UNIVERSITÀ DEGLI STUDI DI MILANO
FACOLTÀ DI SCIENZE E TECNOLOGIE

Dipartimento di Informatica "Giovanni Degli Antoni"
Dottorato in Informatica

DESIGN AND DEVELOPMENT OF AN ADVANCED EXER-GAME BASED AUTONOMOUS HOME REHABILITATION PLATFORM

INF/01

Doctoral Dissertation of:
Manuel Pezzera

Supervisor:
Prof. N. Alberto Borghese

The Chair of the Doctoral Program:
Prof. Paolo Boldi

Academic Year 2019/2020 – Cycle XXXIII

Ringraziamenti

Quando mi iscrissi per la prima volta all'università, nell'ormai lontano 2011, mai avrei pensato di riuscire ad arrivare dove sono arrivato. Tutti questi anni hanno contribuito in modo importante sia alla mia crescita professionale che personale. Questo è anche merito di tutti coloro che ho conosciuto durante questo percorso.

Un percorso lungo, con un ultimo anno particolarmente difficile, soprattutto per la mia cara Val Seriana, ma ormai, finalmente, sembra intravedersi il traguardo.

Mi sembra giusto iniziare ringraziando professor Borghese, che ha iniziato a seguirmi già ai tempi della laurea magistrale e che mi ha dato la grande opportunità di svolgere il dottorato. Con lui ringrazio anche tutto il personale dell'Istituto Neurologico "Carlo Besta" che ha contribuito a questo progetto, senza il quale non sarebbe stato possibile svolgere gran parte del lavoro.

Fondamentali sono stati inoltre tutti i colleghi e studenti che in questi ultimi quattro anni ho conosciuto all'interno dell'AISLab, a partire da Alessandro T. e Jacopo, con cui ho condiviso parte di questo lavoro. Grazie anche ad Alessandro V., Matteo, Nicola e Renato, abbiamo superato molte sfide e ostacoli in questi anni, grazie a tutti.

Grazie a Celeste, Deborah, Luca, Marta e Simona, per tutto il tempo e le serate trascorse insieme, e per avermi sempre sostenuto durante il mio percorso di studi.

Un ringraziamento particolare ad Alberto e Federico, con cui, tra le altre tante cose, ho condiviso fiere ed eventi in giro per il nord Italia, sono sicuro che i nostri sforzi verranno ripagati.

Un caro ringraziamento ai miei genitori per esserci sempre stati e per avermi cresciuto, senza la loro educazione non sarei arrivato fin qui.

Infine, grazie Chiara, mi hai sempre supportato e motivato in questi ultimi bellissimi anni, che rappresentano solo l'inizio del nostro percorso insieme. Sei stata di fondamentale importanza per me, grazie!

Acknowledgments

Financial support

This work is partially supported by the European H2020 project Movecare grant ICT-26-2016b GA 732158, which had no influence on the content of this thesis.

Abstract

As life expectancy increases, we are witnessing continuous aging of the population and consequently an increase in age-related diseases. Also for this reason, the costs of health care and rehabilitation continue to rise, forcing hospital facilities to reduce the period of hospitalization, preventing patients from receiving proper treatment and potentially losing the motor skills acquired so far. To try to mitigate this problem, *autonomous home rehabilitation* has recently begun to spread, allowing patients to practice independently, reducing the workload and costs for hospitals and clinics. However, due to the absence of the therapist, several issues arise regarding the effectiveness of rehabilitation and patient safety.

The aim of this research is to explore the critical aspects related to autonomous home rehabilitation and the recently proposed state-of-the-art platforms, and to develop a comprehensive system that allows patients to perform rehabilitation safely and effectively in full autonomy.

In the project presented here, particular attention has been paid to the long-term motivation of the patient, with the implementation of exergames, i.e., exercise through video-games, and other game design techniques, such as the dynamic adjustment of the difficulty. A platform dedicated to therapists is available, giving them all the tools they need to manage their patients, such as the possibility to schedule customized exercises and review the exercises performed. In addition, we have also explored how new mixed reality technologies could be used in rehabili-

tation and integrated into home rehabilitation platforms.

We conclude with the preliminary results of two pilot studies in which 13 patients affected by multiple sclerosis and 24 healthy elderly participated. These tests have demonstrated the goodness and usability of the platform developed, but also the need for further trials with a larger number of patients to validate the proposed solutions and their long-term effectiveness.

Riassunto

CON l'aumento dell'aspettativa di vita, stiamo assistendo a un continuo invecchiamento della popolazione e, di conseguenza, a un aumento delle patologie legate all'età. Anche per questo motivo, i costi della sanità e della riabilitazione sono in continuo aumento, costringendo le strutture ospedaliere a ridurre la durata della degenza, precludendo ai pazienti la possibilità di ricevere cure adeguate e potenzialmente perdendo le capacità motorie acquisite fino a quel momento. Per cercare di mitigare questo problema, la *riabilitazione domiciliare autonoma* ha recentemente iniziato a diffondersi, permettendo ai pazienti di esercitarsi in modo indipendente, riducendo il carico di lavoro e i costi per ospedali e cliniche. Tuttavia, a causa dell'assenza del terapeuta, sorgono diverse questioni relative all'efficacia della riabilitazione e alla sicurezza del paziente.

Lo scopo di questa ricerca è di esplorare gli aspetti critici legati alla riabilitazione autonoma e alle piattaforme recentemente proposte in letteratura, e di sviluppare un sistema esaustivo che permetta ai pazienti di sottoporsi alla riabilitazione in modo sicuro ed efficace in piena autonomia. Nel progetto qui presentato, particolare attenzione è stata posta alla motivazione a lungo termine del paziente, con la realizzazione di exergames, ossia esercizio fisico attraverso i videogiochi, e altre tecniche di game design, come l'adattamento dinamico della difficoltà. È disponibile anche una piattaforma dedicata ai terapisti, che fornisce loro tutti gli strumenti necessari per gestire i pazienti, come la possibilità di program-

mare esercizi personalizzati e di rivedere gli esercizi eseguiti. Abbiamo inoltre esplorato come le nuove tecnologie di realtà mista possano essere utilizzate in riabilitazione e integrate nelle piattaforme di riabilitazione domiciliare.

