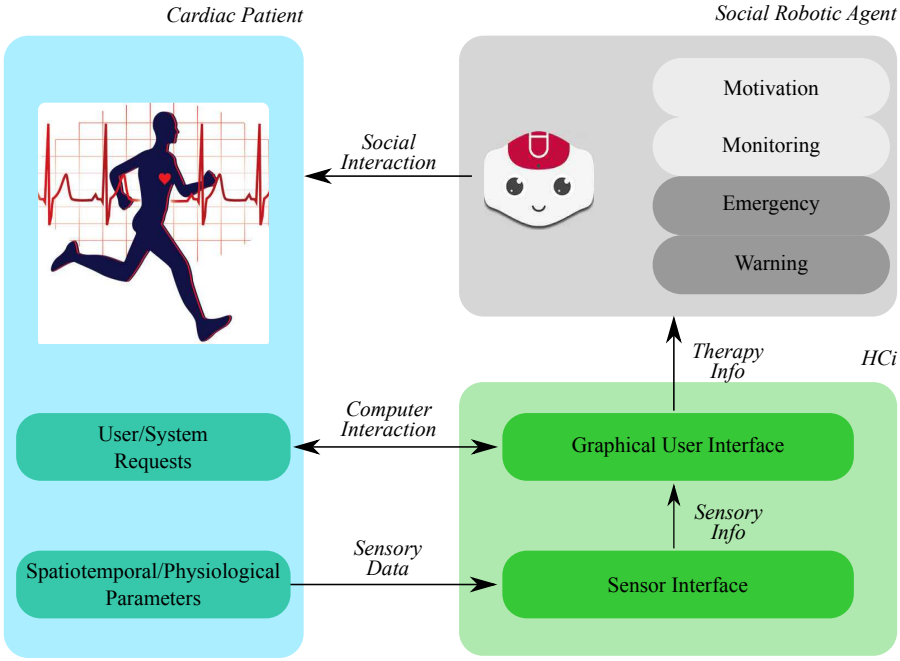


Figure 3.11: Proposed Robot-Based Therapy Model. This model considers two main components: a Human-Computer interface (HCi) designed to retrieve all relevant information from the therapy, and a Social Robotic Agent that will be able to provide feedback to the users regarding their performance and the therapy conditions, based on the information obtained from the HCi.

systems in conjunction, conform the Robot-Therapy Model (RTM) illustrated in Fig. 3.11.

The RTM focuses on three main properties: acquisition of *sensory data*, *computer interaction*, and *social interaction* between the cardiac patient and the system. As depicted in Fig. 3.11, the HCi handles variables described in Table 2.1 by means of a *sensor interface*, and the user requests by means of the *GUI*. The therapy info is processed in the HCi and sent to the *Social Robotic Agent*. The robot analyses these information, and based on the result, the state of the therapy and the behaviour that must be adopted are determined (i.e. Motivation, Monitoring, Emergency and Warning). These behaviours are established according to the risks associated to the therapy identified in section 2.4.3. Hence, with this control loop, the patient's health condition is monitored and controlled, reducing probability of risk occurrences. While at the same time, the robot is able to provide feedback

and motivation through social interaction.

Following the structure of the RTM described in this section, the subsequent chapters are dedicated to describe in detail each component of the model. Thus Chapter 4 will start with the HCi and its validation, followed by Chapter 5, where the robot software architecture is presented.

Chapter 4

Sensor Interface for Cardiac Rehabilitation

4.1 Introduction

Natural Human-to-human interaction is performed by the use of senses (e.g., vision, touch, taste, smell and touch) that facilitate perception of the environment and the ability to communicate by means of diverse information channels [84]. These information serves as the input of cognitive processes that are conformed by a sequence of tasks including reasoning, planning and execution of a given situation [85,86]. Unlike human beings, that use their senses to perceive the world, computers and robotic systems implement interfaces conformed by a set of sensors which provide the required data to perceive the environment, process the information to define a plan, and perform a determined behaviour according to the context [87]. Hence, aiming to generate an effective interaction between the user and the robot, it is of relevance to provide multiple communication channels from different sources, in other words, these interfaces should be multimodal to allow an interaction as natural as possible [85]. For this reason, in most of the HRI systems, there are not

only considered humans and robots, but also multimodal interfaces that work as an intermediary between both agents [87]. Such interfaces are commonly conformed by classic HCi's such as graphical computer interfaces in conjunction with visual interfaces (e.g., camera-based vision and recognition interfaces), and sensors such as Inertial Measurement Units (IMU's), Laser Range Finders (LRF's) or wearable devices associated to different communication modalities that are integrated within the HCi [85].

The previous chapter presented the Robot-Therapy Model (RTM) that will be implemented in this work. As specified in the RTM, two main blocks are considered: the first is the HCi that contains the *Sensor Interface* and the *Graphical User Interface*, and the second block considers the *Social Robotic Agent* (see Fig. 3.11). Following this model, the present chapter introduces the development of the HCi block, which will provide to the robotic system the ability to interact with the user and the therapy environment. This chapter is organized as follows. First, the main components of the HCi are described, thus the structure of the *Sensor Interface* and the communication system that was implemented to access and control the sensor devices is presented. Subsequently, the *Graphical User Interface* is introduced, describing the main features that are available for the user. Similarly, the modular software design is described, introducing the main concept of *Plugin*, which conforms the basic structure to incorporate functionalities to the system. Finally, the chapter concludes with an experimental study conducted with the purpose of validating the system. This validation was carried out under laboratory conditions with a healthy user in a therapy-like scenario.

4.2 Proposed HCi for CR

The HCi proposed in this work is composed of two main parts. (1) the *Sensor Interface* that integrates and processes the measurements provided by each sensor device. (2) The *Graphical User Interface* that displays the feedback data of the therapy as well as the Borg Scale interface to be delivered by the user. These components, in conjunction, work as the multimodal HCi that sends the required information to the robotic platform, which is in charge of analyze it and, based on the result, define the behaviour that the robot should adopt to exhibit a social interaction with the user (e.g., patient). The functioning of the complete system is presented in Fig. 4.1. This section describes the structure of the *Sensor Interface*, in terms of the devices that are integrated and the modular software structure that was adopted to be deployed within the HCi. Additionally, the main *Graphical User Interface* is described as well as the architecture model that was implemented to incorporate all the elements of the robotic system.

4.2.1 Sensor Interface

The *Sensor Interface* measures three types of variables selected by the medical staff to monitor the patient's status during the therapy. (1) *Cardiopulmonary parameters*: peak heart rate, heart rate variability and evolution of heart rate. (2) *Gait spatiotemportal parameters*: cadence, step length and speed, and (3) *physical activity difficulty parameters*: treadmill's inclination. This interface integrates the measurement from a Heart Rate (HR) monitor, an IMU (reporting the treadmill inclination), an LRF (to estimate gait parameters) and periodic results from the Borg scale, as well as a user and an autonomous humanoid social robot platform, NAO (SoftBank Robotics Europe, France). The system is designed to present the three main metrics considered in CR measured as follows:

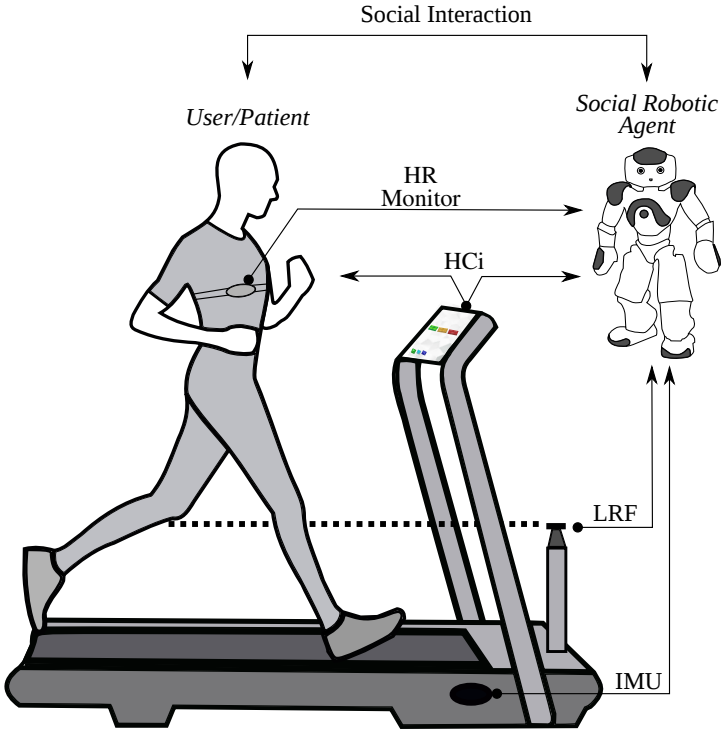


Figure 4.1: Human-Robot interface for cardiac rehabilitation. In this scenario, patients perform physical activity on a treadmill, while the sensor interface records their physiological and spatiotemporal parameters to be processed and analysed by the socially assistive robot. The results of this analysis are provided to patients as feedback by means of social interactions and the HCi that runs on a tablet and communicates with the user through a GUI.

Gait spatiotemporal parameters: As these parameters require to track the displacement of the patient's legs during exercise, the selected sensor must be able to locate the patient in the band and measure the legs difference distance LDD. Additionally, the number of steps per second, namely the cadence must be achieved by the same measurement. Moreover, the sensor must accomplish the measurement at a frequency higher than the gait frequency. However, gait frequency is low compared electronic devices. Hence, one sensor that meets all previous requirements is the Hokuyo-URG 04LX-UG01 [88]. This is a Laser Ranger Finder (LRF) used to measure areas by means of an infrared electromagnetic wave (wavelength of 785nm) and the distance measurement principle is based on light

phase difference. Similarly, this sensor allows to measure in a range of 240 degrees with a maximum distance of 4m (see Fig. 4.2). However, for this application, the measurement range will be limited to 60 degrees in order to limit the measurement of the treadmill band area. The sensor is able to perform a scan composed of 683 measurements in 0.1 s, which indicates a sample frequency of 10 Hz, being suitable for the measurement of gait spatiotemporal parameters.

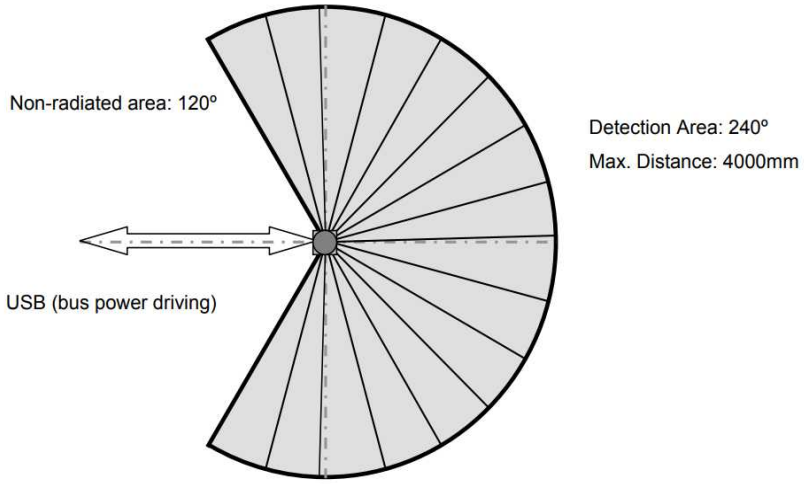


Figure 4.2: Laser range detection. Image taken from [88].

as shown in Fig. 4.1, a LRF sensor reports measurements used to estimate the cadence, step length, and speed of the patient. The estimation of these parameters was proposed and validated in a previous work [85]. As a representative case, Fig. 4.3 shows results of an experiment done with two different velocities. In this case, the gait speed changes during motion from 500 mm/s to 250 mm/s. The position of the legs is calculated in polar coordinates (Fig. 4.3a). The general process is based on the differences between two transition events that define a leg pattern. The Legs Difference Distance signal is used as input for the detection method as shown in Fig. 4.3b. This algorithm estimates kinematic parameters of lower limbs and performs filtering of the oscillatory components contained in the user movement intention [85]. The speed is obtained through the product of gait cadence (GC) and the gait step length from the leg detection process.

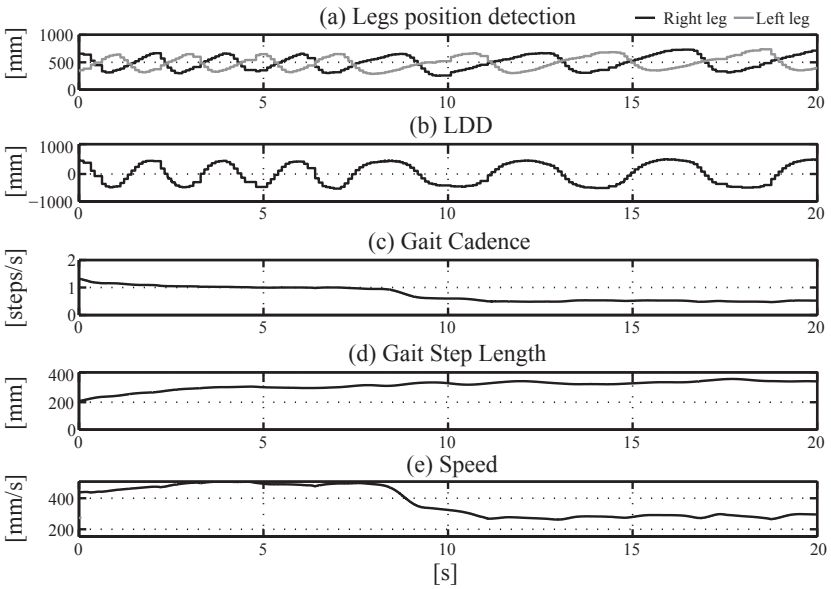


Figure 4.3: Experiment with speed variation from 500 to 250 mm/s. (a) Legs' position detection from the LRF. (b) Legs Difference Distance(LDD). (c) GC estimation. (d) Step length estimation. (e) Human linear velocity.

Cardiopulmonary parameters: the appropriate sensor for this measurement must meet three main requirements: (1) it must allow phyisical activity while performing the measurement, in other words, the sensor must resists movement perturbations. (2) This sensor must allow on-line data transmission, since the heart rate must be monitored in real time during therapy. Finally, (3) the sensor must provide the processed data, namely the sensor has to be able to measure the signal and provide the heart rate value without requiring any additional processing. Hence, a suitable sensor for this application is the heart rate monitor Zehpyr HxM BT [89]. This sensor is located on the chest of the user and reports a wireless and continuous measurement of the heart rate using Bluetooth communication.

The sensor measures the electrocardiogram signal and estimates the R to R interval (see Fig. 4.4). There is a 16 bits counter (0-65526 ms) with a resolution of 1ms, which is used to estimate the R to R interval by registering the time when an R peak is detected. Hence, the heart rate is estimated with the last 15 detections. This condition will limit the sensor for a maximum valid heart rate of 240 BPM [89]

.

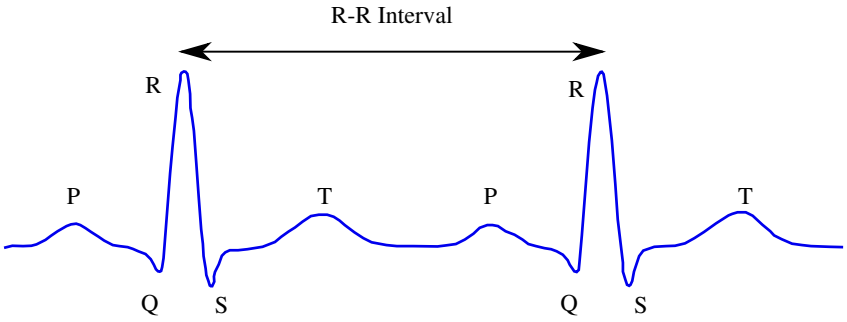


Figure 4.4: Heart rate signal

The communication with the sensor is carried out through Bluetooth with a serial protocol (baudrate 115200, 8 bit with 1 stop bit and no parity). Data collected by the sensor is transmitted to the system at a frequency of 10Hz.

Physical activity difficulty parameters: two different metrics are used to measure the physical activity difficulty: the inclination of the treadmill and the reported difficulty of the exercise. As the inclination can not be accessed directly from the treadmill, an additional sensor must be intalled. This sensor must be capable of measuring inclination angles in a range of 0 to 5 degrees (slope available in the treadmill), and as with the other sensors, it must allow on-line data transfering. Hence a sensor that meet these requierments is the MPU9150 IMU that will be placed on the treadmill in such a way that one of its rotation angles corresponds to the main rotation axis of the treadmill, thus, changes in the measured IMU angle are equal to changes in the treadmill slope.

The MPU9150 fabricated by Invensense [90], is an embedded system that combines a 3-axis gyroscope, one 3-axis accelerometer, a 3-axis magnetometer and a digital motion processor. This is a low consumption device, with high precision and repeatability, that allows the easy integration through serial communication (baudrate 115200, 8 bit with 1 stop bit and no parity). The information of this

sensor is collected by the system at a frequency of 10Hz.

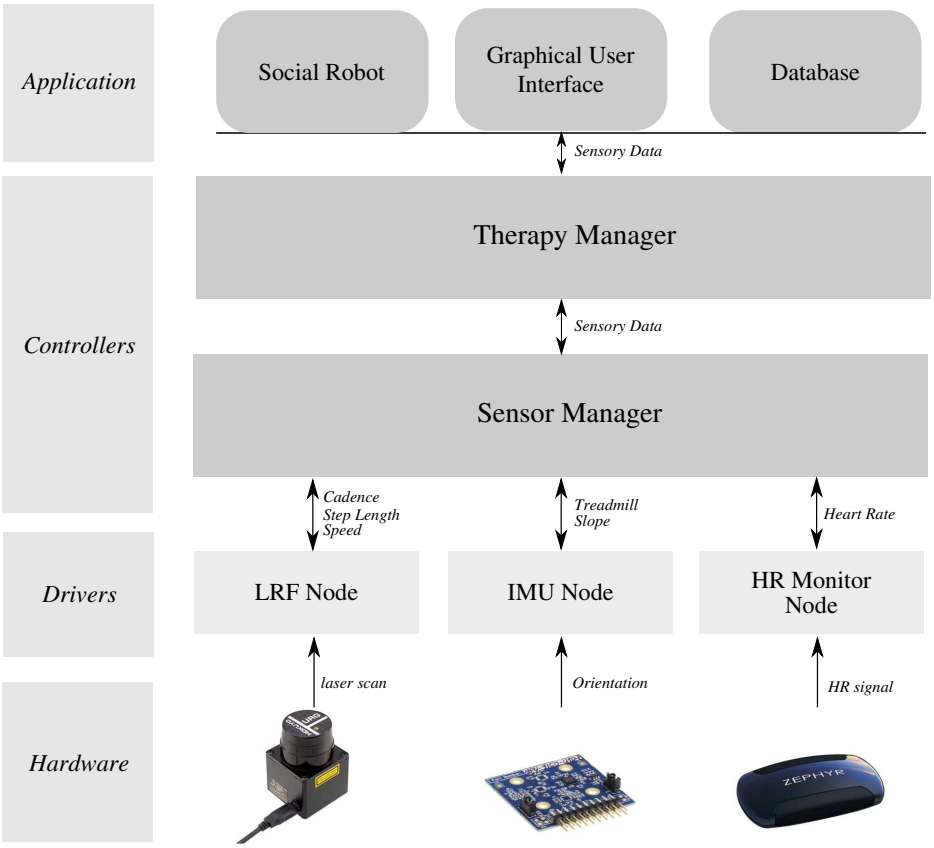


Figure 4.5: Sensor Interface software architecture. The figure illustrates the layers included in the software to retrieve the sensory data from a set of sensors. The *Hardware* layer contains the physical sensors implemented in the interface. The access control to such devices is performed by means of the *Drivers*, that run as separate nodes filtering sensor's signals and sending relevant information to the *Controllers*. The sensor manager synchronizes the sensory data and sends it to the therapy manager that controls the therapy status and has access to the *Application* components.