Concludiamo con i risultati preliminari di due studi pilota ai quali hanno partecipato 13 pazienti affetti da sclerosi multipla e 24 anziani sani. Questi test hanno dimostrato la bontà e l'usabilità della piattaforma, ma anche la necessità di ulteriori studi con un numero maggiore di pazienti per convalidare le soluzioni proposte e la loro efficacia a lungo termine.

Contents

List of Figures

List of Tables

CHAPTER *1*

Introduction

1.1 Background

In recent decades, life expectancy in high-income countries has increased steadily [1]. Italy, with a life expectancy of 83.6 years, is one of the countries where people live the longest [2]; compared to the expectancy in 1950 that was about 66 years old [3], it means that Italians citizens have gained almost 3 months of life expectancy every year. The situation is similar throughout the European Union, where life expectancy is expected to continue to grow over the next 30/40 years [4]. Outside Europe, South Korea could become the first country where women's life expectancy will exceed 90 years, as early as 2030 [1]. This, combined with a decrease in births, in the European Union will reduce the working-age population and increase the average age, thus increasing the percentage of older people (65 years and older), which is expected to increase from 97.7 million (19.2%) at the beginning of 2016 to 151 million (29.1%) by 2080 [5].

With this trend, age-related diseases and disorders have become increasingly common in recent years and will become more frequent [6]. Also for this reason, rehabilitation costs for patients suffering from diseases such as stroke, multiple sclerosis (MS), or traumatic brain injury (TBI) have increased significantly [7] [8]. Every year in the United States nearly 800,000 people are affected by stroke (which is the leading cause of long-term disability) [8], 1.7 million by TBI, and 10,400 by MS [9]. Always considering the U.S., the annual direct costs for these diseases in 2013 were over $58 billion ($33 billion for stroke, $9.2 billion for TBI, and $16 billion for MS). These costs are expected to increase further in the coming years due to population aging. The situation is no different in Europe, where at the beginning of the 2000s, there were about 1.1 million stroke cases per year, by 2025 this number is expected to rise to over 1.5 million per year [10].

For people affected by these kinds of diseases, high-intensity physical (and sometimes also cognitive) rehabilitation is required to recover lost functionalities or to maintain the functional level achieved [8] [11].

Rehabilitation is carried out through a series of personalized exercises, several times a week, helping the patient to recover motor skills with the aim of improving the quality of life as much as possible.

Increased costs are forcing national health systems to reduce the number of days of hospitalization and rehabilitation in hospitals [12]. In the case of stroke, in the U.S., in less than a decade, the average length of stay of patients has decreased from 19.6 to 16.6 days [13]. Another representative example is the duration of rehabilitation for people with spinal cord injuries, which decreased from 84 to 42 days between 1973 and 2008 [14]. Furthermore, the duration of hospitalization can vary from country to country and from structure to structure, creating inequalities between treatments [15]. Since the treatment received in public hospitals is often not sufficient, once the patient has been discharged, it is necessary to rely on private clinics or home visits by a specialist. These expensive solutions are not sustainable for the majority of patients, who will therefore not receive the treatment necessary for proper recovery [12].

In addition to the obvious physical problems that patients face, there may also be psychological problems. Diseases such as MS lead to a slow but steady physical decline, which can only be slowed down by rehabilitation. With this unavoidable perspective, the ease with which a patient can fall into depression, lose confidence and abandon or reduce rehabilitation therapy, which must be daily and long-lasting for it to be effective, is evident [16].

Considering these circumstances, it is easy to understand why patients often do not train as intensively and for as long as necessary and cannot fully recover and may even lose the acquired functionality [12] [17].

1.2 Home rehabilitation

Currently, one of the most reliable solutions to reduce costs and ensure an adequate rehabilitation program is *autonomous home rehabilitation* [18].

Initially conceived in the 1990s as *telerehabilitation* (a branch of *telemedicine* [19]), it allowed the patient to perform exercises from home under the direct supervision of the therapist, who, through a webcam or similar technologies, could follow the patients remotely. Although one of the main goals of telerehabilitation is to reduce costs, it was not really clear whether and how much the costs were actually reduced [20]. If patients had the undoubted advantage of staying at home and not going to the clinic, as far as therapists are concerned, they were always able to treat only one patient at a time, with the complication of having to learn how to use new technologies and any problems that may arise from their use. In addition, there were always time constraints, and it was always necessary to make arrangements with therapists to allow them to supervise the rehabilitation.

Hence, the need to evolve towards what is today called *autonomous home rehabilitation*, in which the patient can exercise independently, without the direct intervention of the therapist, when he/she prefers, at home. This has been possible thanks to the use of devices able to recognize and monitor the patient's posture and movements, which can allow safe and effective rehabilitation, even without the presence of a therapist. In this type of home rehabilitation, patients can practice whenever they want, and therapists will also be free to review the exercises performed when they wish, with considerable advantages for both patient and therapist. In the beginning, systems such as marker-based motion capture (e.g., by BTS Bioengineering[1] and Oxford Metrics[2]) and wear-

[1]BTS Bioengineering, `https://btsbioengineering.com` (visited on 11/30/2020)
[2]Oxford Metrics, `https://oxfordmetrics.com` (visited on 11/30/2020)

able sensors (e.g., Xsens 3D Motion Tracking[3]), devices too expensive and complex to be used on a daily basis, were exploited. As computational capability increased, smaller and less expensive devices, such as RGB-D cameras, were made available, whose low cost allowed them to spread to different areas. Although accuracy obtained with these devices is not at the level of motion capture systems, it has proved to be sufficient for rehabilitation purposes [21] [22]. Using these devices, several home rehabilitation platforms have been developed over the years, allowing therapists to monitor a greater number of patients. The effectiveness of home rehabilitation has been demonstrated by few studies [23] [24]. In some cases, it proves to be even more effective compared to traditional in-person rehabilitation [18].

However, the absence of the therapist, while allowing more patients to be managed at a lower cost, introduces several problems linked to the actual effectiveness and safety of this type of rehabilitation. To increase effectiveness, for example, it is essential that the exercises are strongly adapted to the patient's needs [16] [25]. While too easy exercises can bore the patient, too difficult exercises can bring pain and frustration. In both cases, the patient's motivation is likely to be reduced, resulting in less adherence to therapy [26]. Other problems concern a correct assessment of the patient's condition and potential mechanisms to ensure safety, avoiding falls, or harmful positions.

1.2.1 Qualitative vs quantitative evaluation

Among the various challenges of autonomous rehabilitation, there is the automatic and quantitative evaluation of the patient's status and progress. The evaluation of the patient is of fundamental importance: it is necessary for the definition of rehabilitation therapy that will be followed by the patient. Although technology is progressively replacing men in different areas, it is not the solution to all problems. In rehabilitation, clinicians continue to play a key role, their contribution is fundamental for the definition and adaptation of the therapy and the evaluation of the patient [27].

For years, rehabilitation has been based on a subjective and qualitative evaluation of the clinician through the interpretation of the patient's

[3]Xsens 3D Motion Tracking, `https://www.xsens.com` (visited on 11/30/2020)

physical and mental condition [28]. This delicate process must also take into account the psychological condition of the patient, on which the outcome of the rehabilitation may depend, and technology is currently unable to do so. But, in support of this qualitative approach, whose benefits are well known [28] [29], which are likely to remain critical for a long time, new technologies can offer a quantitative measurement of patient performance, allowing to make decisions based on previously unavailable information [28] [30].

To date, there are already clinically validated assessment tools that are used for patient assessment [31], but they require long and complex tests that cannot be performed frequently. From this point of view, a lot of work is still needed to define a shared and clinically valid protocol for patient assessment in home rehabilitation platforms. So far, several approaches have been attempted, but none of them have been validated.

1.3 Serious games and exer-games

The patient's motivation plays a key role in recovery. One might assume that the patient, eager to recover his/her physical condition, is always motivated and ready to exercise, but this sometimes may not be true. For some diseases, full recovery is not possible, and the sole objective becomes to slow down the decline to ensure a better quality of life for as long as possible. Often patients, after weeks of rehabilitation without any apparent improvement, begin to lose confidence, diminishing adherence to therapy and nullifying the efforts made previously. In this respect, help comes from video-games.

Nowadays, video-games are one of the most popular forms of entertainment. They can offer an enormous amount of content and entertain players for several hours. Although video-games were initially designed to be used mainly by teenagers or enthusiasts, in recent years, they have also started to be designed for the elderly or people who are not familiar with the technology. Thanks to game engines like Unity[4], it has become increasingly easy to develop video-games. What used to be complex, expensive and requiring a lot of experience, today, has become accessible to almost anyone. Moreover, it is always easier to find assets

[4]Unity, `https://unity.com` (visited on 11/30/2020)

(e.g., 3D models, images, ...) for free or with derisory costs, so it is no longer always necessary for the presence of artists or modelers, at least for smaller projects. This, combined with the growing power of processors and video cards, facilitates the development of graphically attractive video-games that are more likely to attract children and the elderly.

Among video-games, the so-called *serious games*, which can be defined as games designed for a primary purpose other than pure entertainment [32], have become increasingly popular [33]. Unlike traditional video-games, therefore, serious games can have different objectives. Their usefulness has been demonstrated in several areas, such as education [34], healthcare [35], military [36], and tourism [37], to name a few. Among the different areas in which they can be used, serious games also find application in the field of physical exercise, taking the name of *exer-games*. There is not yet complete agreement on the precise definition of exer-game. The definition that will be adopted in this thesis, as well as one of the most commonly accepted definitions is: "a video-game that promotes (either via using or requiring) players' physical movements (exertion) that is generally more than sedentary and includes strength, balance, and flexibility activities" [38].

Although it seems a very recent concept, already in 1982, Atari presented *Joyboard*, a balance board (very similar to the much more modern Nintendo Wii Balance Board) with which games could be controlled by shifting the weight. Other devices and games have followed one another unsuccessfully, often due to unripe technology or the niche market they referred to. The situation began to change in the late 1990s, with *Dance Dance Revolution* (Konami, 1998), capable of selling more than 3 million copies, followed by *EyeToy*, a Playstation 2 camera that allowed players to interact with the game by moving around. But the best-known example of commercial exer-games is Nintendo's *Wii Fit*: initially released with the *Wii Remote* controller, which allowed players to control the game by moving their arm, the successor was released with the new *Wii Balance Board*. In addition to its great commercial success, the Balance Board has been widely used for rehabilitation and scientific purposes. The latest evolution of exer-games has been made possible thanks to *Microsoft Kinect*, and more generally by all the RGB-D cameras, which were subsequently developed with similar technologies.

Through RGB-D cameras, it has been possible to obtain the complete tracking of the players' bodies, something not possible with the previous technologies, opening the way, not only to a new concept of video-game but to different research projects. In fact, while Kinect did not really achieve the desired success in gaming, in the scientific field, it has quickly become a widely used device, and numerous projects have benefited from its use.

1.3.1 Rehabilitative exer-games

One of the most studied areas of serious games is their application in rehabilitation. The need to carry out long and periodic rehabilitation sessions, requires great motivation on the part of the patient, which is often lacking, and adherence to therapy begins to decrease.