Sensor Integration In order to integrate all these sensing devices with the system, a modular architecture was designed. This architecture is illustrated in Fig 4.5. Considering that each sensor has different transmission rates and sampling frequencies, representing an issue in terms of on-line synchronization, a *Drivers* layer was implemented to control each sensor independently in separate nodes. These nodes are designed as drivers of the incoming raw sensory data when the module is ready to acquire information. Therefore, a downsampling is performed by each

node with a configurable sampling frequency (for this work, the configured sampling frequency for each node is set to 10Hz). This data is processed and filtered in order to be transmitted to the *Controllers*. The sensor manager is designed to synchronize the sensor data acquired from each node by performing a downsampling (sampling frequency of 1Hz). Similarly, the sensor manager is also able to control each processing module and make it available for the therapy manager, which handles the status of the therapy and communicates with the application components (e.g., Database, Graphical user interface, and Robot).

4.2.2 Graphical User Interface

The *Graphical User Interface* runs in a tactile computer monitor (i.e., Surface Pro-Microsoft USA). This interface presents basic information and control panels regarding the status of the therapy (e.g., current user, session time, start/stop panel, emergency status, and biofeedback display) (see Fig. 4.6). As was presented in Fig. 4.5, the system receives the sensory data to be processed, stored, and displayed on the screen. With this information, the patient has access to visual feedback provided by the HCi. Hence, the graphical interface reports the synchronized and processed data from the sensors, and allows the user to interact and respond to the requests generated either by the the system or the robot. Additionally, the interface estimates the patient's fatigue level by means of the Borg Scale (qualitative measurement that estimates the perceived exertion of the patient, 6 for low intensity and 20 for very high intensity [16]). This value is periodically requested by the system or the robot, which perform the request and wait until the patient delivers the value by clicking on an specific button available in the screen.

Fig. 4.6 presents the main window (i.e., *MainTherapyWin*) that is displayed during the therapy time. However, the system contains additional functionalities and forms that allow the medical staff to register users, log in into the therapy session,

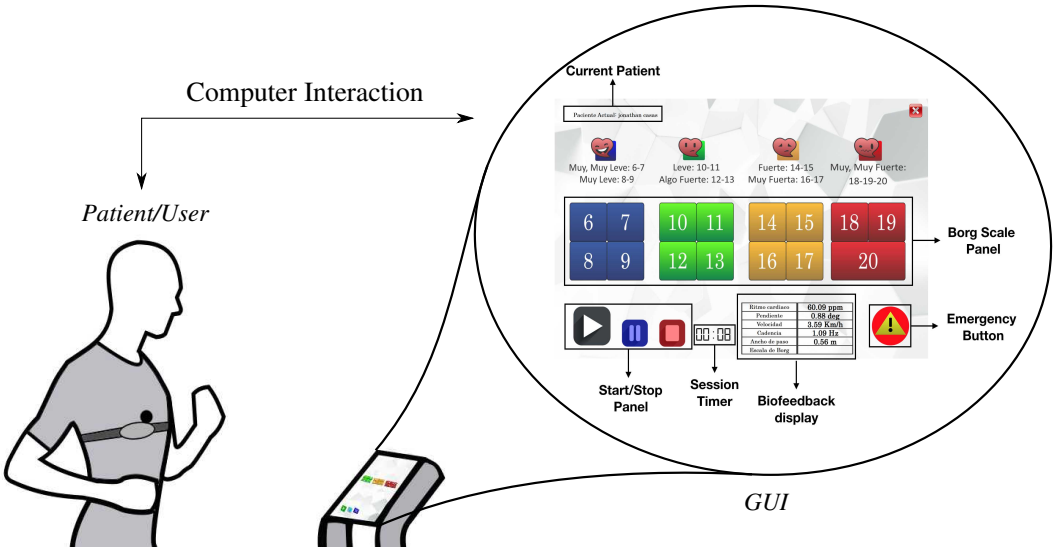


Figure 4.6: Graphical User Interface to assess the patients fatigue, view the therapy parameters as a form of feedback, configure the robot, monitor sensors and control the therapy performance.

and set therapy configuration parameters. Additionally, the system allows the user to select different modalities of the therapy. Currently, there are two modalities available: *control* and *robot* modality. In the first modality, the system only works with the HCi, namely the system only measures performance by means of the sensor interface, and store it in the database. Additionally, the GUI requests the Borg Scale, but feedback is not displayed on the screen. This modality is meant to measure patient's performance without providing any feedback or social interaction (The modality will be used for validation purposes, where the a control group defined as the baseline, will be running the experiments under this condition). On the other hand, the *robot* modality incorporates the social robot to provide social interaction, motivation and monitoring. Similarly, the GUI provides feedback regarding the state of the measured parameters (Biofeedback display, see Fig. 4.6).

Aiming to develop a scalable software that allows the incorporation of additional functionalities to be tested, the software was addressed towards a modular design. Next section describes in detail the modular structure and the patterns that were adopted to provide the desired functionality.

4.2.3 Modular Software Design

This section describes the main components of the software architecture, where the concept and structure of *Plugin* is introduced. Similarly, the general organization of each functionality module and the structure of the main therapy modules is described.

Plugin Structure: The main component that is considered in the software architecture is the *Plugin*. This component has been defined as an object that encapsulates all the necessary elements to perform an specific process within the system. The basic components are illustrated in Fig 4.7. The architecture follows the Model-Controller-View pattern. Hence, the *Plugin* contains three main elements: (1) *Win* contains the graphical components (e.g., views and forms). These components are accessed by means of events triggered by signals. (2) The *Controller* handles the signal connections as well as the communication between the processes that run in the Plugin. The main task of the controller is to integrate models and views and handle the execution of the tasks required for each process. These tasks can have two main modalities: one group of tasks can set values or trigger an action that the view must perform. While the other group of tasks are registered as callback functions that are executed when certain event is triggered by means of a signal. Finally, (3) *Models* are specific libraries or modules that allow the manipulation of the components of the system (i.e., database, robot interface, and sensor interface) as well as general purpose libraries that are required to perform a certain task.

System Architecture: As described in the previous section, the software architecture was designed based on the *MainPlugin* structure. Hence, each process that runs in the interface is encapsulated in a specific *Plugin*. The general structure of the interface is illustrated in Fig 4.8. where the integration of each functionality

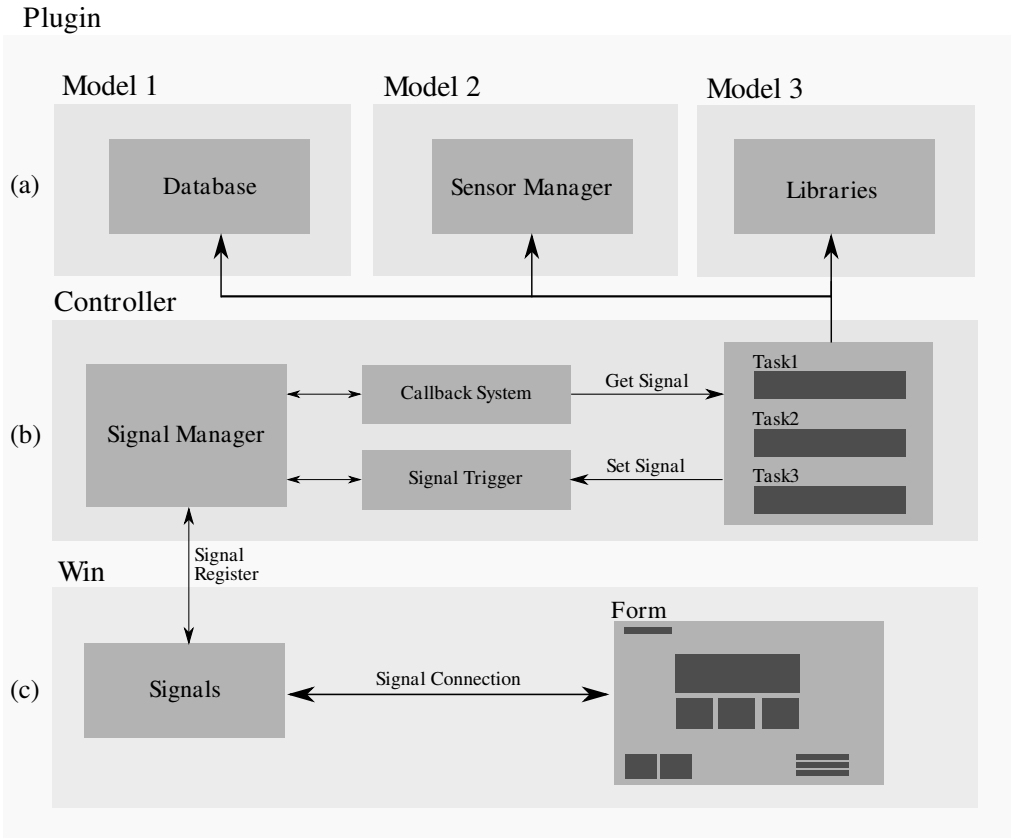


Figure 4.7: Plugin conceptual structure and components. There are three main components: (a) *Models* that include the required libraries to integrate in the system, (b) *Controller* that handles the execution of different tasks as well as the communication between the models and the views, and (c) *Win* that contains the graphical components and the signal connections to allow its access.

(i.e., module) is described. The architecture considers four categories, namely *Index*, *Options*, *Authentication*, and *Application*. The *Index* category contains the starting point of the program. In this case, when the program is started, the *MainMenuPlugin* is deployed to provide the available options of the interface. The next category contains all the options or modules that can be accessed from the main menu. There are available the *SettingsPlugin*, that allows to configure the therapy and the system features, and the *ModalityPlugin*, that provides the available modes of the therapy (control and robot). The *Authentication* category includes all the modules that handle registration and access to the application. Hence, the *LoginPlugin* controls the access to the application, and the *RegisterPlugin* handles the registration and storage in the database. Finally, the *Application* category contains

two modules: the *AlertPlugin* that allows to personalize the therapy according to the patient's health condition and progress, and the *MainTherapyPlugin* that integrates all the functionality of the therapy. This last module is considered as the most important architecture's component, since it integrates most of the resources required to perform the therapy. This Plugin is detailed in the next subsection.

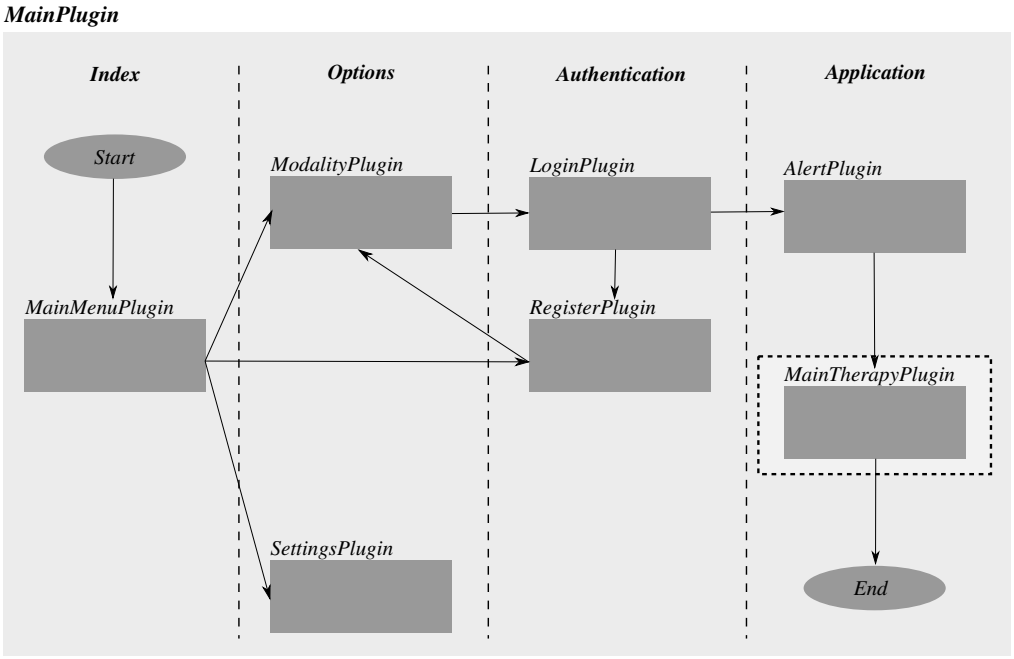


Figure 4.8: System architecture. The illustration presents the structure of the *MainPlugin*, which is designed to integrate the modules and applications according to four main categories (*Index*, *Options*, *Authentication*, and *Application*). These categories contain the modular components encapsulated as *Plugins* that deploy an specific functionality within the system.

Main Therapy Plugin: As previously pointed out, the *MainTherapyPlugin* is considered the most important component of the interface. Hence, this section describes in detail the most relevant blocks that this module contains. As shown in Fig. 4.9, the *MainTherapyPlugin* follows the same structure of the *Plugin* described before. There are 6 models or libraries that are integrated: The *Database* and *ProjectHandler* which are required for all the plugins to have access to the project configuration and storage. The *Sensor Manager*, which allows the access to the sensor devices as well as the sensory data, and the *Gaze Estimator* that provides

information about the camera-based algorithm dedicated to track patient's gaze orientation. Similarly, the *Robot Controller* is incorporated to work as the interface with the robotic platform, and finally, general purpose libraries that allow the execution of specific processes (e.g., timers, events, and multi-threading).

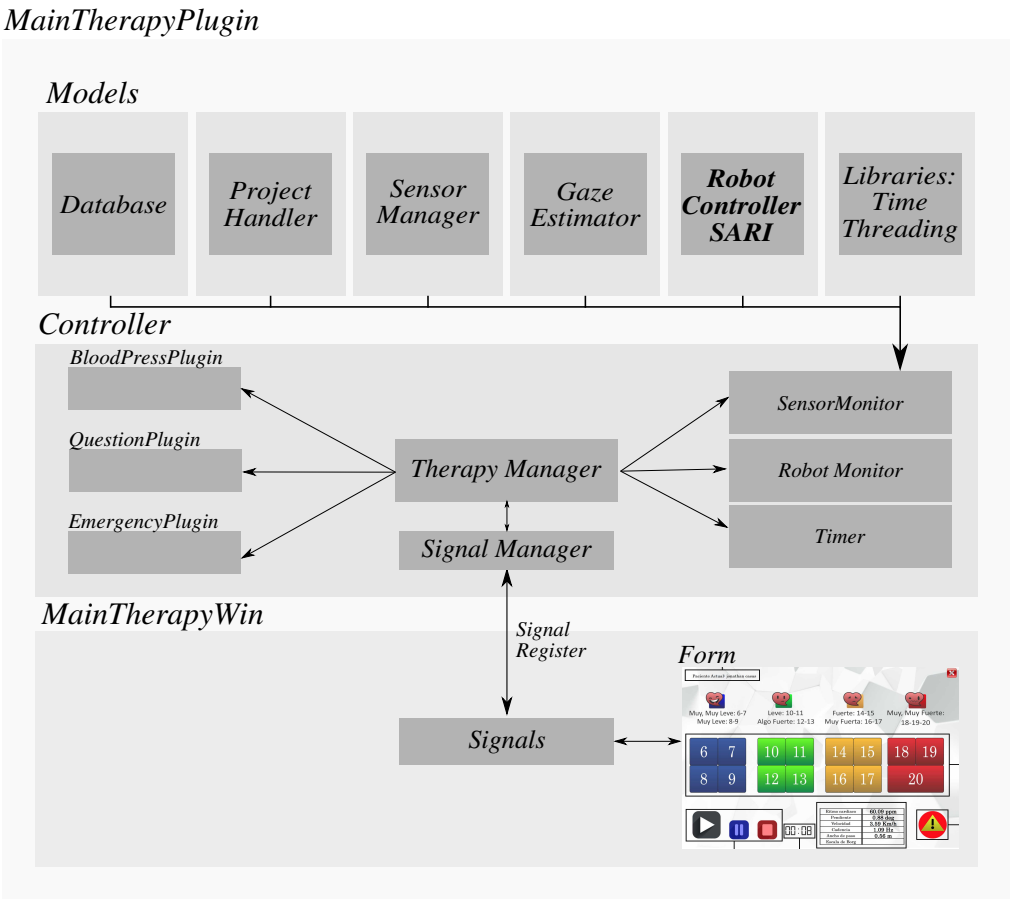


Figure 4.9: The *MainTherapyPlugin* structure is illustrated. This Plugin integrates the required modules to perform the therapy, namely, *Database*, *ProjectHandler*, *Sensor Manager*, *Gaze Estimator*, and *Robot Controller*. These modules are controlled by specific processes defined in the controller (*SensorMonitor*, *RobotMonitor*, and *Timer*). Such processes are handled by the *Therapy Manager*, which at the same time defines the signal connection and synchronization of additional Plugins (*BloodPressPlugin*, *QuestionPlugin*, and *EmergencyPlugin*) that work as sub-modules of this Plugin.

The controller deploys three main processes that control different variables of the therapy at runtime. In first place, there is a *SensorMonitor* task, that is dedicated to handle the communication with the sensor manager and the gaze estimator. This process provides sensory data when the *Therapy Manager* requests it. Similarly,

the *RobotMonitor* runs the process that handles the communication with the robot controller, and sends commands to the robot according to the *Therapy Manager*. Finally, the *Timer* process handles the signaling and timing of the therapy. This process indicates to the *Therapy Manager* when to launch or stop a specific task.

Besides handling the execution of the processess, the *Therapy Manager* defines the logic of execution and signaling control for additional *Plugins*. As the function carried out by the *MainTherapyPlugin* is complex, there are sub-modules that exhibit specific functionalities. Likewise, these modules are encapsulated in *Plugins* that are controlled by the *MainTherapyPlugin*. Hence, the *Therapy Manager* connects and launches the *BloodPressPlugin* that requests blood pressure measurements in the session, the *EmergencyPlugin* that handles warnings and alerts generated during the therapy, and the *QuestionPlugin* that performs a questionnaire that evaluates the usability and user's experience.

Aiming to evaluate the system's performance and the integration of each *Plugin* within the architecture, a validation of the system is performed. Next section presents the procedure that was carried out as well as the results obtained.

4.3 Validation of the System

In order to validate the system, a pilot study was conducted. As shown in Fig. 4.10, one healthy male (1.71 m, 63 Kg, 24 years old), without apparent physical contraindications to treadmill training, participated voluntarily in this study. The protocol was designed in order to simulate the exercise session in an average Cardiac Rehabilitation (CR) protocol and to test the response of the parameters to a change in speed and inclination. Initially, the subject walks at 3 m/s on the treadmill for 10 minutes, then, the speed is increased to 5 m/s and the inclination is increased until its maximum (3.7^o). The subject walks in those conditions for 10 minutes.

Finally, the subject stands still during 8 minutes to simulate the cool down phase aiming to observe the decreasing in the heart rate after the exercise. The setup for this experiment can be seen in Fig. 4.10.

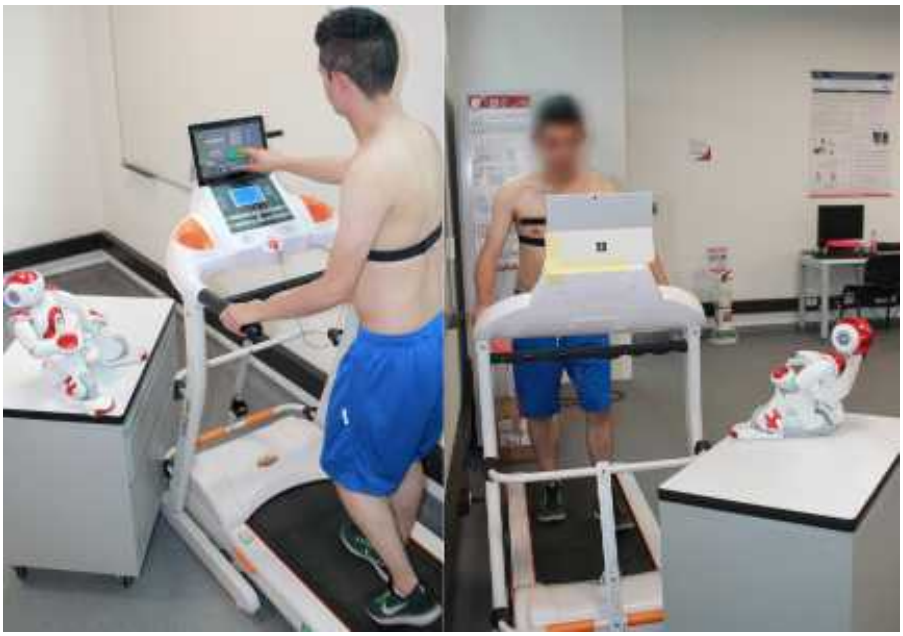


Figure 4.10: Patient exercising on treadmill according to the pilot study protocol for system validation.

4.3.1 Results

According to the protocol previously described, the system was on-line for 28 minutes. Fig. 4.11-4.13 present the continuous record of each parameter as collected by the *Therapy Manager*. The vertical lines correspond to the two events: in green the increase of speed and inclination and in red the end of the physical activity and the start of the cool-down phase. Results are divided according to the three main metrics that were expected to be measured.

Gait spatiotemporal parameters: The patient's gait spatiotemporal parameters can be observed in Fig. 4.11. All of these parameters change instantaneously

after an event, which indicates that the processing and feature extraction module is not interfering with the acquisition. All the values are in a normal range and correspond to the values that can be seen on the display of the treadmill used as reference.

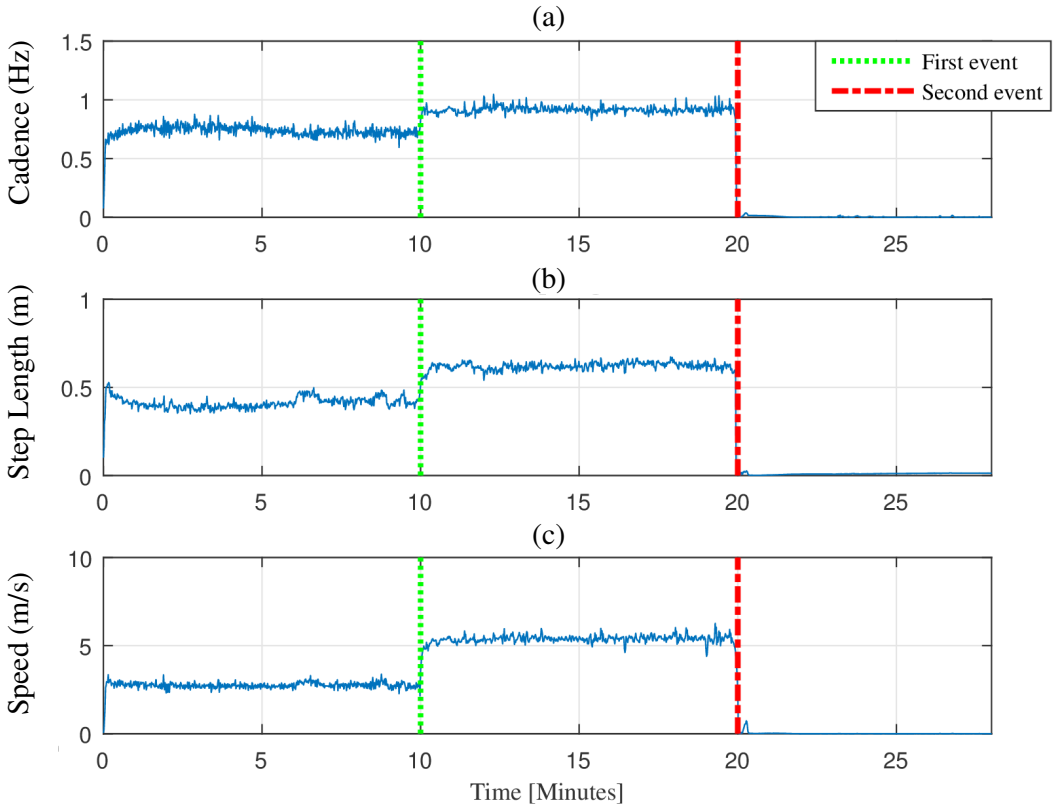


Figure 4.11: Gait spatiotemporal parameters: patient's cadence (a), step length (b) and speed (c).

Physical activity difficulty parameters The treadmill's inclination and the reported Borg scale data are shown in Fig. 4.12. The inclination curve shows clearly a sharp increase or decrease of the value following each event. As no change of the inclination was executed between events, the value stays constant except for small oscillations due to the impact of the steps of the patient on the treadmill. The Borg scale shows a continuous increase for the first 20 minutes of the session as the perception of fatigue increases during that period. The value decreases during

the 8 last minutes and stabilizes. It is important to highlight that the Borg scale is a subjective measure (see section 2.4.2).

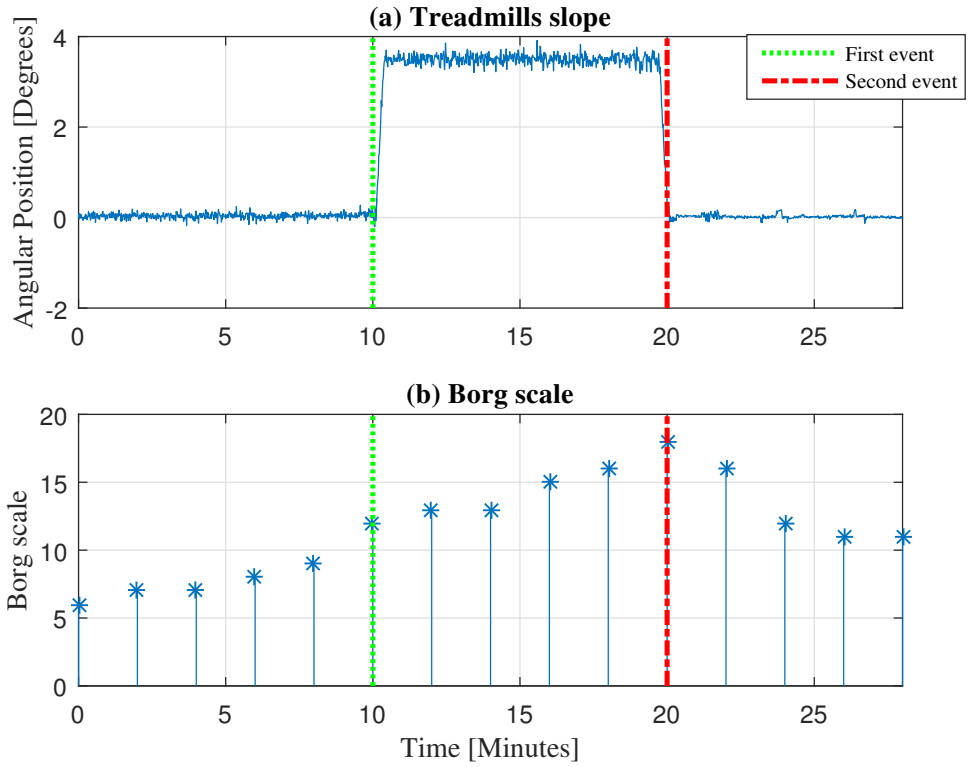


Figure 4.12: The physical activity difficulty parameters: (a) Treadmill inclination angle recorded using the MPU9150 IMU sensor and (b) Patient's fatigue obtained from the user interface.

4.3.2 Cardiopulmonary parameters

Fig. 4.13 shows the patient's heart rate during the session. As shown by the rapid increase and decrease of heart rate, the zephyr sensor has a response fast enough to be used in real time to report the heart rate and react to the events during the therapy. The absence of a clear convergence is due to the physiological response of the cardiac system. The values in the signal change according to the normal range of heart rate in healthy patients with similar conditions in comparison with the voluntary patient. For example, when the patient was walking at the beginning,

the heart rate was around 105 BPM, and when the velocity increased to 5 meters per second, the heart rate was around 145 BPM which represents a moderate effort.

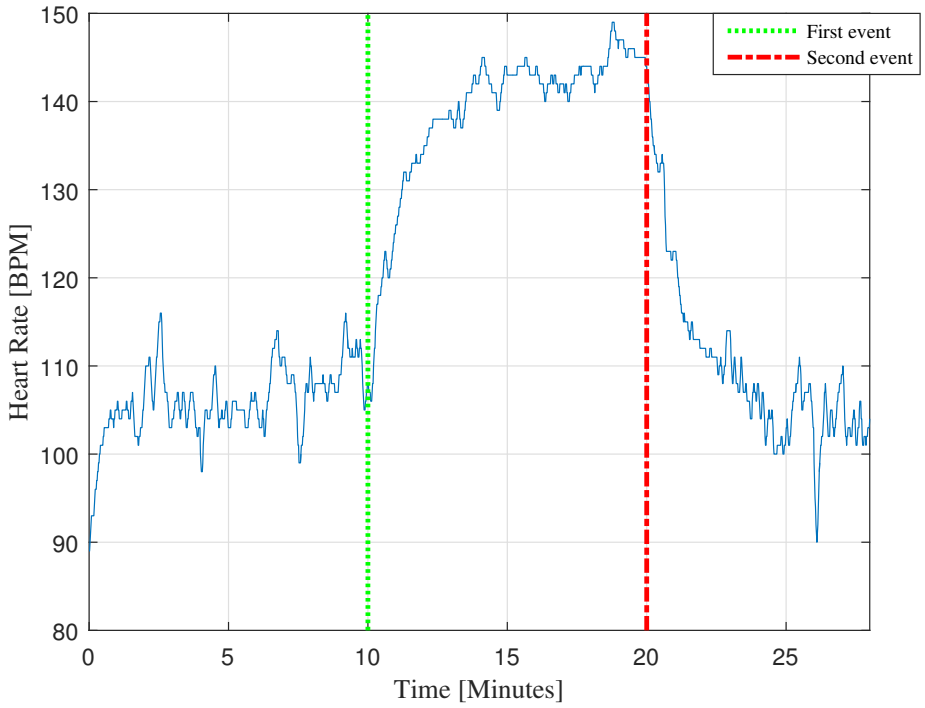


Figure 4.13: Heart rate measurement using the HXM zephyr sensor.

4.4 Chapter Conclusions

This chapter presented the software architecture that was implemented in the HCi for Robot-Assisted cardiac rehabilitation. The system contains two main modules: a *Sensor Interface*, that handles relevant sensory data, and *Graphical User Interface* dedicated to interact with the user and handle the resources according to the therapy state. Furthermore, a validation protocol was conducted aiming to validate the system's performance. The results presented in this chapter show the potential of the sensory system combining a LRF, a HR monitor, an IMU, and a graphical user interface for CR treadmill-based exercise. Spatiotemporal gait parameters are estimated from the LRF results, providing indicators regarding the patient's per-

formance in the rehabilitation therapy, and the correctness of the gait. The system combines information from different sensors to present these values in real-time to the patient and store them in the database for posterior analysis by clinicians. The Borg scale collected by the user interface can be combined with the slope of the treadmill and the heart rate to evaluate the difficulty of each session.

These variables can be presented in real-time to the patient, and the logs can be used by the medical team supervising the rehabilitation to plan the following therapy session. Based on the fact that the measurements are on-line, the system allows to record the physiological indicators, such as the heart rate, in a more precise time, during and after the exercise, compared to the current situation where the measurements are taken by the medical staff and registered in paper.

The development of this interface is a first step on the proposal to integrate a socially assistive robot into CR. Hence, based on previous studies on social robotics and as hypothesized in this thesis, it is expected that SAR could be helpful to the medical staff, reduce risk of the therapy by identifying risk factors, increase performance of the patient and increase its motivation and engagement. In this sense, next chapter will focus on the architecture that was designed for the integration of the social robotic platform to the system.

Chapter 5

Architecture Design for Robot Assisted Cardiotherapy

5.1 Introduction

Previous chapter presented a comprehensive description of the software architecture designed to integrate the components of the robotic system. In first place, the *Sensor Interface* was described, and the plugin-based structure as well as the connection of all required modules and functionalities have been defined. In this order, the present chapter continues with the description of the system, namely the software architecture design that was implemented to integrate the robotic platform with the HCi. As was illustrated in chapter 3, the Robot-Therapy Model (RTM) is composed of two main blocks (see Fig. 3.11). The first block (HCi) was presented in chapter 4, while the purpose of this chapter is to introduce the *Social Robotic Agent* block. As was highlighted in chapter 3 and 4, the HCi provides all the required sensory data to enable the robotic agent to interact with the user and the therapy environment. Therefore, the robot must implement an interface that facilitates the communication with the HCi. The integration of such interface

was introduced in Fig. 4.9, where the *MainTherapyWin* incorporates the *Robot Controller (SARI)*. This chapter presents a detailed structure of the SARI and describes each layer of the architecture that were implemented. Additionally, the therapy scenario where the robot will be tested is described.

This chapter is organized as follows. First, a three-layer architecture design is presented. In this section, the components that conform the robot interface are detailed. The *Application*, *Model-Controller*, and *Hardware* layers are presented with their respective functionalities and configurations. Once the complete architecture has been introduced, the robot-therapy scenario where the experiments will be carried out is described. Finally, a performance assessment is conducted aiming validate the functioning of the system, and hence, be able to integrate the system to the HCi and complete the structure of the RTM.

5.2 Architecture Design

The software architecture design for the robotic platform considers three main layers. Each layer was designed to encapsulate a specific functionality and facilitate the development of each module and its respective integration. From a top-bottom perspective, the architecture integrates an *Application* layer, which contains the components that allow the robot to interact with external systems and provide access to its resources, followed by the *Model-Controller* layer, that handles the execution of specific robot behaviours according to given conditions, and finally, the *Hardware* layer that controls the physical resources available in the platform in order to allow each behaviour to have access to them. This architecture is presented in Fig. 5.1. and the subsequent sections describe in detail the configuration of each layer.

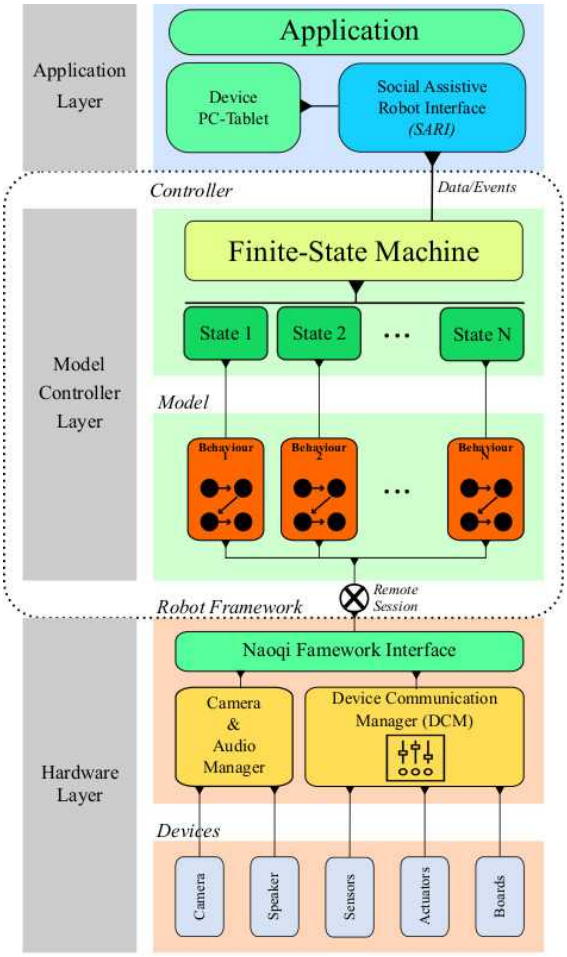


Figure 5.1: Three-layers architecture for the social robot model.

5.2.1 Application Layer

The application layer connects the HCi to the robot. As described in chapter 4, The application running on a tablet (Surface Pro-Microsoft, USA), integrates the SARI in the *MainTherapyPlugin* as a module that is accessed from the therapy manager controller. This interface allows external applications to set and get events from the robotic platform. Thus, the therapy manager is able to control each intervention of the robot during the session. This is possible by means of a set of functions, contained in the SARI, that allow the application to trigger and receive specific events (See Table 5.1).

Table 5.1: SARI event-function set

Event	Type	SARI Function
Launch robot interface	send	*launch()*
Request Borg Scale value	receive	*request_borg()*
Send Borg Scale value	send	*send_borg(val)*
Confirm Borg Scale value	send	*request_borg_confirm()*
Gaze posture correction	send	*correct_posture()*
Send sensory data	send	*send_data(data)*
Start cool-down phase	send	*set_cooldown()*
Stop robot interface	send	*shutdown()*

As described in Table 5.1, the SARI contains a block of functions that allow to trigger or receive events from the robotic platform. These events are classified in two types (i.e., *send* to trigger an action on the robot, and *receive* to get from the robot an order and perform a specific task in the application). There are basic functions that allow to start and stop the processes carried out by the robot (*launch()*, *set_cooldown*() and *shutdown()*). Similarly, there is a set of functions to handle the Borg Scale request, which is performed when the robot sends the order ($request\_borg()$) and the system returns the value to be analyzed by the robot ($send\_borg()$), or when the value requires confirmation ($request\_borg\_confirm()$). Regarding the sensory data acquired by the system, there are functions to send this information to the robot ($send\_data()$), and to request a posture correction ($correct\_posture()$) when the gaze orientation is not the desired. As shown in Fig. 5.1, these set of functions communicates with the *Model-Controller* layer by means of the events and the data that is transmitted trough the SARI.

5.2.2 Model-Controller Layer

As its name suggests, this layer is divided in two main modules, namely the *Controller* and the *Model*. These modules in conjunction provide the decision framework that enables the robot to interact with any external application according to the data obtained from the SARI in the *Application* layer.

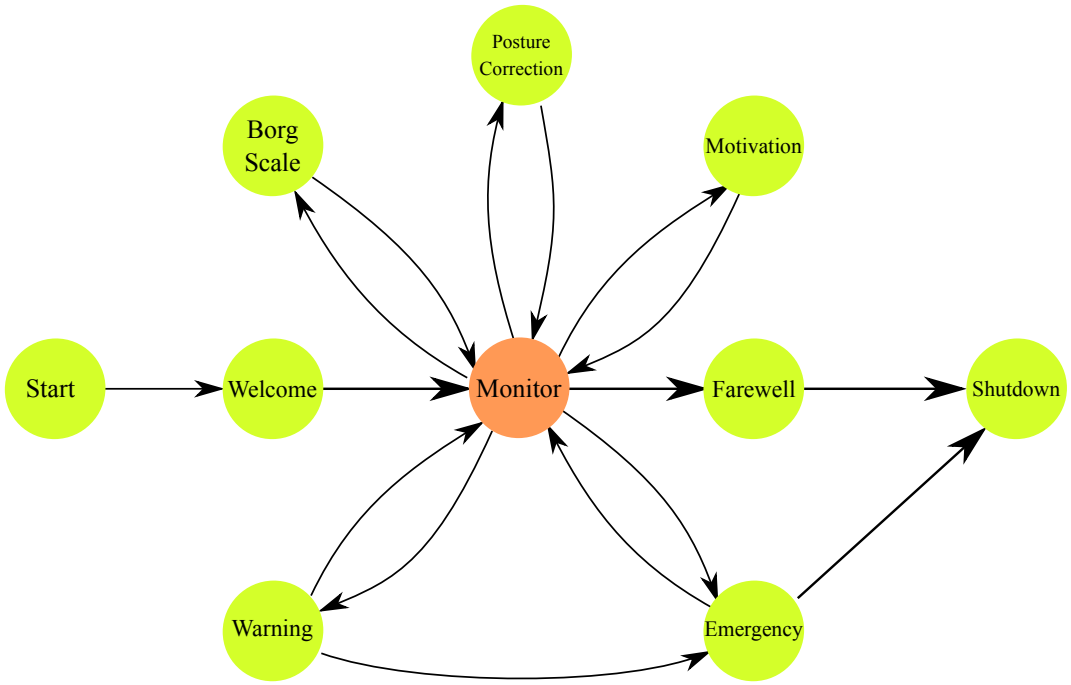


Figure 5.2: Robot behaviours in the Finite-State Machine (FSM).