Video-games can support the patient and entertain him/her during the execution of the exercises, trying to reduce boredom. Given the complexity of the diseases involved and the fragility of the subjects, it is not possible to use the classic commercial games because they would be too difficult or dangerous for the patients. Think, for example, of Wii Fit, designed to combine fun and exercise, is conceived for healthy people and would be too dangerous if used by people with mobility impairments. An exer-game of this type must be carefully designed, even with the help of therapists, integrating the playful part with the real exercise, necessary in rehabilitation therapy. This requires the use of devices with good reliability to record the correct movements of the user. Furthermore, many problems need to be addressed during the development of these video-games to ensure the safety and effectiveness of rehabilitation.

Exer-games approach makes exercising more fun compared to traditional exercises and seems to help in boosting patients' motivation, fundamental especially when training alone at home [39] [40]. Several exer-games based rehabilitation platforms have already been developed [41] [42] [43] [44]. Exer-games have proven to be more fun and effective than traditional exercises: the ability of video-games to entertain people can be useful to help the patient to increase adherence to therapy.

But, unfortunately, the numerous constraints (e.g., the use of particular tracking devices, requirements in the execution of the exercise) still make it difficult to maintain long-term motivation.

1.4 HoRe & MoveCare projects

This work is part of the *HoRe* (Home Rehabilitation) Project, in collaboration with the medical staff of Neurological Institute “Carlo Besta” in Milan. The aim of this project is the development of a home rehabilitation platform for patients with multiple sclerosis, allowing them to perform customized exercises at home, in a safe and fun way. It must also provide therapists with all the necessary tools for the remote management of their patients. We started with the research conducted in the FP7 *Rewire* Project[5], where a virtual reality-based rehabilitation platform system was developed and tested, whose goal was to provide post-stroke patients discharged from the hospital with the possibility to continue their rehabilitation at home under the remote supervision of clinicians. We have modified, extended, and adapted the original platform to be more usable by patients with multiple sclerosis and therapists, also focusing on the motivational side, in addition to the use of exer-games, we explored and developed new game-design solutions with the aim of increasing adherence to therapy. Part of the work has also been integrated into the H2020 *MoveCare* Project[6]. In particular, a subset of the developed exer-games has also been selected and implemented in the MoveCare project. MoveCare aims to help and support the elderly, trying to prevent physical and cognitive decline. It includes a robotic platform and smart objects to monitor the physical and mental condition of the elderly, and an activity center, which allows the elderly to communicate with each other, avoiding isolation, very common in older people. Among the various activities proposed to the elderly, which include, for example, social card games or puzzles, there is also the possibility of doing gentle exercises with other elderly or playing a subset of our exer-games, which could help prevent physical decline.

1.5 Thesis contribution

Below, the contributions of this dissertation.

1. We reviewed the state of the art of the recently developed home

[5]Rewire Project, `http://www.rewire-project.eu` (visited on 11/30/2020)
[6]MoveCare Project, `http://www.movecare-project.eu` (visited on 11/30/2020)

rehabilitation platforms, identifying their main advantages and limitations.

2. We developed a comprehensive platform that allows therapists and clinicians to manage the entire rehabilitation cycle, including exercise scheduling and results analysis.
3. We propose a set of metrics that can define the quality of the execution of the exercises both in the short and long term.
4. We developed some game design solutions to improve long-term patient motivation, including a new mixed approach to dynamically adjust the difficulty of the exercises according to both the physical abilities and the patient's mood.
5. We present an application developed for Hololens, which supports therapists in in-person rehabilitation by providing them with additional information about the patient's status. It also allows therapists to real-time adjust the parameters of the exer-games.
6. We tested the first prototype of the platform with 13 people suffering from MS, collecting physical information from more than 3,100 exercises; we also collected usability data about the platform.
7. We tested a subset of our exer-games with 24 elderly in the Move-Care project, verifying the usability and acceptance of the platform by the elderly.

1.6 Thesis organization

This thesis is organized as follows:

In **Chapter 2**, we begin by briefly introducing home rehabilitation and the history of telemedicine, as it has evolved over the years, the most commonly used devices, and the main open problems of autonomous home rehabilitation platforms. For each of these, we will explore the articles currently available in the literature, with the aim of providing the reader with a clear picture of the state-of-the-art of home rehabilitation. We will also provide an overview of some of the exer-games for rehabilitation with respective characteristics.

In **Chapter 3**, we introduce all the fundamental features and the architecture of the solution we propose, briefly analyzing the various components from which it is composed and their requirements. At the end of this chapter, the reader will have a high-level view of the developed system, the problems it faces, and how they have been solved.

In **Chapter 4**, we present the *Patient Station*, the platform that will be installed and used by patients in their homes. In particular, we will describe the exer-games and the most important components that allow patients to perform safe and effective rehabilitation.

In **Chapter 5**, we describe the design and implementation of the *Hospital Station*, the component through which therapists can manage all aspects related to the rehabilitation of their patients, such as the scheduling of personalized exercises and the analysis of the quality of the exercises performed by the patient.

In **Chapter 6**, we analyze some game design solutions we designed and developed, aiming at entertaining the patient in the long term, trying to avoid a reduction of adherence to the therapy and the consequent lowering of its effectiveness.

In **Chapter 7**, we explore how the use of modern augmented or mixed reality devices can be applied in rehabilitation. In particular, we will describe *Mirarts*, a software for Hololens, which, integrated into the architecture with the Hospital Station and Patient Station, can help the therapist by providing additional functionality and information in real-time.

In **Chapter 8**, we illustrate the first preliminary results obtained from tests with patients with multiple sclerosis in the HoRe project and with the elderly in the MoveCare project.

In **Chapter 9**, we conclude with a discussion on the platform and the results obtained, also presenting advantages, disadvantages, and future developments.

CHAPTER 2

Home rehabilitation: state of the art

After the brief introduction to home rehabilitation, we will now describe the current state of the art of these platforms. We will start with the recent history of telemedicine and how it has evolved in recent years. Then we will analyze the requirements and main components of a home rehabilitation platform, and for each requirement, some works that deal with it. Towards the end of the chapter, a brief summary is available with some observations, to take stock of the current situation and problems not yet fully resolved.