Robot Controller

This module defines the state of the robot in a given situation. This task is performed with the incorporation of a Finite State Machine (FSM). Thus, as described in the *Application* layer, sensory data is sent to the controller and received by the FSM. The FSM evaluates the current state, as well as the data received, and determines the next state of the system. Once the new state is calculated, the information is sent to the *Robot Model* to adopt the corresponding behaviour. The structure of the FSM is illustrated in Fig. 5.2.

Preliminary observations were performed at the Fundación Cardio Infantil-Instituto de Cardiología (FCI-IC) to analyse the context of the therapy. These observations allowed to determine the procedure within the CR therapy, and to interpret the interaction between the patient and the therapist (see Chapter 2). The main activities performed during the therapy by clinicians are motivation, monitoring and assistance. These were considered to design a suitable FSM for the therapy and for

the behaviour of the social robot: (1) *Motivation* is provided periodically (every 5 minutes) through encouraging speech and movement, (2) *Monitoring*, which is the continuous analysis of the data (taken every second). This is considered to be the main task carried out by the robot, since most of the time it remains in this state, as shown in Fig. 5.2. (3) *Assistance* is meant to be provided when warning or emergency situations are perceived.

As depicted in the graph (see Fig. 5.2), the initial state (called *start*) initializes the FSM and triggers the *welcome* state. This state triggers the greets the user and briefly describes the therapy parameters (e.g. speed and slope) to start the therapy. *Monitoring* state is activated to receive sensory data at a frequency of 1 Hz. As can be observed in Fig. 5.2, the *monitoring* state is positioned as the central state, since all the data analysis is carried out there. According to this analysis, a decision is taken to remain in the current state or to trigger another one, such as *motivation, posture correction* or the *Borg Scale*. Posture correction occurs when the patient tilts their head down. This position can cause dizziness and it is considered as a risk factor during the therapy. The Borg Scale is considered as a qualitative exertion rate that is used to assess the intensity of the activity and the perceived exertion level by the patient. This value is requested periodically (i.e., every 7 minutes after the third minute of therapy) by the system. However, after one of these events finishes, they return to the *monitoring* state.

In addition, the *warning* state is triggered when the data provided reaches critical values depending on the physical profile of the patient. A confirmation is requested from the patient to validate the conditions through the GUI. According to the response, the system can either return to the *monitoring* state and continue the therapy or trigger the *emergency* state that requests the health professionals to provide assistance. The *emergency* state can also be activated by the *monitoring* state, if the data reaches critical values, indicating that immediate assistance is

required. This state can also return to the *monitoring* state when health professionals have controlled the situation and the patient is able to continue or if the situation is critical, the system must activate the shutdown state and finish the session.

Each state defines a behaviour that is associated with a given situation. Once the next state is defined, the Controller communicates with the *model sub-layer* to adopt the desired behaviour. This layer is described in the next section.

Robot Behaviour

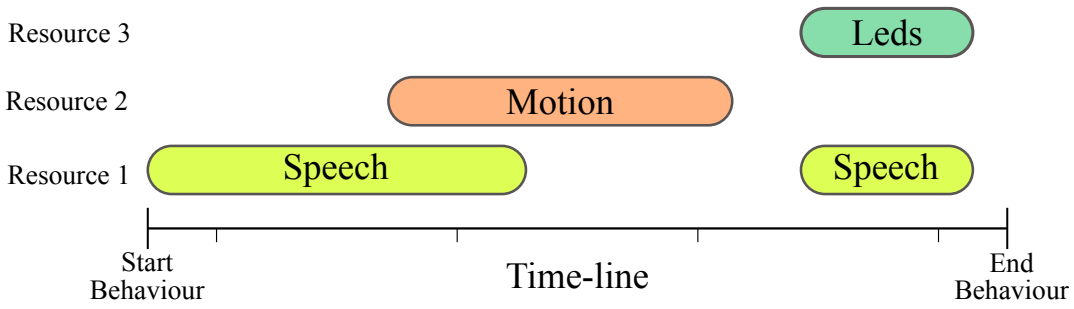


Figure 5.3: Exemplary structure of the assigned resources during the behaviours of the robot.

As described above, this sub-layer receives the information from each state to activate a determined behaviour (see Fig. 5.1). A behaviour is considered as a sequence of actions that the robot must perform. Each sequence requires some specific resources, namely cameras, speakers, speech synthesizers and other resources from the robot. Therefore, a behaviour can be structured as a timeline that allocates resources in different instants of time. The representation of a behaviour structure is illustrated in Fig. 5.3, which shows how different resources (e.g., speech, motion, tactile sensors) are required at different times to accomplish the desired behaviour. In the case of Fig. 5.3, three resources are required for the behaviour, namely speech, motion, and leds. The behaviour starts with the speech and approaching to the end, some motion is required. Finally, again speech is requested at the

same time that some leds are activated. Following this structure, all behaviours developed for this application were designed and are presented below.

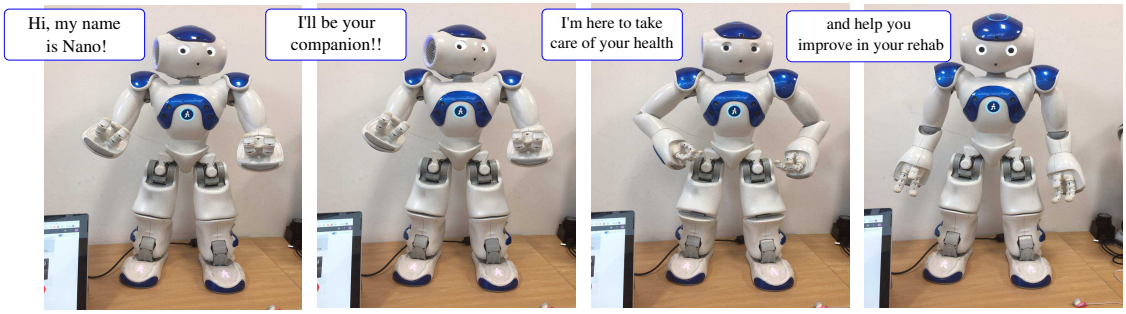


Figure 5.4: Welcome behaviour. (1) The robot starts by greeting the patient-. In (2), (3) and (4) explains its role in the therapy.

As mentioned in the previous section, each state triggers a specific behaviour of the robot. According to the FSM, the system initially set the *welcome* behaviour. This behaviour greets the patient and indicate its role within the therapy (see Fig. 5.4). After the welcome state, the robot will remain monitoring and specific behaviour is adopted until the other states are triggered.

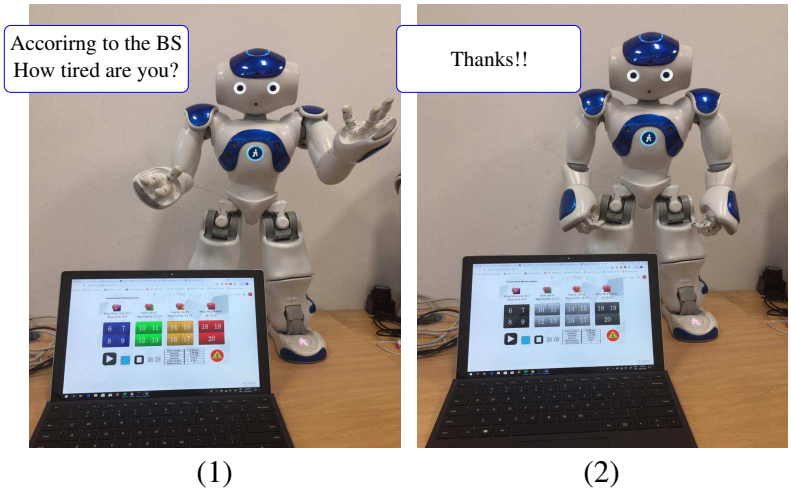


Figure 5.5: Borg scale request behaviour. (1) The robot ask for the Borg scale while the GUI enables the keyboard on the screen. (2) Once delivered the value, the robot thanks, and the GUI locks the keyboard until the next request.

From the monitoring state there are 5 states that can be activated. The Borg scale state is one of them, in which the *borg request* behaviour is triggered (see Fig. 5.5).

When the robot requests the BS, it indicates the patient to deliver the value and the GUI activates the keyboard. Once, the value has been submitted, the GUI locks the keyboard and the robot thanks the patient. As previously specified in section 5.2.2, this behaviour is periodically triggered.

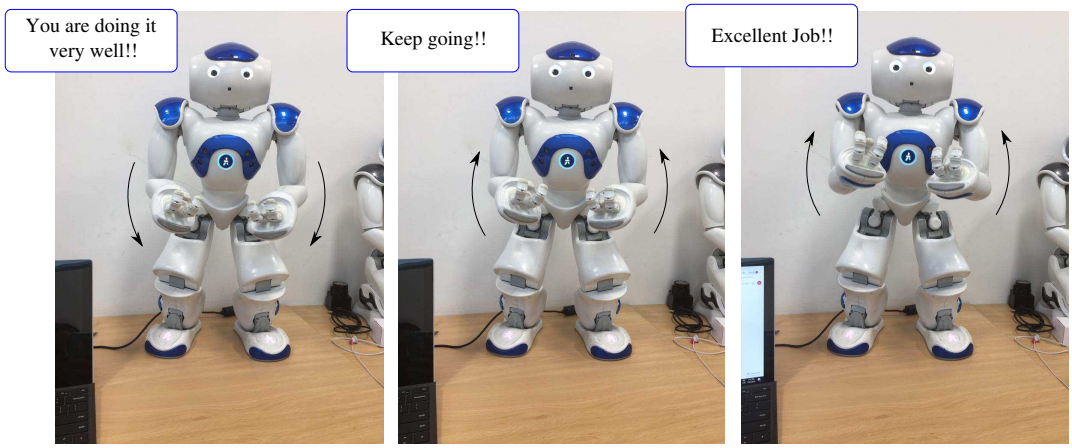


Figure 5.6: Motivation behaviour. The robot says different motivational expressions while pushing its arms up (2), and down (1) and (3).

Likewise, motivation state is periodically triggered. Once this states is on, the *motivation* behaviour is adopted by the robot (see Fig. 5.6). As illustrated in the figure, the robot uses motivational expressions in conjunction with body movement to encourage the patient during therapy. This behaviour was inspired on the observations performed in chapter 2, while analyzing the therapist-patient interaction.

Depending on the state of the therapy, two more behaviours can be triggered. When the system detects an increasing in physiological parameters, such as HR, that is used to monitor patient's health condition. As illustrated in Fig. 5.7, when patient reaches the HR level indicated in (a), the FSM triggers the *warning* behaviour, in which the robot checks the state of the patient and asks if the session is going well (Fig, 5.8). However, if the HR overcomes this level and reaches (b), it indicates a potential risk of over-training and the *alert* behaviour is adopted, where the robot calls the staff to handle the situation (see Fig. 5.9).

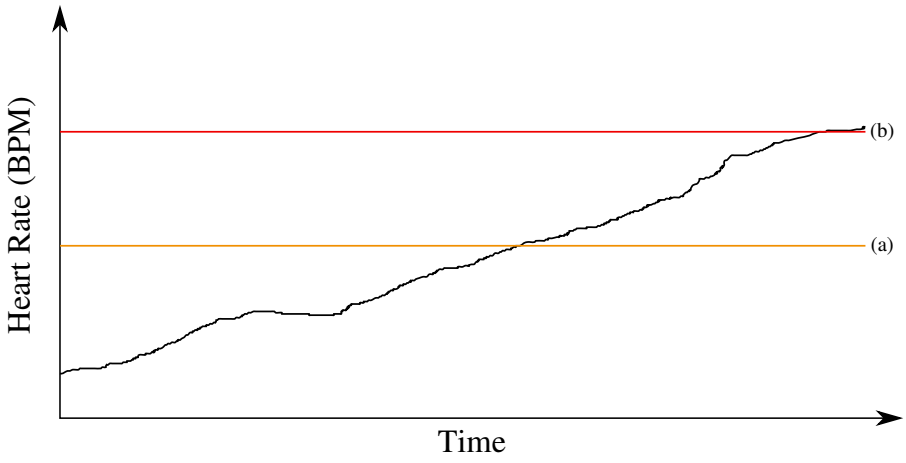


Figure 5.7: Heart rate alerts. Two alerts are defined, (a) the first triggers the warning state and check that the patient feels good. (b) the second level indicates that the patient has overcome the allowed exertion during therapy and the alert behaviour is triggered.

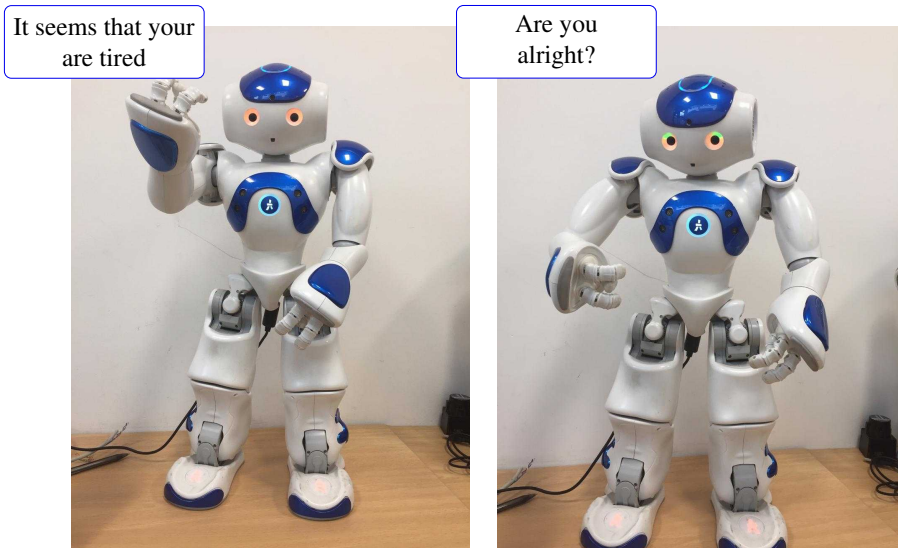


Figure 5.8: Warning behaviour. (1) The robot detects an unusual condition and indicates to the patient. (2) The robot asks whether patient is feeling well.

Finally, when the therapy time is over, the FSM triggers the shutdown state, and the robot adopts the *farewell* behaviour, indicating that the session has finished and reminds the patient to measure the final parameters after exercise (see Fig. 5.10).

All the processes up to this stage are carried out on the application device (i.e.,

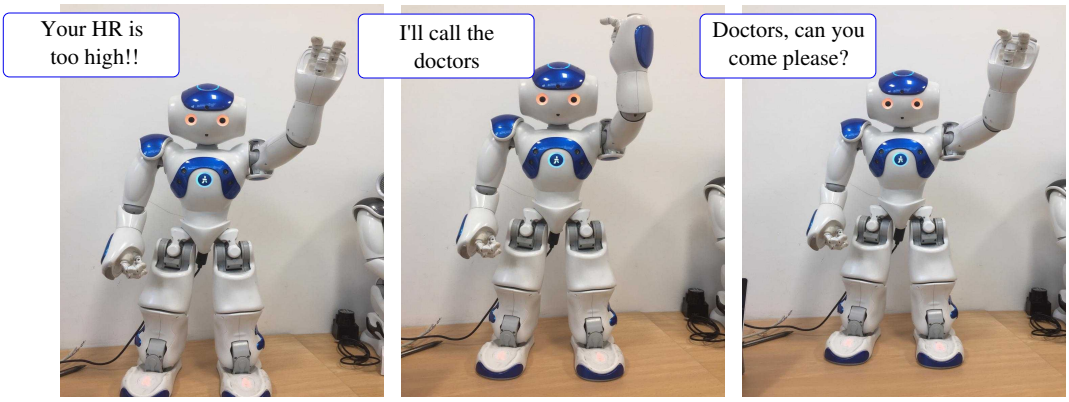


Figure 5.9: Alert behaviour. (1) The robot detects a high parameter level (e.g., heart rate). (2) It indicates to the patient that will call the medical staff. (3) The robot calls the medical staff.

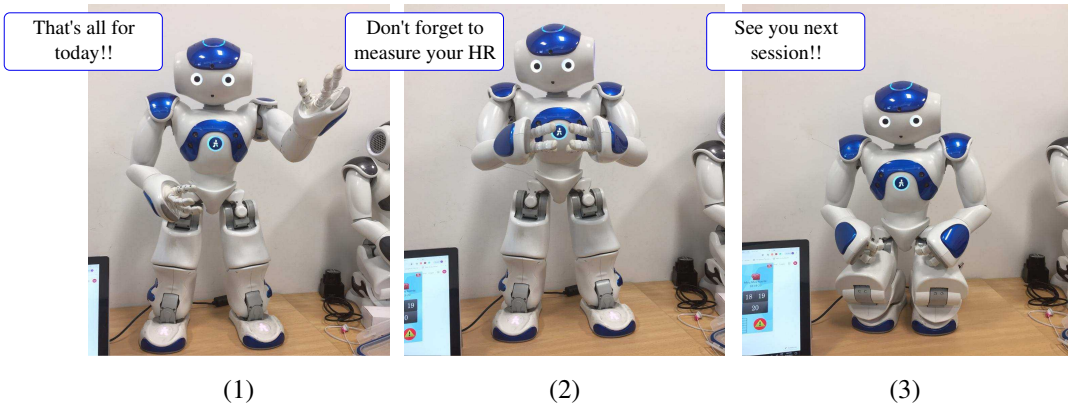


Figure 5.10: Farewell behaviour. (1) The robot indicates the end of the therapy. (2) It reminds the patient to measure the final parameters. (3) The robot say goodbye and shutdown.

tablet). Once the sequence of the resources is defined, this information is deployed to the robot platform through a remote session that enables the interface to communicate with the *Hardware* layer which contains the hardware resources (see Fig. 5.1). Next section describes this layer in more detail.

5.2.3 Hardware Layer

This layer is accessed remotely from the application device. The *interface* uses the *NAOqi Framework*[1], which enables access to the robot's resources as services via TCP-IP protocol. As depicted in Fig. 5.1, the interface manages two modules, *Camera & Audio Manager* that administrates camera, microphones and speakers. On the other hand, the *Device Communication Manager* (DCM)[2] module controls the rest of the resources such as the sensors, actuators and the board integrated into the robot.

As mentioned before, the robot platform that is integrated into this architecture is the humanoid robot NAO (SoftBank Robotics Europe, France). NAO is an autonomous programmable robot with 25 degrees of freedom[3]. The platform includes inertial measurement units to provide stability and space positioning, force-sensing resistors, two bumpers, microphones for sound recognition and sound localization, speakers (for text-to-speech synthesis) and two cameras used in computer vision and recognition applications. Additionally, this robot has an onboard Atom processor (Z530 1.6 GHz) and *Wi-Fi* interface IEEE 802.11.

Having integrated the components of the robotic system, next section presents the structure of the scenario where the robot will be deployed.

5.3 Robot-Therapy Scenario for CR

This section describes the experimental scenario and the conditions that have been designed to deploy the application within the CR unit at FCI-IC. First, the exper-

[1]http://doc.aldebaran.com/2-1/ref/index.html
[2]http://doc.aldebaran.com/2-1/naoqi/sensors/dcm.html#dcm
[3]http://doc.aldebaran.com/2-1/family/robots/index_robots.html#all-robots

imental conditions as well as the considerations on each condition are described, followed by description of the follow-up schema and the stages considered in the therapy.

5.3.1 Experimental conditions

This thesis will consider two main conditions, namely *control* and *robot* conditions. These conditions have been designed aiming to compare both scenarios. From this comparison it is expected to evaluate the effect that incorporating a social robotic companion have within therapy. Hence, *control* condition will be considered as the baseline of the study and the intervention will be carried out with the *robot* condition. These scenarios are described below.

Control Condition the purpose of this condition is to measure the performance of the patient during the therapy, without interfering or altering the normal conditions of the session. In this case no intervention of the robot agent is presented and is used as the baseline, corresponding to classic therapies without robot. According to this condition, the user only interacts with the GUI to deliver the Borg scale when the system requests (i.e. according to the health professionals, the system was configured to request the Borg scale each 7 minutes). In order to perform the experiments under these conditions the system was selected on the first modality, which has been also defined as the *Control* modality (see Chapter 4).

Robot Condition In this condition, a social robot is introduced with a standard behaviour designed to support the patient during the exercise, providing motivation and monitoring of his/her physiological performance. The robot is placed one side of the treadmill, below the eye level of the patient. Once the therapy begins, the robot stands in order to draw the attention of the patient and starts the inter-

action according to the FSM. In this case, the system is configured with the second modality, which is known as the *Robot* modality (see also Chapter 4 for reference).

5.3.2 Experimental Setup

The experiments that will be conducted throughout this thesis are carried out in the CR at FCI-IC, where one treadmill of the unit was reserved for the study. Fig. 5.11 illustrates the distribution of the CR center, where the experiment is carried out next to conventional therapy patients. Additionally, the robot's location (red dashed line) and the cool-down area can be observed.

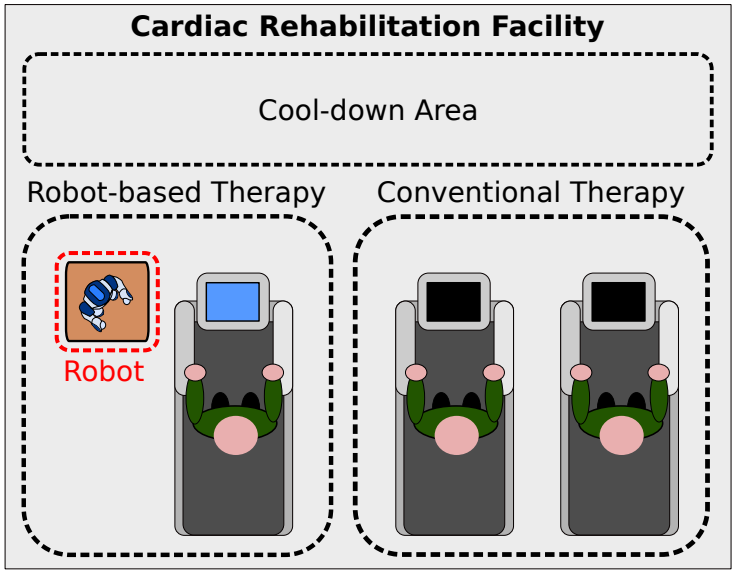


Figure 5.11: Cardiac Rehabilitation facility: the image shows the distribution in the clinic and the location of the proposed robot-based therapy. The conventional therapy and the cool-down area are also depicted

5.3.3 Experiment Procedure

In order to accomplish all the experiments, a standard session procedure has been defined. Hence, Fig. 5.12 illustrates the events and the occurrences that take place during a conventional intervention. As depicted in Fig. 5.12, the session for the

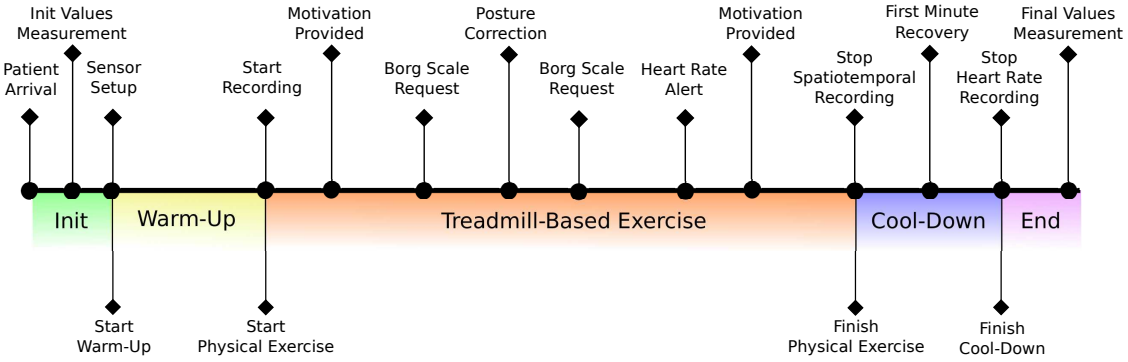


Figure 5.12: Exemplary schema of a therapy follow-up. This illustration represents all the stages existing in the therapy and the most relevant events that are considered in each stage.

experiments will be divided in 5 stages (i.e. *Init, Warm-Up, Treadmill Exercise, Cool-Down* and *End*). During theses stages, different processes are accomplished. The session starts with initial measurements performed by health professionals (e.g., Resting Heart rate and Blood Pressure). Once the *Warm-Up* is starting, the experimenter installs the heart-rate monitor on the patient and establishes the communication with the system to start when they are ready for the *treadmill-based exercise*(see Fig. 5.13). During this stage, most of the interventions are present since the system provides *motivation*, requests the *Borg Scale* and monitors all the *alerts*. Followed by this stage, continues the *Cool-Down*, where the spatiotemporal recording is disabled and only the heart-rate is monitored to evaluate the physiological recovery after the first minute. Finally, after the *Cool-Down*, the session concludes with measurement of final parameters (e.g., final heart rate and blood pressure) stored in the system before closing the session.

Next section presents a pilot study that were carried out under the conditions described in this section, aiming to assess the robot architecture's performance.

Figure 5.13: The experimental setup of the cardiac rehabilitation therapy at Fundación Cardioinfantil-Instituto de cardiología (FCI-IC), with the proposed human-robot sensor interface.

5.4 Performance Assessment

In order to assess the performance of the architecture, a male patient (age: 55, height: 1.66 m and weight: 75 kg) with an acute myocardial infarction was evaluated during a CR session. As mentioned in the architecture, the interface is remotely connected to the robot and all data and events are transmitted through this channel. The system was operating during the whole duration of the therapy (38 minutes). Fig. 5.14 shows the occurrences of each event that triggered a specific state of the FSM. The events are classified in colours and the distribution during the therapy is represented.

Table 5.2: Number of occurrences of each event during an exemplary CR therapy

State	Occurrences
Welcome	1
Borg Scale	6
Motivation	6
Posture Correction	1
Warning	3
Emergency	0
Farewell	1
Shutdown	1

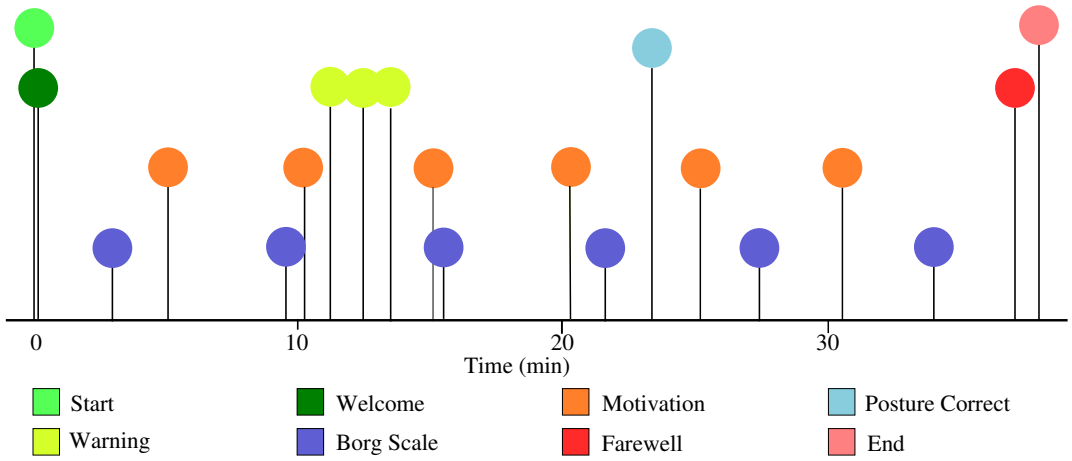


Figure 5.14: Event plot of an exemplary CR therapy with duration of 38 minutes with the proposed architecture.

Table 5.2 summarises the number of times that the FSM was on each state during the session. *Welcome*, *farewell* and *shutdown* states occur only once, since it is not possible to return to those states during the therapy. On the other hand, event-depending states and data-depending states were triggered more than once. This is the case for the *motivation* state and *Borg Scale* states, that were triggered both six times. The *posture correction* state was triggered only once, however, according to the observations of the experimenter, there were more situations present that should have triggered, but the system did not respond fast enough.

A similar situation occurred with the *warning* state that was triggered three times, wherein all the occasions the patient did not report an emergency. However, the sensor interface detected high parameters and triggered the state repeatedly. During the therapy, the *emergency* state was not triggered as the patient did not display any complications. As the FSM remains most of the time in the *monitoring* state, it is not taken into account in Table 5.2.

5.5 Chapter Conclusions

With the implementation of the proposed robot architecture, it was possible to integrate a social assistive robot with the HCi proposed in chapter 4, and deploy the system into a real CR therapy scenario, responding accordingly to the different situations presented. The robot was fully operative during the therapy session without presenting any technical difficulties (e.g. system failure or disconnection). However, the evaluation of the study presented the following necessary adjustments to the behaviour structure, namely, the states sequence of the FSM: (1) For the *posture correction* state it is necessary to increase the response time, in order to provide a more accurate correction during the session. As described in the last section, the robot was able to detect a bad posture only once, even though there were more situations present. Additionally, the latency of the response was considerably high since the correction was requested by the robot a few seconds after the patient corrected their posture. (2) The warning state requires an inhibition feature. As explained in Section 5.4, the warning occurred three times and the patient in the first event reported no complications, which was again triggered after one minute, receiving the same response from the patient. Therefore, to avoid a third consecutive repetition or more, the FSM must verify the conditions of the patient and lock the warning state for a predetermined period and continue with the therapy.

Taking into account the patient's first impression of the robot therapy, initial observations were positive. Some comments were : "*the robot was a useful accompanying tool*", " *the robot incentives positively to continue the therapy*", and "*the system seems to have more accuracy than a conventional therapy*", showing the potential use of a social robot in a preliminary phase of the study. Hence, with the preliminary pilot studies that have been conducted to evaluate the system, there is evidence of the potential of deploying the architecture in a larger experimental

study. Thus, the next chapter will present the experimental studies that were carried out at the clinic, considering two main aspects. First, the system performance and response in a real scenario with multiple patients, and the effect of the system in terms of patients' physiological condition as well as their perception of the technology.

Chapter 6

HRI Experimental Study

6.1 Introduction

As introduced in the last chapter, the objective of the present chapter is to describe two experimental studies that were performed at the FCI-IC with cardiac patients during multiple CR sessions. The first experimental study will be focused mainly on evaluating the system's performance and the effect that the robot-therapy has on the patient's physiological conditions. Although a perception assessment is also conducted, this aspect will be comprised in the second study, where a more complete perception study is carried out.

6.2 Experimental Study 1: Quantitative Assessment

This first experimental study was designed to evaluate the system's effect in terms of patient's physiological conditions as well as the interaction between the user and the robotic system. For this purpose, a longitudinal study is conducted, considering

two groups: *Control group* and an *Intervention group*. Participants that are allowed to take part of the study, as well as the experimental design and variables to measure are presented below.

6.2.1 Participants

In this study a total of 6 patients (age: M 58 SD 3.9 years old) took part of the experiments. These patients have been selected according to the inclusion and exclusion criteria described below:

Inclusion Criteria: within the study, there are going to be considered patients that are starting the Phase II of the CR programme and that only attend twice a week to the sessions. Patients with Acute myocardial infarction (AMI), Percutaneous Coronary Intervention (PCI) and in POP (Post-Operatory Procedure) from coronary artery bypass graft and valvular replacement are to be considered in the study.

Exclusion Criteria: according to the experimental setup and the system features (see section 5.3.2), people that present difficulty or any impairment to work on a treadmill, as well as patients with height lower than 1.50 m must be excluded from the study. Additionally, patients presenting any visual, auditive or cognitive impairment that impede the manipulation and correct understanding of the system cannot take part of the study. Finally, patients that present a different cardiovascular pathology from the pathologies mentioned in the inclusion criteria, will not be considered for the experiments.

Elimination Criteria: during the study there are two cases where an elimination will be considered: (1) In case that the participant does not attend to three

unjustified session in a row, he/she must be excluded from the study and is considered as a drop-out. (2) In case that the health conditions of the patient reach a critical point that impede the realization of the physical activity the patient must abandon the study.

6.2.2 Experimental Design

A longitudinal study was designed with two groups in consideration according to the experimental conditions defined in section 5.3.1. These groups are expected to provide conditions for assessing the impact of the social robot in the CR context. Associated to each group, a condition has been assigned: the control group will perform the experiments under *the Control Condition (C_{con})*, whilst the intervention group will perform experiments under the *Robot Condition (R_{con})*.

Participant Assignation

The assignation of incoming patients to a determined group is carried out with a randomized process. Once the patient accepts to participate in the study, he/she is randomly assigned to one group and the responsible of the protocol explains the conditions under which the experiment is going to be performed. All participants are free to abandon the study whenever they decide. In these cases, patients are taken into account in the drop-out rate, which is also analyzed at the end of the experiments.

In order to evaluate the aforementioned conditions, the experiments have been designed for a group of 6 patients divided into the two conditions (i.e. 3 patients in R_{con} and 3 in C_{con}). Patients do not have knowledge about the other experimental conditions (i.e., Control patients do not know about the robot or have any contact

with it). All patients are supposed to carry out the complete phase II of the CR programme, which has a standard duration of 36 sessions [1].

Session Exclusion Considerations

During the experiments can be presented circumstances where the data recorded is invalid or the complete study with the patient should be finished. These events are described below:

- In presence of a system failure, a sensor malfunction or disconnection with the robot, the session will be invalidated and is reported as a lost session.
- When there is a justified absence of the participant, the session is reported as lost. However, this is not taken into account in the nonattendance rate statistic.
- When the participant does not attend to three unjustified sessions in a row, should be excluded from the study and considered as a drop-out.

Experiment Procedure

Following the experiment procedure carried out on each session described in section 5.3.3, this study was designed to be carried out through the complete phase II of the CR programme for each patient. During this period, patients in both conditions will be monitored by the system, and a set of metrics and variables will be retrieved in order to evaluate performance during the programme. These variables are explained in the next section.

[1] Duration of the phase II might differ between patients, according to their physiological condition

6.2.3 Variables

In order to evaluate the study, the experimental protocol contemplates metrics related to the variables that can be recorded and stored with the system and provide information about the performance and evolution of the patient along the sessions. These variables are three: *nonattendance rate*, *physiological variables* and *interaction variables*.

Nonattendance Rate: this measurement takes into account the number of absences that participants presented during the study in both conditions. These absences are considered when patients miss the session without informing or justifying the reason of missing the therapy.

Physiological Variables: here are considered two metrics. (1) *Resting Heart rate* which is the heart rate level that patients present without performing any physical activity. The development of this variable is directly related to the physical fitness and is commonly used in physical training studies [91]. This parameter is measured at the beginning and the end of the session (See Fig. 6.1 event 1 and 4). (2) *Recovery Heart rate* is measured within the first minute of cool-down and is estimated as the difference between events 3 and 2 (See Fig. 6.1). This parameter provides information related to the recovery capability that a patient has after the exercise and is directly related to the degree of fitness of one person [92]. These two variables are meant to provide key information about the physical condition of the patient and how this condition is evolving during the programme.

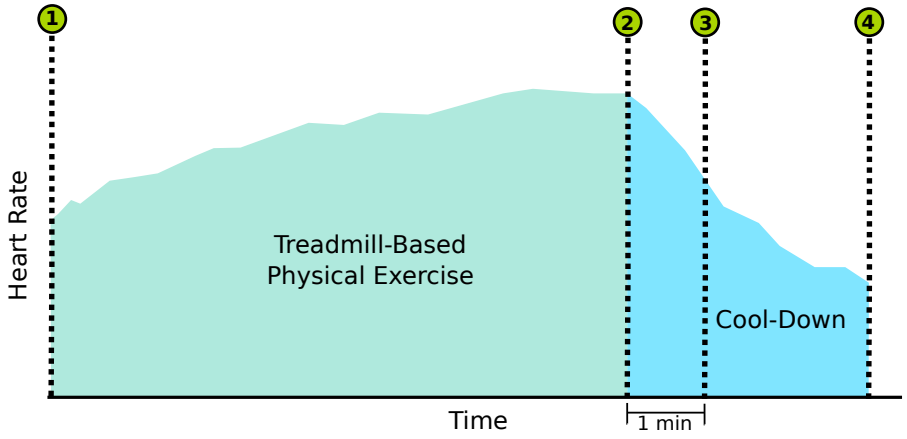


Figure 6.1: Physiological Variables Events: (1) Initial HR (Resting Heart Rate), (2) Heart rate at the beginning of the cool-down, (3) Heart Rate after the first minute and (4) Final Heart rate (Resting Heart Rate)

Interaction Variables: are meant to quantify the interaction that patients have with the system. This interaction is also evaluated through two different metrics. (1) *Response Time (RT)* defined as the time (in seconds) that patients take to deliver the Borg Scale (BS) value when the the robot has requested and (2) *Posture Corrections*, which quantifies the amount of corrections that the robot requests to adopt a correct posture and reduce the risk of falling or present dizziness during the exercise (these parameters are only measured with the R_{con}).

6.2.4 Results

This section presents the results of 6 patients that participated in the experiments. Participants were equally distributed (i.e., 3 in the control group and 3 patients in the intervention group). Table 6.1 illustrates the number of sessions that all participants performed in their respective condition. As shown in Table 6.1, in the R_{con} a total of 119 sessions were programmed and in C_{con} 90 sessions were programmed. Differences in number of sessions per group are presented due to the patient's conditions during the programme (i.e., some patients require more

therapy than others to recover their optimal physical condition). Additionally, for this particular experiment, one patient ($P1 - C_{con}$) was removed from the sessions, due to one of the exclusion criteria previously defined (3 consecutive sessions were unattended without justification).

Table 6.1: Sessions summary

Control Condition		Robot Condition	
Patient	Sessions	Patient	Sessions
$P1 - C_{con}$	**16***	$P1 - R_{con}$	40
$P2 - C_{con}$	33	$P2 - R_{con}$	39
$P3 - C_{con}$	41	$P3 - R_{con}$	40

*The patient was removed from the experiments

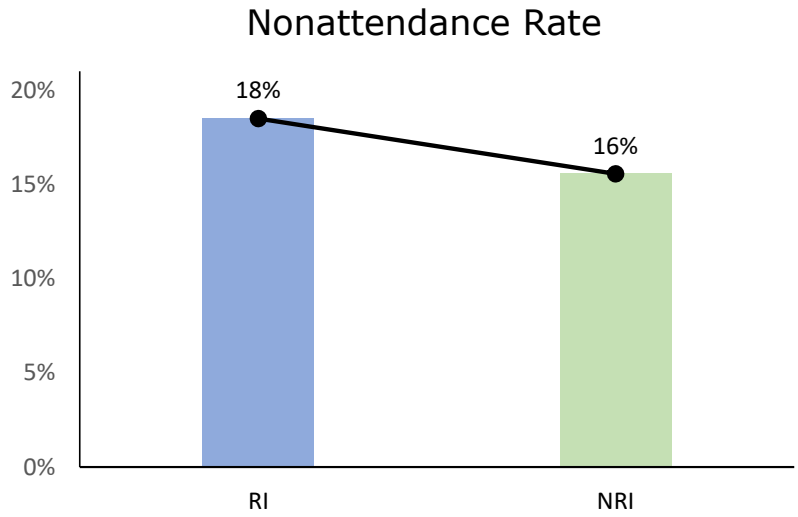


Figure 6.2: Nonattendance rate between R_{con} and C_{con}

Attendance Results related to the attendance in both conditions are presented. Fig. 6.2 shows the nonattendance rate in both conditions, where the R_{con} (intervention) presented a 18% of sessions unattended (i.e. 22 of 119 sessions). On the other hand, in the C_{con} (control) a 16% of nonattendance was reported (i.e. 14 of 90 sessions). The attendance reported a slight difference between control and intervention, where patients appeared to miss more sessions in the intervention group than in the control group. However, in the control group a drop-out was present. Although In both cases this rate do not exceed the 20%, which is a positive result

independently of the condition, this result can be biased by the experiment conditions, that might change the participants' behaviour and make them feel more compromised to assist to the therapies.