2.1 History of telemedicine and telerehabilitation

Although the concept of telemedicine seems recent, actually the first well-documented application dates back as far as 1929 [45]. At that time, the Royal Flying Doctor Service was founded with the aim of providing medical assistance to the most remote places in Australia, the Morse code was used to communicate.

Telemedicine has changed over time; at the beginning, any basic form of remote assistance could be considered telemedicine. The introduction of the first computers, the internet, the constant miniaturization of electronics, which led to increasingly powerful notebooks and smartphones, have revolutionized the lives of all, and they have also changed the definition of what was initially called telemedicine.

Over the years, countless terms such as telehealth, eHealth, mHealth, were born. The difference between these terms is not always clear and debated [46], and since there is no universally accepted definition of them, in this thesis, we will use the generic term “telemedicine” to identify all applications that concern medicine and health, and that are offered through Information and Communication Technologies (ICT). This definition also includes important innovations, such as Electronic Medical Records, defined in 1991, containing the entire clinical history of the patient, which are now of fundamental importance for the best possible treatment of patients.

Among the various domains of telemedicine, *telerehabilitation*, the focus of this thesis, is also included. Telerehabilitation consists of providing rehabilitation services at home, through the use of ICT, allowing people from rural areas or with mobility impairments to avoid going to the nearest hospital each time. It has also evolved considerably in recent years, taking advantage of new technologies and increasingly fast internet connections.

In the first experiments of telerehabilitation, the telephone was used to communicate with the patient; later, at the end of the ’80s, the diffusion of pre-recorded video material to be provided to the patient began. It is clear that with these communication systems, it was absolutely impossible for the therapist to verify the correct execution of the exercise or the state of the patient, so their effectiveness was quite limited. This problem was partially solved with the introduction of the first real-time video conferencing systems, which allow the therapist to view the patient while exercising and evaluate his/her activity.

The big step forward was obtained thanks to the development of low-cost sensors, such as RGB-D cameras, for the recording of the patient’s posture. Through these systems, the therapist’s real-time presence was no longer required, who can instead review the three-dimensional videos of the patient while exercising, with a clear advantage over the classic 2D camera, when he/she desires. Both thanks to these devices and to a higher internet speed and computational power, several platforms for home rehabilitation begin to spread recently.

But, from the authors' best knowledge, to date, there are still no home-rehabilitation platforms and protocols clinically validated and used outside the scope of research projects.

2.2 Home rehabilitation: application area

When we talk about home rehabilitation, we must take into account that we are talking about any kind of platform which allows remote rehabilitation. This can take place in two different ways, either autonomously or with a therapist who monitors remotely. Moreover, exercises can be carried out by following the instructions of pre-recorded videos or by a more entertaining approach using video-games. Even the good old phone can be used as a communication tool [20]. Patient monitoring devices (e.g., wearable sensors, RGB-D cameras, and so forth) may also be used. Thanks to this heterogeneity, and the possibility of having countless solutions, the areas in which home rehabilitation has been applied are numerous.

We can first of all divide between physical rehabilitation, which aims to recover physical abilities, and cognitive rehabilitation, designed to recover cognitive abilities. Sometimes physical and cognitive rehabilitation can be carried out simultaneously, flanking traditional exercises with cognitive questions or tasks to be solved.

Among the most widespread diseases that call for rehabilitation, stroke is certainly the most important. Many platforms have been developed with the aim of allowing post-stroke patients to recover both motor and cognitive functions as much as possible (an interesting review can be found in [47]).

A similar situation with multiple sclerosis [48] and injuries (e.g., TBI [49]), which also have a significant impact on the costs of national healthcare systems. Another area of increasing importance is physical exercise for the elderly [47] [50]. As the aging population increases, it becomes crucial to follow the elderly in their natural aging process through targeted exercises, with the aim of slowing down physical and cognitive decline.

Home rehabilitation has also been applied to other diseases such as chronic obstructive pulmonary disease [51] [52], heart problems [53] [54], Parkinson's disease [55], or hip fractures [56] [57].

2.3 Main features of a home rehabilitation platform

After having briefly seen the history and the application areas of home rehabilitation, before starting to describe the work in the literature, we would like to make a brief overview of the main requirements that should be satisfied by a home rehabilitation platform. Fig. 2.1 shows all the main components usually requested; each of them will be addressed in this chapter.

First of all, note that the heterogeneity of the previously mentioned diseases and the patients affected is one of the critical points of these platforms. A platform designed for one disease may not work with another disease. Often it does not even work with all the patients suffering from the same disease, because, for example, someone is too compromised.

Flexibility and customization are, therefore, certainly two important keywords in home rehabilitation, providing a tool with which therapists can assign personalized exercises tailored to the patient's needs is the first essential requirement to ensure safety and effectiveness.

The second fundamental requirement is the possibility to *evaluate the patient's performance and condition*. This has been possible thanks to the development of inexpensive devices such as Microsoft Kinect, which for a few tens of euros make it possible to track people's joints, allowing the patient's movements to be recorded with a good degree of precision [21] [22]. Before their advent, it was necessary to use more advanced systems, such as marker-based motion capture, expensive technologies with long and complex set-up procedures. Difficult, if not impossible to use independently at home, and hardly acceptable to the patient both in terms of cost and size.