Failures: During the experiments, the system has presented different technical issues that in some cases compromised the data that was being measured or the interaction with the user. These issues were mainly related to sensor malfunctions, system crashing or disconnection of the devices (e.g. robot network, sensor ports). For these experiments a total of 24 failures for the intervention group were presented, representing the 20.1% of the sessions. On the other hand, for the control group a total of 21 failures has been registered (23.4% of the sessions).

Physiological evolution The physiological evolution is estimated based on the resting heart rate (i.e. the heart rate level that patients present in normal conditions, without performing any physical activity). Results show the relative heart rate that is calculated based on the value registered in the first session.

Fig 6.3 shows the relative resting heart rate for both conditions (red line for R_{con}, green line for C_{con}). The linear model, estimated with the pearson linear correlation test, shows a decreasing rate for the R_{con} ($-0.0036x + 0.984$, p= 0.049), whilst the C_{con} presents an increasing rate ($f(x) = 0.0142x + 1.083$, p= 0.017). Similar results were found in [91] for the robot condition, where a robot companion for physical training was developed. However, for the control condition a decreasing rate was also expected.

Heart Rate Recovery Another parameter that has significant relevance is the heart rate recovery index. This parameter is measured after the exercising has concluded and patients start the cool-down phase on each therapy. In this particular

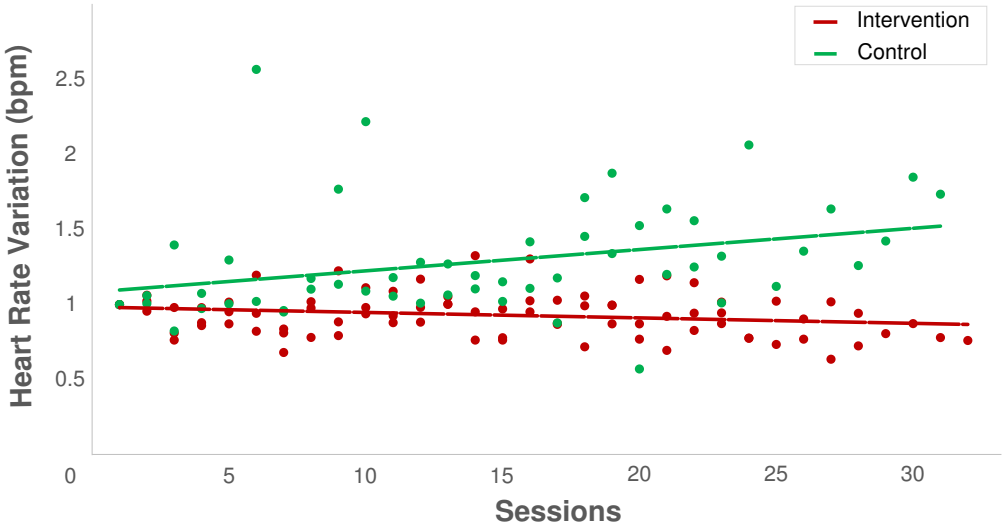


Figure 6.3: Resting heart rate on each session in both conditions, Intervetion and Control. Data are normilized with the value presented in the first session

case, the recovery after the first minute of cool-down is measured (i.e. reduction of the beat per minute (bpm) rate after the first minute). For this index was also applied the Pearson linear correlation test. However, no statistical support was found ($p > 0.05$). Additionally, a Wilcoxon - Mann Whitney test to compare the median was carried out. Results indicate a significant difference between intervention and control (Intervention: M 3.57 bpm SD 4.12, Control: M 1.25 bpm SD 1.19, $p = 6.7e^{-7}$).

According to the physiological results obtained, the resting heart rate variable presented an improvement in the intervention group (i.e. the resting heart rate shows a decreasing rate during the programme), which is related to the level of fitness. Similar results found in [91] support this outcome. However, although the number of sessions that participants carried out during the study is significant, the number of patients must be extended to support these results. On the other hand, for this group of patients, was not possible to obtain a linear model to describe the development of the recovery heart rate. Nevertheless, with the median analysis can be observed that the intervention group presents a higher recovery rate than in the

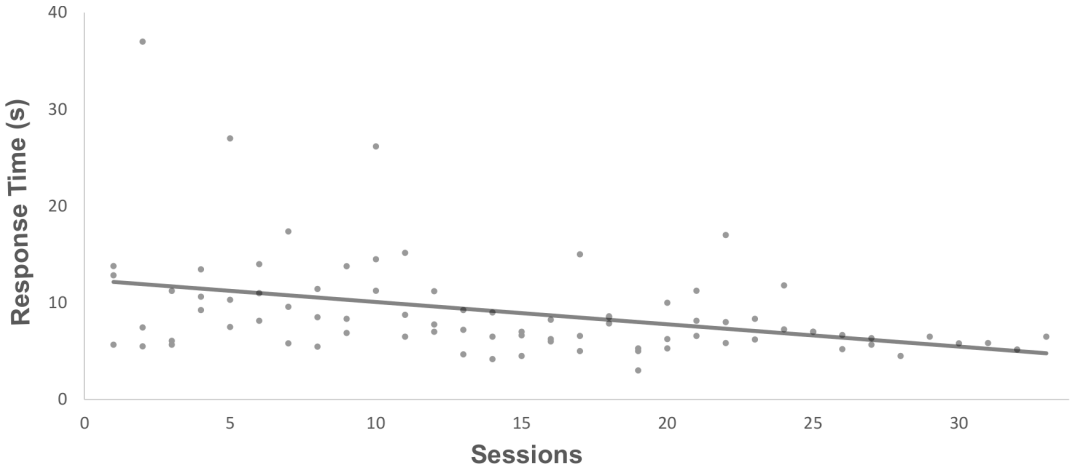


Figure 6.4: Borg scale response time along the sessions for the patients in the R_{con}. This plot represents the time in seconds that patients take to respond to the robot's instruction, when the Borg Scale is requested on each session.

control group. This is a positive outcome, since a high variability can be directly associated to a better cardiovascular condition [92].

Human-Robot Interaction: Previous results were focused on the physiological aspects. In this subsection, metrics dedicated to measure the Human-Robot interaction are presented. To achieve this objective, there has been defined two metrics: (1) the Borg scale response time (RT) to measure the time that took the patient to deliver the value to the system when the robot requests to do it and (2) the number of posture corrections that the robot performed during each session. This metrics are only measured for the R_{con}, since they are exposed to the robot.

Borg Scale RT: As illustrated in Fig 6.4, the response time exhibits a decreasing rate ($-0.2301x + 12.372$, p *value*$= 0.00051$). This can be interpreted as an adaptation of the user to the system and the robot's requests along the sessions.

Posture Correction The posture correction is performed by means of the built-in camera from the tablet. This information is sent to the robot and according to

the data, the robot performs the correction. For this group 79 corrections took place in the experiments. The pattern of these corrections did not show any tendency.

Regarding the response time, results show that people present a positive adaptation to the system (i.e., they respond progressively faster and better to the robot's requests). This result is also evidenced by the self impression that patients expressed during the socialization activity, where they experienced a better understanding of the system along the sessions, having difficulties at the beginning to understand the robot's voice and therefore taking more time to respond to any request. This result shows the importance of the learning curve that users have to experience and how they successfully overcome it. In this case, patients succeeded in understanding and adapting to the robot's requests, which shows a promising potential of the system to be introduced in this context.

On the basis of the results obtained with this study, it is evidenced the positive impact that patients perceive while interacting with the robotic system. Considering that a significant group of patients have seen the robot-therapy system operating, while the experiments where performed, the next study will focus on the expectations and perception that potential users would have regarding the implementation of the system within the therapy.

6.3 Experimental Study 2: Perception & Acceptance Assessment

Technology acceptance has been commonly described as the favorable reception and ongoing use of newly introduced devices and systems [93]. The Technology Acceptance Model (TAM) [94] has been adopted as one of the basis to evaluate acceptance in different applications (e.g., e-commerce acceptance model (EAM)

to evaluate the technology acceptance associated to mobile health devices [95]). However, the TAM has been criticized as it lacks of precision and ignores influential factors such as complexity of the technology, and user characteristics that are relevant on many applications [93]. On response of this limitation, in [96] the Unified Theory of Acceptance and Use of Technology (UTAUT) was developed. This model has been successfully used in healthcare to evaluate different applications. For example, acceptance of web-base aftercare devices [97], therapist acceptance of new technology for rehabilitation [98], and new models based on UTAUT for rehabilitation technologies [99].

However, people perceive social autonomous robots differently from other computer technologies due to the nature of the interaction (i.e., social robots seek to interact as humans do) [100]. Hence, in some cases conventional models of perception are limited, which has led researchers to develop adaptations of these models to meet their needs [41, 101–103]. Heerink et al., implemented the UTAUT model, finding that the model had low explanatory power and it insufficiently indicated that social abilities contribute to the acceptance of a social robot [104]. In consequence, an adapted version was developed in [105] with the purpose of incorporating social aspects that are relevant to asses social robotic agents. They described user acceptance as “the demonstrable willingness within a user group to employ technology for the tasks it is designed to support". This model integrates several constructs that enables to have knowledge on social factors influenced by a social robot (e.g., anxiety , attitude, facilitating conditions, social influence, intention to use, perceive adaptability, perceived enjoyment, perceived ease of use, perceived sociability and perceived usefulness).

As pointed out at the beginning of this chapter, the purpose of this study seeks to evaluate patients’ and clinicians’ perception and attitudes towards a socially assistive robot incorporated in the phase II of the CR programme at FCI-IC. Aiming

to achieve this goal, a questionnaire based on the model proposed by Heerink et al [105] is conducted. This model evaluates acceptance of the robot as a cardiac therapy assistant in different dimensions (i.e., Utility/Advantages (U/A), Usefulness (U), Perceived utility (PU), Safety (S), Easy of Use (EU), Perceived Trust (PT), Perceived Sociability (PS) and Social Presence (SP)). Each question was scored with a 5 points Likert scale (being 1 strongly disagree, 2 disagree, 3 neutral, 4 agree and 5 strongly agree). The study has been divided in two parts: The first, focuses on the perception and attitudes carried out with patients, and the second implements a focus group to analyse acceptance and perception of this technology with clinicians. Participants recruitment criteria and the protocol followed in this research is presented below.

6.3.1 Participants

A total of 43 participants were included in the study (Table 6.2). For the patient group 28 persons were recruited (male = 63.15%, female = 36.84% in control group, male = 87.5%, female = 12.5% in intervention, age = 54 ±8.48 years old). These patients finished the inpatient phase and started the phase II or III of CR program. On the other hand, 15 clinicians who work in CR took part of the study (male = 6.66%, female = 6.66%, age 36.86 ±8.78 years old, years of expertise years 11.13 ±7.68). This group is conformed by different types of medical specialities and have no previous interaction with the robot, but they have at least a level of technical use with other technology devices as computers and tablets.

6.3.2 Patients Study

As illustrated in Table 6.2, for the patients group two conditions were defined: (1) an *intervention* condition, where patients attending the phase II of the CR pro-

Table 6.2: Participants in the perception study

	Study	Participants
Patients	Intervention: long-term study (N=8) Control: interviews (N=20)	Patients attending Phase II Patients attending Phase II-III
Clinicians	Focus Group (N=15)	3 Nurses 4 Outpatient Clinic / CR 6 Physiatrists 2 Occupational Therapists

gramme participated in a long-term study. (2) An interview for a *control* group was conducted for patients attending phase II and III of CR. These groups are considered in order to compare opinions between patients that had a long-term interaction with the system and experienced the benefits and disadvantages (intervention group), and patients that have no experience with the robot (control group). Hence, based on this comparison, will be possible to analyse patients' perception and attitudes towards the incorporation of this technology in clinical applications such as CR, from both perspectives. The description of the protocol implemented in both scenarios is presented below.

Long-Term Study

The long-term study included patients that carried out therapies with the social assistive interface described before, during a period of time of 18 weeks (36 sessions of phase II). Once they finished the program, a perception questionnaire was applied to evaluate their attitudes towards the robot after a long-term interaction (Table 6.3). Additionally, two open questions stated below were implemented to have more detailed information about their experience and recommendations.

Question 1: Would you recommend the use of the robotic system to the patients that are starting the rehabilitation therapy?

Table 6.3: Questionnaire implemented to evaluate robot's perception for the patients group

Construct	No.	Questions
U	1	I consider that using robots it's a good tool to assist cardiac rehabilitation therapies.
	2	I consider that my interaction with the robot was comfortable.
	3	I enjoyed when the robot gave me verbal encouragement when I did a good job.
	4	I'm satisfied with the work the robot did.
	5	I consider that the robot adapts to my needs.
PU	1	I consider that the interaction with the robot was beneficial for my recovery.
	2	I consider that the rol of the robot was important for the therapy development.
	3	I think that the use of the robot helps me to compromise me to do a good job.
S	1	I feel safe at the therapies working with the robot.
	2	I consider it was easy to give information to the robot.
EU	1	I consider that the robot is ease to use.
	2	I consider that using the robot didn't affect the time of therapy sessions.
	3	I consider that the robot's instructions were clear.
PT	1	The robot made me confident.
	2	I did instruction the robot told me because I trusted him.
	3	I like using the robot during the therapies.
	4	It gave me confidence that the robot guides my therapy.
PS	1	I consider the robot a pleasant conversational partner.
	2	I find the robot pleasant to interact with.
	3	I feel the robot understands me.
	4	I think the robot is nice.
SP	1	When interacting with the robot I felt like I'm talking to a real person.
	2	It sometimes felt as if the robot was really looking at me.
	3	I can imagine the robot to be a living creature.
	4	I often think the robot is not a real person.
	5	Sometimes the robot seems to have real feelings.

Question 2: According to your experience, what would you recommend to improve the robot-based therapy?

Interviews

As aforementioned, the interviews were applied to patients who are in an early stage of the phase II or phase III of the CR program. Similarly, they must have no previous experience with the above-described robotic system. According to these conditions, participants are briefly contextualized about SAR systems, the benefits that they can provide and the variables that are measured in this application, followed by the presentation of a video where the real cardiac scenario is displayed

and the robot with its functionality can be appreciated. Later, the questionnaire (Table 6.3) is introduced by the experimenter with the purpose of specifying the purpose of the questionnaire and the correct way to complete it. In addition to the questions based on Likert scale, there were also included two open questions regarding the users opinions questions are stated below.

Question 1: Would you use the robot during the therapy? Why?

Question 2: What expectations do you have about the therapy assisted by a robot?

6.3.3 Clinicians

A group of clinicians that work at FCI-IC in areas associated to CR, were invited to participate in a focus group. The purpose of this activity was to understand how clinicians are familiarized with technology and the effects that this might have within rehabilitation programmes. Furthermore, this focus group aimed to introduce SAR and discuss about their questions and concerns associated to the technology. The activities are carried out in order to identify how participants change their opinion and perception, once the robotic application has been explained and had the opportunity to witness an in situ demonstration. The structure of the focus group, described below, was inspired on the work developed by [106].

Focus Group

The schedule of this focus group is presented in Table 6.5. As performed with the patients group, an initial acceptance study based on the UTAUT [105] questionnaire was applied to clinicians to understand their perception regarding social robotics

Table 6.4: Acceptance Questionnaire for Clinicians

Construct	No.	Questions
U/A	1	I consider that using robots is a good tool to measure the HR and the BP during CR sessions.
	2	I consider that using robots it's a good tool to alert me if there is an abnormal heart rate.
	3	I consider that it can be useful know the number of steps made by a patient during a session.
	4	I consider that using robots can help me carry out my tasks faster.
	5	I consider that the robot would not affect the time of cardiac rehabilitation sessions.
	6	I consider that the robot would not affect the time of cardiac rehabilitation sessions.
	7	I consider that using robots could improve my productivity during a therapy.
U	1	My interaction with the robot could be clear and understandable.
	2	I might find the system easy to use.
	3	Learning to use the robot could be easy for me.
PU	1	I consider that using robots can bring benefits for the patients.
	2	I consider that using robots could help me to make a more personalized therapy patient.
	3	I consider that using robots could aid me to evaluate better the therapy.
	4	I consider that using robots could make my work more interesting.
	5	I feel that the robot could replace me.
S	1	The robot would represent a risk to the patient's health.
PT	1	I would feel safe using the robot in the therapies.
	2	I could trust the work done by the robot in the sessions.
	3	I would like to use the robot during the therapies.
	4	I would trust the robot to help me guide the therapy.
	5	I would be afraid to use a robot in therapy..
PS	1	I consider that robots can be a pleasant conversationalist for the patient.
	2	I would like that the interaction between the patient and the robot can be pleasant.
	3	I would like the robot to understand the needs of the patient.
	4	I would like the robot to act as a friendly companion.
	5	I would like the robot to have an different modalities (monitoring, assistance and motivation).
	6	I would like to choose the program that the robot should perform during therapy.
SP	1	I consider that the interaction with the robot might feel like talking to a real person.
	2	I would consider good if the patient had the feeling that the robot will observe him in therapy.
	3	I consider it's good to imagine the robot as a living creature.
	4	I consider patients would usually think that the robot is not a real person.
	5	I consider the robot could have real emotions.

in CR (see Table 6.4) , followed by a preliminary discussion session. In this section current technologies used in medicine and social assistive robotics were explained to the medical staff in order to contextualize about the benefits (motivation, adherence and engagement) of using SAR in rehabilitation scenarios. Later, a demonstration of the human-robot interface functionality was shown to the therapists. Finally, therapist discussed about new needs, challenges, changes and improvements that can be developed in the interface.

Table 6.5: Focus Group with Clinicians

Pre-Session Questionnaire
Acceptance & usability based on UTAUT [105]
Opening Discussion
Pre-Demo Discussion
Introduction of conventional technologies in medicine
Presentation of Socially Assistive Robotics
Motivation: how social robots can benefit therapy programs
Project Demonstration
Demonstration of the cardiac rehabilitation SAR interface with Nao
Post-Demo Discussion
Demo feedback
Suggestions and applications with potential use

6.3.4 Results

The perception assessment for patients was completed by 28 participants (8 participated in the long-tern study, and 20 in the interviews). Answers were grouped by category, in order to perform the analysis for each construct defined in the questionnaire. A Mann Whitney-Wilcoxon (MWW) test was applied to determine significant differences on each construct between groups. This test has found to be suitable for five-points Likert scale, since it presents minimal type I error rates and equivalent power with the 2-sample t-test [107]. Furthermore, it has been demonstrated that the MWW test provides better results for small sample sizes than the t-test [108]. Results of this test are depicted in Table 6.6, where the p value corresponding to each category was computed.

As Table 6.6 shows, in most of the constructs defined in the questionnaire a significant difference (i.e., p value < 0.05) was found. These categories are (Perceived Trust (PT), Easy of Use (EU), Perceived Utility (PU) and Usefulness (U)). On the other hand, Safety (S), Perceived Sociability (PS) and Social Presence (SP) do

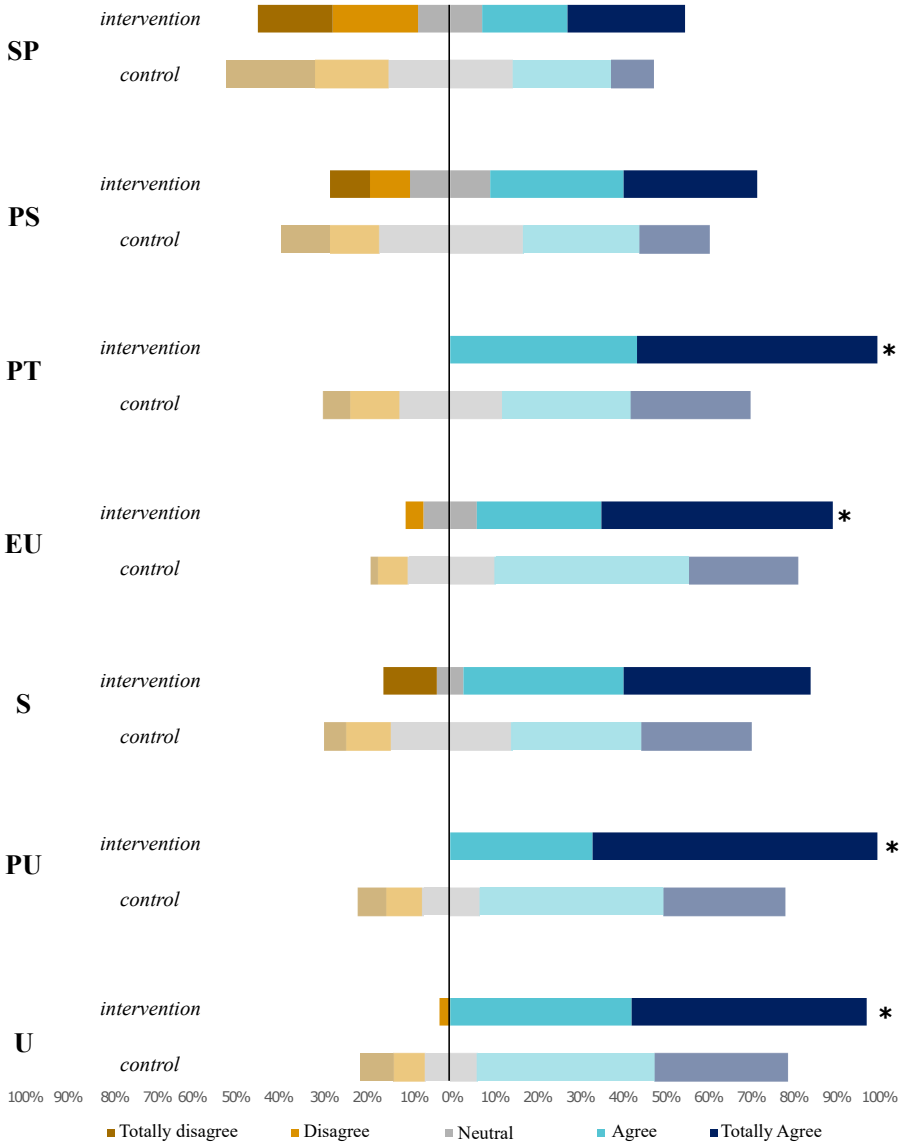


Figure 6.5: Likert scale distribution for each construct of the acceptance and perception questionnaire applied to patients

not present a significant difference between groups. The distribution of the Likert questions grouped by category is presented in Fig. 6.5. Each category contains the results obtained from control and intervention groups. This plot is presented with a central axis, indicating a neutral position regarding the question (positive perceptions are plotted on the right side of the graph, while negative perceptions are represented on the left side).

Table 6.6: Mann-Whitney-Wilcoxon test p values

Construct	Control vs Intervention
SP	0.1612
PS	0.087
PT	**0.00006**
EU	**0.02476**
S	0.13782
PU	**0.00027**
U	**0.00069**

Regarding the open questions, in the long-term study, all participants showed high interest in the robot-based therapy. 100% of the participants would recommend the therapy to incoming patients. On the other hand, interviewed group, 75% of participants found the therapy interesting and functional, and would recommend the system for future use, while 25% demonstrated no interest in the application and would not recommend the therapy due to different reasons that are considered and analyzed in the discussion.

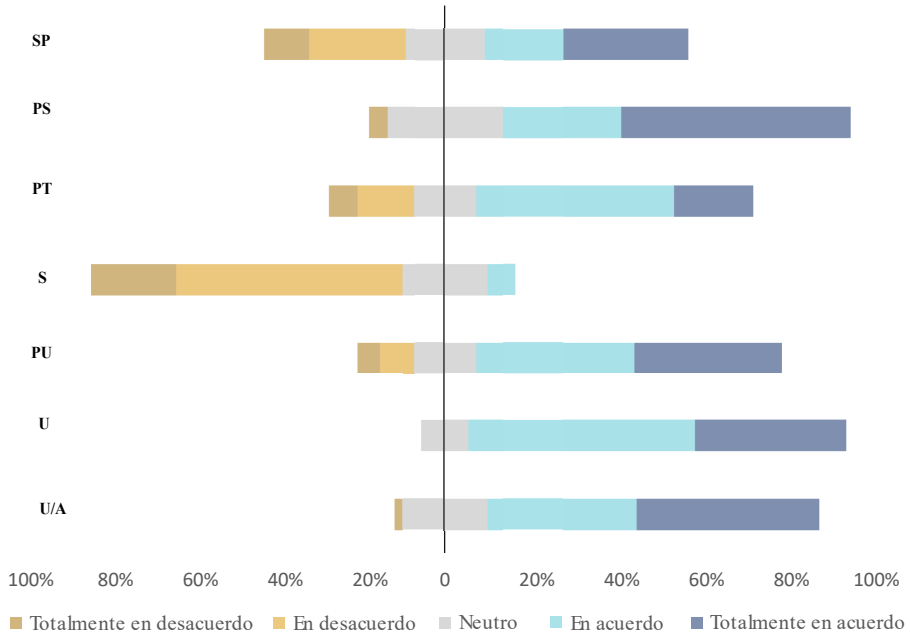


Figure 6.6: Likert scale distribution for each construct of the acceptance and perception questionnaire applied to therapists

For the clinicians, the UTAUT results are illustrated in Figure 6.6. Each construct represents a percentage of the total responses, taking into account the Likert scale. While remarkable results regarding (U/A), (U), (PU), (PS) and (PT) categories

have a positive score. For (S) construct is negative taking into account that the question refers to the robot as a risk during CR therapies.

Commentaries of the pre and post discussion, regarding clinicians' opinions on social robotics and the proposed interface, were recorded. Pre-discussion results showed that clinicians were worried about being replaced by the robot, this was expressed in commentaries as: "The robot can measure all the parameters that I usually monitor" and *"The robot can replace my work"* . Also doubts in the functionality and features of the interface were expressed (*"Why a robot? Can not be other device?*, Sensors can failed in the measurements and report wrong data"). After the demo presentation and the introduction of social assistive robotics in healthcare (Table 6.5), these commentaries turn positive as a detailed explanation of the interface was given. Results of the post-discussion showed an interest of the clinicians to improve and add features to the interface. Remarkable positive commentaries as: "Personally, I'm very interested in the capabilities of the robot to help me measure some parameters so I can focus more on the other patients' needs", *"It could be nice if the robot can be more sociable and less repetitive with its behaviours"*, "I'm very interest in knowing the performance of the patient at specific times, this feature can be added" and "the online measurement that the robot provide is useful, this is important when a patient has an elevated heart rate".

6.4 Chapter Conclusions

This chapter presented two studies designed to evaluate the system's performance, the effect of the robot-therapy in terms of physiological condition and interaction, and finally, to evaluate expectations and perception regarding the implementation of the robotic system in the CR programme. This section presents the conclusions

and final remarks of both studies.

6.4.1 Study 1:

Data reflect a slight difference between both groups, where intervention group seems to improve its recovery. However, in the light of the limited number of participants, this result must be further evaluated with a larger sample in the future.

Regarding safety and risk reduction during therapy, the system presented a reliable performance at monitoring possible risk factors associated to the therapy. This was supported by the patients' perception as they felt that the system provided safety to the therapy and controlled their parameters to avoid health risks. Similarly, the data recorded showed that the system was able to detect and provide feedback to avoid risk of falling and over-training, demonstrating that it can be implemented as a reliable tool that would potentially leverage the tasks carried out by the health professionals.

As the model proposed for the robot behaviour was mainly based on conditional statements and all the interventions were predefined, future work will consider to enhance robot's behaviour, in such a way that it can manage to sustain a long-term relationship with the patient. In order to achieve this objective, as a next stage in this research it is proposed to define a third scenario, with a personalized robot that can recognize the patient and perform a follow-up of the work and the evolution of the therapy.

6.4.2 Study 2:

This section addresses results previously presented. The discussion will be focused first on the patients study, followed by the outcomes obtained with the clinicians

study. This analysis will be carried out considering the result obtained on each construct of the perception's questionnaire.

Patients

According to the results presented in the previous section, each construct for the patient's perception questionnaire is discussed.

Perceived Trust (PT): As observed in Fig. 6.5, the perceived trust is higher in the intervention group, than in the control group. Additionally, some patients from the control group expressed low confidence in the robot, where statements such as *"not trustable"* and *"I would trust more in human therapists"* were found. This is an expected reaction associated to the lack of experience and contact with the robot. However, not all patients expressed negative impressions towards the robot: there were found answers such as *"I think is an appropriate approach"*, *"I would be monitored all the time"* or *"It supports the patients' needs, since it contributes to the continuous and satisfactory improvement"*. This positive perception is endorsed by participants from the intervention group, who expressed a higher perceived trust to the robot. This is an indicator that trust in this sort of technology can be positive impacted throughout considerable period of interaction.

Easy of Use (EU): As was expected in this category, the intervention group perceives more easy of use than the control group. This is due to the time that these patients spent interacting with robot, where they have the opportunity to realize how complex the interaction with the robotic platform can be, and after a period of time feel comfortable performing the therapy in presence of the social agent. As the patients in the control group have a limited knowledge of the system and its functionality, it is difficult to figure it out, how complex the use of the

platform can be.

Perceived Utility (PU): As this category is associated to the utility and the benefits that the system could provide in the rehabilitation of the patients, it was evidenced a higher perceived utility in the intervention group than in the control group. This result is expected, since patients that have the opportunity to interact with the robot during the complete rehabilitation process, can evidence the benefits and the results that the social agent provided. During the therapies, they expressed to be motivated and encouraged to perform better (*"I'm very encouraged to complete the rehabilitation"*, *"The robot motivates me to exercise well"* or *"This is a novel tool that could help the rehabilitation of any kind"*). Although control patients perceive a high degree of utility, it can be evidenced that after the interaction, this expectation is overcame.

Usefulness (U): This category is mostly focused on the perception that patients have of the system and its functionality (e.g. robot interventions, adaptability, interface and manipulation, etc). In this case, the same pattern as the previous categories is presented. The intervention group attributes more usefulness to the system than the control group. in this case patients expressed: *"I would like to have the opportunity to interact with the robot again"* and that *"the robot was beneficial to the development of the therapies"*. This results reflect the positive impact that the platform provided and the potential that it might have in future cardiac therapies.

Summarizing, the perception presented in both groups can be interpreted as positive, since Fig. 6.5 shows most of the values located in the right side of the scale. However, it is also worth mentioning the results of the Social Presence (SP) category. In this case, there is a neutral opinion in both groups, which can mean that

patients do not notice significant social features in the demonstration (control) and even after a considerable period of interaction (intervention). According to this result, it is necessary to improve this feature, since the impact and outcomes of the therapy can be potentially increased if the robot is more socially engaged to the patient [49], considering that most of the robot interventions are based on the social interaction and the way that it can develop in a social context.

Clinicians

For the clinicians group the UTAUT shows positive opinions regarding (U/A), (U), (PU) and (PS) categories, which means that clinicians think that the robot and the parameters measured are useful in CR sessions. The (S) construct was scored negative due the question formulation, however, the results regarding this construct are positive as the clinicians do not consider the robot as a risk for the patients. The social presence perception showed neutral response in general, this can be due to the perception of the robot as a social agent before the focus group was performed. During the questionnaire comments regarding the robot role were interesting. Some clinicians think that the robot has to be only a coach with social cues that feedback the patient, but not a friendly companion as the patients needed to concentrate in the therapy and the exercise.

One of the most important aspects that were observed during the focus group, was the change of clinicians perception as they went through the system's demonstration and received more information. As pointed out in the opening discussion, some clinicians perceived the incorporation of a social robot as a thread, since they regard the robot as a potential replacement. However, after the explanation of the technology and the objectives, where it was emphasized that the robot must be considered as a tool that can improve their efficiency during therapy, and highlighting the relevance that the clinical staff has within the programme, their conception

of the system turned into a positive one. Moreover, clinicians showed interest and provided improvement suggestions. Among these suggestions, more sociability is requested, as they realized the importance of this factor after the demonstrations and discussions.

Taking into account patients and clinicians perception, one common factor that they emphazise is the sociability or social behaviours that the robot can exhibit. Results suggest that the current social features presented by the robot during therapy must be enhanced. This means that more algorithms and features such as memory and vision recognition can play an important role to increase the impact within therapies. However, there is a positive opinion regarding the usefulness of the system in this context and the reliability of their monitoring that generates confidence to the users. These results hold promising potential and are encouraging to continue these research approach.

This chapter presented experimental studies carried out to validate the SAR system proposed in this thesis. First, a performance assessment alongside with a quantitative study was conducted. This study allowed to validate the system and determine its reliability under clinical conditions. Furthermore, physiological and interaction variables were analyzed to evaluate patients' evolution during the programme. A second study focused on the user perception and acceptance of the robotic system was conducted, finding potential advantages over conventional therapy. Patients and clinicians consider the system a reliable tool to be deployed in real scenarios. Moreover, suggestions and recommendations were provided for further improvement of the platform.

Chapter 7

Conclusions and Future Works

As discussed throughout this thesis, there is a significant interest in increasing the attendance to CR programmes. It has been evidenced the importance of such therapies in the reduction of potential secondary cardiac events and improvement on physical condition of cardiac patients. In this regard, this thesis proposed a Robot-Therapy Model (RTM) to be applied in CR aiming to engage patients with the therapy and increase their motivation and performance.

The components that integrate the RTM were described and validated with the users. First, the Human-Computer interface (HCi) was introduced. This interface comprises the Sensor Interface to provide sensory data required to monitor and control the therapy development, and the Graphical User Interface (GUI) designed to allow interaction with the user and the system. These components were validated by means of a pilot study carried out under laboratory conditions (chapter 4). During this validation the system presented an adequate performance, recording periodically sensory data and the events generated in a period of 28 minutes.

As a future work, it is proposed the enhancement of the sensor capabilities that were introduced in this thesis. Thus the development of camera-based algorithms

that allow the estimation of fatigue during exercise, as well as the measurement of physiological variables such as heart rate and blood pressure, are proposed to complement the current measurement and provide a more robust and reliable interface.

Similarly, the second component of the RTM, namely the Social Robotic Agent was introduced in chapter 5, where the software architecture and its integration in the RTM was described. As performed with the HCi, the robot architecture was validated with a pilot study, this time, with a CR patient under clinical conditions. This validation was performed during a CR session, where the patient had the opportunity to interact with the social robot. Likewise, with the study was possible to validate the robot's behaviour and the correct functioning of the architecture.

With the validation of the complete system that composed the RTM, this thesis also proposed a longer experimental study, aiming to assess the effect that the robot-therapy has in CR with real patients. Hence, two studies were conducted: (1) The first sought to evaluate physiological evolution for a group of patients, and compare their evolution with patients that performed conventional therapy. (2) The second study focused on the acceptance and perception assessment of the system. Thus, a group of patients and clinicians participated in a set of activities designed to evaluate their attitudes toward the incorporation of social robots in CR.

From the experimental studies it was possible to evaluate the effect of incorporating social robotic agents in CR. Regarding physiological evolution, compared to conventional therapy, the study showed improvement in patients' health condition after completing the CR programme with the robot, showing a significant difference ($p = 0.049$) regarding the reduction of resting heart rate between patients that interacted with the robot and patients with conventional therapy. Moreover, regarding the recovery capacity after training, it was evidenced that intervention

group presented a better result, reducing an average of 3.57BPM against 1.25 BPM for conventional therapy. However, the study was performed with a reduced group of patients. Therefore, future work will be oriented to perform a large scale study to further validate the results obtained in this thesis.

Remarkably, one of the most important aspects identified throughout the development of this thesis, was the attitude and perception that patients and clinicians expressed. Where all patients that interacted with the robot found the therapy interesting and were willing to continue the treatment with the technology. Furthermore, It was possible to change clinician's perception once the benefits and functionality was evidenced, turning into positive and constructive feedback. Additionally, more than 75% of participants (patients and clinicians) regarded the system as safe, being this a key aspect in the rehabilitation context.

In this context, the work developed at FCI-IC was accepted positively by patients and clinicians, who provided valuable feedback regarding functionalities and applications of the system. Among them, one common request was the improvement of the social abilities of the robot. Thus, future work will consider the enhancement of social behaviours that allow a better and pleasant interaction with the user. From this point, it is proposed the exploration of personalized behaviours, based on memory, that enable to robotic platform to recognize each user and adapt its interventions according to the patient's evolution and performance. Furthermore, the incorporation of deep-learning algorithms focused on the enhancement of the dialog speech and human emotions recognition are proposed to be evaluated in future applications.

Bibliography

[1] World Health Organization. WHO | Cardiovascular diseases (CVDs), 2018.

[2] American Heart Association. What is Cardiovascular Disease? | American Heart Association, 2017.

[3] World Health Organization. WHO | Global atlas on cardiovascular disease prevention and control. *WHO*, 2015.

[4] World Health Organization. WHO | World Heart Day, 2018.

[5] Pablo Chaparro-Narváez, Carlos Castañeda-Orjuela, Willian León-Quevedo, and Fernando De La Hoz-Restrepo. Cardiovascular Disease Mortality among Under 75 Years Old Population: An Analysis in Colombia of 1998-2011 Period. *International Journal of Health Sciences & Research (www.ijhsr.org)*, 5:325, 2015.

[6] Wilkins E., Wilson I., Wickramasinghe K., Bhatnagar P., Leal J., Luengo-Fernandez R., Burns R., Rayner M., and Townsend N. European Cardiovascular Disease Statistics 2017 edition. *European Heart Network, Brussels*, page 192, 2017.

[7] R. S. Taylor, B. Unal, J. A. Critchley, and S. Capewell. Mortality reductions in patients receiving exercise-based cardiac rehabilitation: how much can be attributed to cardiovascular risk factor improvements? *European Journal of Cardiovascular Prevention & Rehabilitation*, 13(3):369–374, jun 2006.

[8] Adrin Bolvar-Meja and Boris E. Burden of Cardiovascular Disease in Colombia. In *Current Topics in Public Health*. InTech, may 2013.

[9] PanAmerican Health Organization. |COLOMBIA CARDIOVASCULAR DISEASES PROFILE. Technical report, Pan American Health Organization, 2014.

[10] H J Bethell, S C Turner, J A Evans, L Rose, J Bethell, C Turner, A Evans, and L Rose. Cardiac rehabilitation in the United Kingdom. How complete is the provision? *Journal of cardiopulmonary rehabilitation*, 21(2):111–5, 2001.

[11] Nizal Sarrafzadegan, Katayoun Rabiei, Shahin Shirani, Ali Kabir, Noushin Mohammadifard, and Hamidreza Roohafza. Drop-out predictors in cardiac rehabilitation programmes and the impact of sex differences among coronary heart disease patients in an Iranian sample: a cohort study. *Clinical Rehabilitation*, 21(4):362–372, apr 2007.

[12] Marian U.C. Worcester, Barbara M. Murphy, Virginia K. Mee, Susan B. Roberts, and Alan J. Goble. Cardiac rehabilitation programmes: predictors of non-attendance and drop-out. *European Journal of Cardiovascular Prevention & Rehabilitation*, 11(4):328–335, aug 2004.

[13] Massimo F. Piepoli, Ugo Corrà, Paul Dendale, Ines Frederix, Eva Prescott, Jean Paul Schmid, Margaret Cupples, Christi Deaton, Patrick Doherty, Pantaleo Giannuzzi, Ian Graham, Tina Birgitte Hansen, Catriona Jennings, Ulf Landmesser, Pedro Marques-Vidal, Christiaan Vrints, David Walker, Héctor Hector Bueno, Donna Fitzsimons, and Antonio Pelliccia. Challenges in secondary prevention after acute myocardial infarction: A call for action. *European Journal of Preventive Cardiology*, 16(18):1994–2006, dec 2017.

[14] Rosie Essery, Adam W. A. Geraghty, Sarah Kirby, and Lucy Yardley. Predictors of adherence to home-based physical therapies: a systematic review. *Disability and Rehabilitation*, 39(6):519–534, mar 2017.

[15] L Jackson, J Leclerc, Y Erskine, and W Linden. Getting the most out of cardiac rehabilitation: a review of referral and adherence predictors. *Heart*, 91(1):10–14, jan 2005.