Through the data recorded by these devices, it is possible to extract information and metrics for automatic or manual evaluation of patient status and progress, allowing therapists to remotely monitor their condition. The extraction of meaningful data is still one of the most complex topics to deal with. As we will see in Paragraph 2.3.4, a few approaches

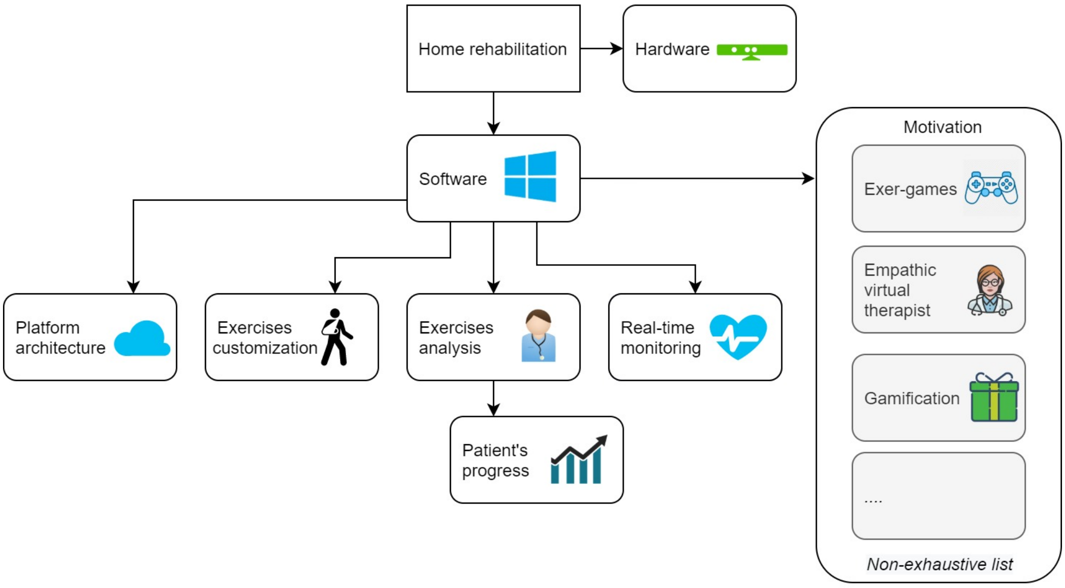

Figure 2.1: *Key points of a home rehabilitation platform that will be described and addressed in this chapter. Note: the motivational elements on the right (exer-games, empathic virtual therapist, ...) are just examples; many other solutions can be used.*

have been proposed so far in the literature.

Finally, *real-time monitoring* is also necessary to ensure patient safety, and it can be used to identify falls and reduce risks of bad posture that can easily lead to maladaptation injuries.

All these elements are required to provide the patient with an effective platform that can be used in conjunction with (or alternative to) classical rehabilitation.

Besides these requirements, however, the patient's motivation also plays a key role in the effectiveness of rehabilitation. Regardless of the goodness and quality of the system, without adequate motivation, the patient may soon stop using it. Without the presence of the therapist, adherence to the therapy is entirely in the hands of the patient, who, in the absence of stimuli, could reduce or abandon the rehabilitation program [58]. These stimuli can be represented, for example, by exer-games, a kind of video-game that can help make rehabilitation more fun. In addition to exer-games, empathic virtual therapists have also demonstrated good effectiveness in entertaining the patient [59], and solutions such as gamification can also be helpful. From this point of view many different solutions can be used.

Furthermore, one of the most critical parts comes from the evaluation of the effectiveness of a platform. Given the need to have a large number of patients available for a long period of time, only a few works have been able to achieve significant results.

Some of the platforms in the literature deal with only one or two of these points. In this chapter, we will discuss the features just described by citing and describing some of the most representative works that have addressed every aspect.

At the end of the chapter, a short final summary is presented, with a table containing all the most representative works mentioned here and the topics they dealt with.

2.3.1 Platforms architecture

Most modern platforms have been implemented through a client-server approach (just to cite a few: [60] [61] [62] [63] [64] [65] [66] [67] [68] [69]). On the one hand, is the patient, at home, with the hardware and software required for rehabilitation; on the other, is the therapist, in the clinic or hospital, who needs to monitor the patient from his/her office.

The client-server architecture fully meets the needs of these two figures. In our case, the client component is the platform installed at patients' homes, which communicates with a server where all the patient-related information is stored (e.g., personal information, rehabilitation schedule, exercises performed, ...). The therapist, instead, thanks to another application, usually through a web-browser, accesses all this information through his/her account and manages the rehabilitation of the patient.

This is the most widely used architecture, there are obviously works that focus on particular rehabilitation issues (for example, the patient assessment), and for this purpose, it was useless for them to design such a complex system. From the scientific point of view, the architecture is in no way relevant, but it was right to inform the reader about the type of software currently exploited, both in research and commercial field.

2.3.2 Commonly used devices

We can probably consider 2010 as the most important turning point in the development of affordable and easy to use home rehabilitation platforms.

At that time, the breakthrough came with the release of Microsoft Kinect: the convenience and cost-effectiveness of this device have made it the optimal tool for dealing with this type of application. With a cost of about $150, it was possible to have a reliable RGB-D camera [70] [71], which made it possible to extract motion information of the patient's skeleton, and consequently, get all the data that until now it was only possible to gather through complex and uncomfortable devices.

Think, for example, of motion capture systems, advanced and precise tools, but with very high costs and complex to set-up and use. Widely used in gait analysis (e.g., [72] [73]) could clearly not be used in the domestic environment.

Other common devices at the time, wearable sensors, although cheap, did not fully meet the requirements. Generally equipped with sensors such as accelerometers and gyroscopes, used to detect changes in acceleration or rotation, these devices can be used in many different rehabilitation areas, such as multiple sclerosis [74], stroke [75], or knee rehabilitation [76]. Despite their lower cost, this type of device is not always particularly comfortable and requires some care in wearing them properly. Moreover, they are sensitive to the sensors' position, and their cost may not always be cheap. But compared to motion capture systems, it is certainly an important step forward.

The real game-changer in the rehabilitation field, as previously said, was the spread of RGB-D cameras (also called depth cameras), starting from Kinect 1 (e.g., [60] [77]), the real turning point, continuing with Kinect 2 (e.g., [67] [78]) and passing through their competitors such as the Orbbec cameras (e.g., [79]) and Intel Real Sense (e.g., [80]). Low-cost devices, easily purchased, which require practically no type of installation or assembly. The advantage of this type of device is the possibility to calculate the distance between the camera and each pixel of the image. In this way, it is easy, for example, to recognize a person with respect to the background, independently of the colors and the light distribution. Starting from this 3D image, the silhouette of the person framed can be extracted, obtaining the patient's posture data without resorting to the use of wearable sensors.