[16] Johannes Scherr, Bernd Wolfarth, Jeffrey W. Christle, Axel Pressler, Stefan Wagenpfeil, and Martin Halle. Associations between Borg's rating of perceived exertion and physiological measures of exercise intensity. *European Journal of Applied Physiology*, 113(1):147–155, jan 2013.

[17] American Heart Association. What is Cardiac Rehabilitation? | American Heart Association.

[18] Lindsey Anderson, Neil Oldridge, David R. Thompson, Ann-Dorthe Zwisler, Karen Rees, Nicole Martin, Rod S. Taylor, Neil Oldridge, Ann-Dorthe Zwisler, Karen Rees, Nicole Martin, and Rod S. Taylor. Exercise-based cardiac rehabilitation for coronary heart disease. *Cochrane Database of Systematic Reviews*, 67(1):1–12, jan 2016.

[19] Axel Schlitt, Patricia Wischmann, Andreas Wienke, Florian Hoepfner, Frank Noack, Rolf-Edgar Silber, and Karl Werdan. Rehabilitation in Patients With Coronary Heart Disease: Participation and Its Effect on Prognosis. *Deutsches Arzteblatt international*, 112(31-32):527–34, aug 2015.

[20] Chul Kim, Jo Eun Youn, and Hee Eun Choi. The Effect of a Self Exercise Program in Cardiac Rehabilitation for Patients with Coronary Artery Disease. *Annals of Rehabilitation Medicine*, 35(3):381, 2011.

[21] Susan Michie, Daryl O'Connor, Julian Bath, Mark Giles, and Louise Earll. Cardiac rehabilitation: The psychological changes that predict health out-

come and healthy behaviour. *Psychology, Health and Medicine*, 10(1):88–95, 2005.

[22] Balraj S Heran, Jenny Mh Chen, Shah Ebrahim, Tiffany Moxham, Neil Oldridge, Karen Rees, David R Thompson, and Rod S Taylor. Exercise-based cardiac rehabilitation for coronary heart disease. *The Cochrane database of systematic reviews*, (7):CD001800, jul 2011.

[23] Gene Kwan and Gary J. Balady. Cardiac rehabilitation 2012 advancing the field through emerging science. *Circulation*, 125(7), 2012.

[24] Gary J. Balady, Barbara J. Fletcher, Erika S. Froelicher, L. Howard Hartley, Ronald M. Krauss, Albert Oberman, Michael L. Pollock, and C. Barr Taylor. Cardiac rehabilitation programs: A statement for healthcare professionals from the American Heart Association. *Circulation*, 90(3):1602–1610, 1994.

[25] Neil F Gordon and William L Haskell. Risk Reduction in a Cardiac Rehabilitation Setting. 9149(97):69–73.

[26] Claudia V. Anchique, Carmen Pérez-Terzic, Francisco López-Jiménez, and Mery Cortés-Bergoderi. Current status of cardiovascular rehabilitation in Colombia (2010). *Revista Colombiana de Cardiología*, 18(6):305–315, 2011.

[27] J J Diaztagle-Fernández, S I Latorre-Alfonso, S E Maldonado-Arenas, G P Manosalva-Álvarez, J S Merchán-Cepeda, and C D Centeno-García. Research on heart failure in Colombia 1980-2015: a systematic review. *Rev. Fac. Med*, 66(2):139–51, 2018.

[28] Juan M. Anchique, Claudia V. Rincon, Mònica R. Sarmiento. *Rehabilitacion cardiovascular y prevención secundaria.* Bogotá, 2011.

[29] F. Naranjo-Estupiñan Nestor Diaz-Quijano Fredia A. y G.Garcia Ronald G. Influencia de la rehabilitación cardíaca sobre la tasa de re-hospitalización en

pacientes con infarto agudo de miocardio, Santander, Colombia. *Rev. salud pública*, 14(5):831–841, 2012.

[30] Rehabilitación Cardíaca - FCI - Fundación Cardioinfantil.

[31] K Lange Andersen. The cardiovascular system in exercise. *Exercise physiology*, pages 79—-128, 1968.

[32] WALTER C. WILLETT, WILLIAM H. DIETZ, and GRAHAM A. COLDITZ. for H Ealthy W Eight. *Sciences-New York*, pages 427–434, 2009.

[33] Georg B. et al. Ehret. Genetic variants in novel pathways influence blood pressure and cardiovascular disease risk. *Nature*, 478(7367):103–109, oct 2011.

[34] Romualdo Belardinelli, Demetrios Georgiou, Vito Scocco, Thomas J. Barstow, and Augusto Purcaro. Low intensity exercise training in patients with chronic heart failure. *Journal of the American College of Cardiology*, 26(4):975–982, 1995.

[35] Jack H Wilmore and David L Costill. *Training for sport and activity: The physiological basis of the conditioning process*. Wm. C. Brown Dubuque\^{} eIA IA, 1988.

[36] Van Elderen-van Kemenade T., Maes S., and Van den Broek Y. Effects of a health education programme with telephone follow-up during cardiac rehabilitation. *British Journal of Clinical Psychology*, 33(3):367–378, 1994.

[37] Albert Bandura. Health promotion by social cognitive means. *Health Education and Behavior*, 31(2):143–164, 2004.

[38] Pierre Jouven, Xavier and Empana, Jean-Philippe and Schwartz, Peter J and Desnos, Michel and Courbon, Dominique and Ducimeti{\‘e}re. Heart-rate profile during exercise as a predictor of sudden death. *New England Journal of Medicine*, 352(19):1951—-1958, 2005.

[39] David Feil-Seifer and Maja J. Matarić. Defining socially assistive robotics. *Proceedings of the 2005 IEEE 9th International Conference on Rehabilitation Robotics*, 2005(Ci):465–468, 2005.

[40] Terrence Fong, Illah Nourbakhsh, and Kerstin Dautenhahn. A survey of socially interactive robots. 42:143–166, 2003.

[41] Dong-Hee Shin and Hyungseung Choo. Modeling the acceptance of socially interactive robotics: Social presence in human–robot interaction. *Interaction Studies*, 12(3):430–460, jan 2011.

[42] Understanding Social Interaction | Boundless Sociology.

[43] R.M. Krauss. Verbal Communication, Psychology of. *International Encyclopedia of the Social & Behavioral Sciences*, pages 16161–16165, 2004.

[44] Joshua Wainer, David J. Feil-Seifer, Dylan A. Shell, and Maja J. Matarić. The role of physical embodiment in human-robot interaction. *Proceedings - IEEE International Workshop on Robot and Human Interactive Communication*, pages 117–122, 2006.

[45] Rolf Pfeifer and Christian Scheier. *Understanding Intelligence*. MIT Press, Cambridge, MA, USA, 1999.

[46] Kerstin Dautenhahn, Bernard Ogden, and Tom Quick. From embodied to socially embedded agents – Implications for interaction-aware robots. *Cognitive Systems Research*, 3(3):397–428, sep 2002.

[47] James Kennedy, Paul Baxter, and Tony Belpaeme. Comparing Robot Embodiments in a Guided Discovery Learning Interaction with Children. *International Journal of Social Robotics*, 7(2):293–308, apr 2015.

[48] Tony Belpaeme, Paul E Baxter, Robin Read, Rachel Wood, Heriberto Cuayáhuitl, Bernd Kiefer, Stefania Racioppa, Ivana Kruijff-Korbayová, Geor-

gios Athanasopoulos, Valentin Enescu, Rosemarijn Looije, Mark Neerincx, Yiannis Demiris, Raquel Ros-Espinoza, Aryel Beck, Lola Cañamero, Antione Hiolle, Matthew Lewis, Ilaria Baroni, Marco Nalin, Piero Cosi, Giulio Paci, Fabio Tesser, Giacomo Sommavilla, and Remi Humbert. Multimodal Child-Robot Interaction: Building Social Bonds. *Journal of Human-Robot Interaction*, 1(2):33–53, 2013.

[49] Aaron Powers, Sara Kiesler, Susan Fussell, and Cristen Torrey. Comparing a computer agent with a humanoid robot. In *Proceeding of the ACM/IEEE international conference on Human-robot interaction - HRI '07*, page 145, New York, New York, USA, 2007. ACM Press.

[50] Jibo Robot - He can't wait to meet you.

[51] BeatBots - Keepon Pro.

[52] aibo.

[53] Ylva Fernaeus, Maria Håkansson, Mattias Jacobsson, and Sara Ljungblad. How do you play with a robotic toy animal? In *Proceedings of the 9th International Conference on Interaction Design and Children - IDC '10*, page 39, New York, New York, USA, 2010. ACM Press.

[54] Pepper the humanoid robot | SoftBank Robotics EMEA.

[55] NAO the humanoid robot | SoftBank Robotics EMEA.

[56] Cesar Vandevelde, Jelle Saldien, Maria-Cristina Ciocci, and Bram Vanderborght. The use of social robot ono in robot assisted therapy. *ICSR 2013*, 2013.

[57] Kaspar the social robot | Kaspar the social robot.

[58] BUDDY The Emotional Robot.

[59] Projet ROMEO.

[60] Kyong Il Kang, Sanford Freedman, Maja J Matarić, Mark J Cunningham, and Becky Lopez. A Hands-Off Physical Therapy Assistance Robot for Cardiac Patients. *9th International Conference on Rehabilitation Robotics, 2005. ICORR 2005.*, pages 337–340, 2005.

[61] Adriana Tapus, Cristian Tapus, Maja Mataric, Adriana Tapus, Cristian Tapus, Maja Mataric, User-robot Personality Matching, and Adriana Tapus. User-Robot Personality Matching and Robot Behavior Adaptation for Post-Stroke Rehabilitation Therapy To cite this version : User-Robot Personality Matching and Assistive Robot Behavior Adaptation for Post-Stroke Rehabilitation Therapy. *Intelligent Service Robotics*, 1(2):169–183, 2013.

[62] Juan Fasola and Senior Member. Monitor and Encourage Physical Exercise for the Elderly. 2010.

[63] Roger Bemelmans, Gert Jan Gelderblom, Pieter Jonker, and Luc de Witte. Socially Assistive Robots in Elderly Care: A Systematic Review into Effects and Effectiveness. *Journal of the American Medical Directors Association*, 13(2):114–120.e1, feb 2012.

[64] Sarah M. Rabbitt, Alan E. Kazdin, and Brian Scassellati. Integrating socially assistive robotics into mental healthcare interventions: Applications and recommendations for expanded use. *Clinical Psychology Review*, 35:35–46, feb 2015.

[65] Francisco Martín, Carlos E. Agüero, José M. Cañas, Meritxell Valenti, and Pablo Martínez-Martín. Robotherapy with Dementia Patients. *International Journal of Advanced Robotic Systems*, 10(1):10, jan 2013.

[66] Christopher James Calo, Nicholas Hunt-Bull, Lundy Lewis, and Ted Metzler. Ethical implications of using the Paro robot with a focus on dementia patient

care. *Twenty-Fifith AAAI Conference on Artificial Intelligence*, WS-2011-20:20–24, 2011.

[67] Maja J Matarić, Jon Eriksson, David J Feil-Seifer, and Carolee J Winstein. Socially assistive robotics for post-stroke rehabilitation. *Journal of Neuro-Engineering and Rehabilitation*, 4(1):5, dec 2007.

[68] Kijong Kim and Rania Antonopoulos. Working Paper No . 691. (691), 2011.

[69] P. Marti, M. Bacigalupo, L. Giusti, C. Mennecozzi, and T. Shibata. Socially Assistive Robotics in the Treatment of Behavioural and Psychological Symptoms of Dementia. In *The First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, 2006. BioRob 2006.*, pages 483–488. IEEE.

[70] Emmanouil G. Tsardoulias, Athanassios M. Kintsakis, Konstantinos Panayiotou, Aristeidis G. Thallas, Sofia E. Reppou, George G. Karagiannis, Miren Iturburu, Stratos Arampatzis, Cezary Zielinski, Vincent Prunet, Fotis E. Psomopoulos, Andreas L. Symeonidis, and Pericles A. Mitkas. Towards an integrated robotics architecture for social inclusion – The RAPP paradigm. *Cognitive Systems Research*, 43:157–173, 2017.

[71] Wing-Yue Geoffrey Louie, Derek McColl, and Goldie Nejat. Acceptance and Attitudes Toward a Human-like Socially Assistive Robot by Older Adults. *Assistive Technology*, 26(3):140–150, jul 2014.

[72] Stroke rehabilitation: What to expect as you recover - Mayo Clinic.

[73] Ross Mead, Eric Wade, Pierre Johnson, Aaron St. Clair, Shuya Chen, and Maja J Mataric. An architecture for rehabilitation task practice in socially assistive human-robot interaction. In *19th International Symposium in Robot and Human Interactive Communication*, pages 404–409. IEEE, sep 2010.

[74] Hee-Tae Jung, Jennifer Baird, Yu-Kyong Choe, and Roderic A Grupen. *Upper-Limb Exercises for Stroke Patients through the Direct Engagement of an Embodied Agent.*

[75] Gideon Vardi and Joav Merrick. Neurological Disorders: Public Health Challenges. *Journal of Policy and Practice in Intellectual Disabilities*, 5(1):75–75, 2008.

[76] WHO | What are neurological disorders? *WHO*, 2016.

[77] Susan B. O'Sullivan, Thomas J. Schmitz, and George D. Fulk. *Physical rehabilitation.* F.A. Davis Co, 2014.

[78] David López Recio Mobile, Elena Márquez Segura, Luis Márquez Segura, and Annika Waern. The NAO models for the elderly. In *Proceedings of the 8th ACM/IEEE international conference on Human-robot interaction*, pages 187–188. IEEE Press, 2013.

[79] José Carlos Pulido, José Carlos González, and Fernando Fernández. NAOTherapist: Autonomous Assistance of Physical Rehabilitation Therapies with a Social Humanoid Robot. Technical report.

[80] C.D. Kidd and C. Breazeal. Robots at home: Understanding long-term human-robot interaction. In *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 3230–3235. IEEE, sep 2008.

[81] Prathik Gadde, Hadi Kharrazi, Himalaya Patel, and Karl F. MacDorman. Toward Monitoring and Increasing Exercise Adherence in Older Adults by Robotic Intervention: A Proof of Concept Study. *Journal of Robotics*, 2011:1–11, oct 2011.

[82] Rosemarijn Looije, Fokie Cnossen, and Mark Neerincx. Incorporating Guidelines for Health Assistance into a Socially Intelligent Robot. Technical report, 2006.

[83] Ilaria Baroni, Marco Nalin, Paul Baxter, Clara Pozzi, Elettra Oleari, Alberto Sanna, and Tony Belpaeme. What a robotic companion could do for a diabetic child. In *The 23rd IEEE International Symposium on Robot and Human Interactive Communication*, pages 936–941. IEEE, aug 2014.

[84] Rajeev Sharma, Vladimir I. Pavlovic, and Thomas S. Huang. Toward Multimodal Human-Computer Interface. *Proceedings of the IEEE*, 86(5):853–869, 1998.

[85] Carlos A Cifuentes and Anselmo Frizera. Human-Robot Interaction Strategies for Walker-Assisted Locomotion. *Springer Tracts in Advanced Robotics 115*, 115(September):105, 2016.

[86] Editors Bruno, Siciliano Oussama, Khatib Frans, Edited B Siciliano, O Khatib, and F Groen. *Springer Tracts in Advanced Robotics*, volume 26.

[87] Michael A. Goodrich and Alan C. Schultz. Human-Robot Interaction: A Survey. *Foundations and Trends® in Human-Computer Interaction*, 1(3):203–275, 2008.

[88] Yamamoto Maeda Kamitani. Scanning Laser Range Finder Corrector Amended Reason. pages 1–4, 2009.

[89] Zephyr Technology. HXM Bluetooth API Guide. pages 1–21, 2011.

[90] Invensense. MPU-9150 Datasheet. 1(408):1–50, 2013.

[91] Luise Sussenbach, Nina Riether, Sebastian Schneider, Ingmar Berger, Franz Kummert, Ingo Lutkebohle, and Karola Pitsch. A robot as fitness companion: Towards an interactive action-based motivation model. In *The 23rd IEEE*

International Symposium on Robot and Human Interactive Communication, pages 286–293. IEEE, aug 2014.

[92] Juul Achten and Asker E Jeukendrup. Heart Rate Monitoring. *Sports Medicine*, 33(7):517–538, 2003.

[93] Kate Laver, Stacey George, Julie Ratcliffe, and Maria Crotty. Measuring technology self efficacy: reliability and construct validity of a modified computer self efficacy scale in a clinical rehabilitation setting. *Disability and Rehabilitation*, 34(3):220–227, feb 2012.

[94] Fred D. Davis, Richard P. Bagozzi, and Paul R. Warshaw. User Acceptance of Computer Technology: A Comparison of Two Theoretical Models.

[95] Rebecca Schnall, Tracy Higgins, William Brown, Alex Carballo-Dieguez, and Suzanne Bakken. Trust, Perceived Risk, Perceived Ease of Use and Perceived Usefulness as Factors Related to mHealth Technology Use. *Studies in health technology and informatics*, 216:467–71, 2015.

[96] Viswanath Venkatesh, Michael G. Morris, Gordon B. Davis, and Fred D. Davis. User Acceptance of Information Technology: Toward a Unified View. *MIS Quarterly*, 27(3):425, 2003.

[97] Severin Hennemann, Manfred E Beutel, and Rüdiger Zwerenz. Drivers and Barriers to Acceptance of Web-Based Aftercare of Patients in Inpatient Routine Care: A Cross-Sectional Survey. *Journal of medical Internet research*, 18(12):e337, 2016.

[98] Lili Liu, Antonio Miguel Cruz, Adriana Rios Rincon, Vickie Buttar, Quentin Ranson, and Darrell Goertzen. What factors determine therapists' acceptance of new technologies for rehabilitation – a study using the Unified Theory of Acceptance and Use of Technology (UTAUT). *Disability and Rehabilitation*, 37(5):447–455, feb 2015.

[99] Mohammad Hatami Kaleshtari, Ileana Ciobanu, Petre Lucian Seiciu, Andreea Georgiana Marin, and Mihai Berteanu. Towards a Model of Rehabilitation Technology Acceptance and Usability. *International Journal of Social Science and Humanity*, 6(8):612–616, aug 2016.

[100] Astrid Weiss, Regina Bernhaupt, Michael Lankes, and Manfred Tscheligi. The USUS Evaluation Framework for Human-Robot Interaction, 2009.

[101] Maartje M.A. de Graaf, Somaya Ben Allouch, and Tineke Klamer. Sharing a life with Harvey: Exploring the acceptance of and relationship-building with a social robot. *Computers in Human Behavior*, 43:1–14, feb 2015.

[102] Marcel Heerink, Ben Kröse, Bob Wielinga, and Vanessa Evers. Measuring the influence of social abilities on acceptance of an interface robot and a screen agent by elderly users, 2009.

[103] Marina Fridin and Mark Belokopytov. Acceptance of socially assistive humanoid robot by preschool and elementary school teachers. *Computers in Human Behavior*, 33:23–31, apr 2014.

[104] Marcel Heerink, Ben Krose, Vanessa Evers, and Bob Wielinga. Measuring acceptance of an assistive social robot: a suggested toolkit. In *RO-MAN 2009 - The 18th IEEE International Symposium on Robot and Human Interactive Communication*, pages 528–533. IEEE, sep 2009.

[105] Marcel Heerink, Ben Kröse, Vanessa Evers, and Bob Wielinga. Assessing Acceptance of Assistive Social Agent Technology by Older Adults: the Almere Model. *International Journal of Social Robotics*, 2(4):361–375, dec 2010.

[106] Katie Winkle, Praminda Caleb-Solly, Ailie Turton, and Paul Bremner. Social Robots for Engagement in Rehabilitative Therapies. pages 289–297, 2018.

[107] Joost C F De Winter and Dimitra Dodou. FivePoint Likert Items: t test versus MannWhitneyWilcoxon. *Practical Assessment, Research & Evaluation*, 15(11):1–16, 2010.

[108] R. Clifford Blair and James J. Higgins. A Comparison of the Power of Wilcoxon's Rank-Sum Statistic to that of Student's t Statistic Under Various Nonnormal Distributions. *Journal of Educational Statistics*, 5(4):309–335, dec 1980.