Moreover, real-time tracking APIs have been released by Microsoft, able to automatically extract the skeleton of the moving person frame by

Figure 2.2: *Some of the devices used. From left to right: Microsoft Kinect 2, Orbbec Astra, Intel RealSense 435, Nintendo Wii Balance Board, Nintendo Wii Remote, and Oculus Rift.*

frame, thus realizing a true motion capture system.

In addition to the RGB-D cameras, another series of devices have been used sometimes, such as the Leap Motion (e.g., [81] [82]), capable of detecting the skeleton and gestures of the hand, the Nintendo Wii Balance (e.g., [83] [84]), which, thanks to its four load cells, can determine the patient center of pressure (CoP), a fundamental parameter of postural rehabilitation, or the Wii Remote, a controller equipped with accelerometers, sometimes used in the rehabilitation of the arms (e.g., [64] [83]). Among these devices, the Nintendo Wii Balance Board, which has been exploited in countless works in the literature to track the center of pressure, was certainly the most widely used.

Even virtual reality is finding space in this area, are beginning to spread works in which devices such as Oculus Rift (e.g., [85]) and HTC Vive (e.g., [86]) are being introduced to rehabilitation.

We also expect, in the coming years, a greater spread of augmented and mixed reality devices, such as Microsoft Hololens. To date, given its current low diffusion, there are still very few works in which Hololens has been used in rehabilitation (e.g., [87] [88]). In this thesis, as we will see in detail in Chapter 7, we have carried out exploratory work to understand if and how Hololens could be used in rehabilitation.

2.3.3 Exercises customization and scheduling

One of the crucial factors that determine the effectiveness of rehabilitation is the rehabilitation program, i.e., the mix of exercises to be performed, their difficulty, and frequency of rehabilitation sessions.

Patients with different needs and problems need ad hoc therapies designed specifically for them (what is called *Personalized Medicine*). The patient's psychology and attitude also play a key role and must be taken into account when defining the rehabilitation plan. It is the therapist's task to analyze the patient's situation and define the therapy. In the case of home rehabilitation, it is therefore clear that it is necessary to offer the hospital staff all the functionalities that allow defining a proper rehabilitation plan and an adaptation of the exercises and their difficulty, according to the needs of each patient.

It is also for this reason that it is not generally possible to use commercial video-games for rehabilitation: they are designed for healthy people, they have a fast pace and could turn out even dangerous if used by people with limited mobility [89].

Clearly, a platform can support more or less complete customization of exercises. We have identified five possible levels of customization, starting from the total absence of customization up to its full support:

- ***No customization***: at this level, no customization or modification of the exercises is possible. All patients have the same set of exercises available.

- ***Poorly supported***: clinicians have at their disposal some levels of difficulty (e.g., easy, medium, difficult) to choose from, to better adapt the exercise to patients' level. This customization, useful for healthy people, could not be enough for unhealthy subjects. This category includes commercial video-games, which usually have a set of pre-defined levels of difficulty, where also the easiest level can be too difficult for the patients.

- ***Partially supported***: this category includes all the works in which therapists have the possibility to create highly customizable exercises, but with great practical limitations. A clear example, as we will see, are those platforms where the therapist must physically record the correct execution of the exercise with the right pace, and the patient must copy his/her movements. Despite the high level of customization, such an imprecise and complex method has great limitations that can reduce its effectiveness mainly because it requires a lot of time for the therapist.

- ***Supported***: all systems in which it is possible to modify a series of parameters of each exercise quickly and easily fall into this category. This means that each exercise has a set of parameters that change the aspects and difficulty of the exercise.

- ***Fully supported***: finally, as the last category, for "fully supported", we mean a platform that supports the customization of the aspect and the difficulty of the exercise and in addition, it has an easy way to schedule these tailored exercises to the patient (e.g., therapists through a web-browser adjust the parameters and the patient automatically receives the new schedule).

This classification has also been used in the final table of this chapter. This is only one of the possible guidelines on how to categorize the exercise customization of a home rehabilitation platform. Clearly, there can be several facets; we have not taken into account some advanced features in this categorization. Dynamic difficulty adjustment (DDA) [90], for example, can automatically adjust the difficulty according to the user's performance (already widely used for decades in video-games), and it is in all respects a form of personalization of the exercises, even if it is not performed directly by the therapist. In these cases, it is not always easy to classify a work with certainty.

Although designing exer-games and their parameters may seem like a relatively simple problem, close collaboration between game designers, developers, and therapists is necessary. The latter are the only ones who know the difficulties of their patients, and all the parameters and aspects that may be relevant to the problem or disease being treated.

For the sake of clarity, we will now describe a few platforms with different levels of customization.

In [60], clinicians can record custom exercises that will be administered; the patient will then copy the movements of the avatar representing the therapist's skeleton. This case falls perfectly in our "partially supported" definition: the therapist can create ad hoc exercises for each patient, but it is a complex and coarse procedure. Other similar works include [61] [91].

Comparable, but slightly more sophisticated, is the approach proposed in [78]. Also here, therapists are required to manually record the exercises, but in this case, the speed of the execution is automatically adapted using the Cross-Correlation, calculated by comparing the position of the patient's joints with their position in pre-recorded exercises, improving the quality of the customization.

For what concerns the "Supported" and "Fully Supported" platforms, in [62], authors developed 18 customizable exer-games: therapists can adapt exercise duration and difficulty according to the patient's need. The therapist is always in contact with the patient through video calls, questionnaires, and also from the results of the exercises performed. In this way, it is possible to better adapt the therapy.

Another example of a fully supported platform is [63], where a set of exer-games for the elderly has been developed. Using a client-server architecture, clinicians can change the patient's schedule, adapting the exercises as they need.

Other examples of works describing tailored exercises are [42] [64] [66] [67].

Although the customization and adaptation of the exercises is a crucial factor in the effectiveness of rehabilitation, it is generally an iterative process with therapists in the definition of each exercise, and, from an IT point of view, it is not particularly interesting. For this reason, for now, we will not dwell further on this topic. What, instead, is more interesting, always related to the problem of customization, is the automatic adaptation of the parameters that define the level of difficulty of each exercise, which could, on the one hand, reduce the work of therapists, on the other hand, ensure greater efficiency, if well designed.

Advanced systems: towards automatic adaptation

When the exercises or exer-games are characterized by many parameters, it becomes complex for the therapists to manage the adaptation of the difficulty of the exercises. To this end, some platforms have automatic or semi-automatic systems for the adaptation of the parameters, reducing the work required by the therapist. These types of systems have a twofold reason: on the one hand, it is clear that providing the patient with the exercise suitable for his/her level increases the effectiveness of the therapy; on the other hand, an incorrect degree of difficulty could lead to boredom or frustration, reducing the patient's motivation.

This solution is known in the literature by the name of Dynamic Difficulty Adjustment [90]. DDA systems started to spread already tens of years ago in a small set of video-games, with the aim of providing the best level of difficulty to entertain the player, only a few years ago they started to be applied also to serious games and exer-games. In the development of these systems in rehabilitation, various factors, both physical and psychological, must be taken into account to achieve satisfactory results. The difficulty must reflect both the physical abilities of the patient, to avoid pain or risk of falling, and his/her attitude. For example, someone may prefer a slower but safer rehabilitation path.

More information on this topic can be found in Chapter 6, where the DDA system implemented in our platform is also described in detail.

2.3.4 Patient assessment: executed exercises analysis

In traditional rehabilitation, therapists guide patients in the execution of the exercises, thus they are able to assess the patient's condition only qualitatively. Nevertheless, they can ensure the correctness of the exercises and to adapt the exercises to the patient's current state. In addition, patients are required to periodically perform validated clinical tests to assess their physical condition using scales such as the Berg Balance Scale [92] or Tinetti Balance Scale [93], or instruments such as the Smart Balance Master[1]. Using these systems, the patient performs a series of exercises, from which clinically validated indexes are extracted. These indexes represent a clear view of the patient's ability, allowing therapists to understand the patient's progress, supporting them in modifying, if necessary, the patient's rehabilitation program.

A frequent assessment helps in best tuning the therapy but, with home rehabilitation, it becomes more complex to obtain reliable and complete information about the patient's as this equipment cannot be brought to the patient's house. This reduces the ability to adjust the therapy and could potentially decrease the effectiveness of rehabilitation. For this reason, it is essential to provide an automatic analysis of the patient's exercises that allows therapists to quickly understand the patient's condition. An accurate remote analysis also makes it possible to reduce the

[1] Smart Balance Master, `https://www.mossrehab.com/smart-balance-master` (visited on 11/30/2020)

number of recall visits in the hospital for testing, giving advantages both to the patient (which saves time avoiding going to the hospital) and to the hospital, reducing stress and workload on therapists and medical equipment.

Several solutions have been proposed for the analysis of patient performance. To date, we can roughly divide the approaches into two main categories: *template-based* and *rule-based*. We will now illustrate the two approaches, citing some of the works in which they have been used.

Template-based

The template-based approach consists of comparing the exercise currently performed by the patient with a series of pre-recorded exercises performed by therapists, other experts, or the patient himself/herself under the supervision of the therapist, which are used as a baseline. The greater the difference, the lower the quality of the exercise. Possible solutions to estimate the difference are, for example, the Euclidean distance, the Mahalanobis distance, the Gaussian log-likelihood mixture model [94], or the Dynamic Time Warping (DTW) algorithm [95].

The DTW algorithm, already extensively applied in speech processing, usually provides the most reliable results. This is why we will focus primarily on the works that use it, giving secondary importance to other metrics. DTW works with two time sequences whose speed may vary, reducing shifting and distortion effects over time. It has been shown to work well when applied to rehabilitation [96]; in home rehabilitation, it has already been widely used in several platforms.

In [60], DTW and fuzzy logic have been used to evaluate three different shoulder rehabilitation exercises. The DTW was used to calculate the similarities in the trajectory of a set of pre-selected joints between the current patient's execution and the baseline (represented by the correct execution of the exercise by the patient, supervised by the hospital staff). These similarities are then given as input to a fuzzy system, the output of this fuzzy system is finally matched to the "Bad", "Good" or "Excellent" classes, which represents the quality of the exercise. To verify the quality of the system, four healthy people executed the three exercises. Authors asked a physician for an evaluation of the execution of the exercises; its evaluation in about 80% of cases matched the fuzzy system evaluation. The absence of tests on real patients (and also a small number of healthy subjects tested), as admitted by the authors themselves, is a clear limitation of the study.

In [96], DTW has been exploited to assess the quality of rehabilitation of the elderly. Authors selected a subset of eight joints and the angle between two joints as a representative metric for the quality of execution. Twenty-one healthy middle-aged and older subjects tested the system; the subjects performed a complex Tai Chi exercise instead of traditional rehabilitation exercises. The quality of the execution is represented by a number from 0 to 100; the value calculated by the algorithm was successfully compared with the evaluation of three experts. Their evaluation was consistent with the evaluation given by the system, demonstrating the goodness of the algorithm. Also in this work, a major limitation is the small number of subjects tested, including many middle-aged, not consistent with the study target (older adults).

We would also like to mention [97]. In this work, Khan et al. proposed the Incremental DTW (IDTW). The main advantages of this algorithm are the possibility to compare an incomplete sequence with a complete one and the ability to provide results in real-time. The real-time evaluation allowed to provide a real-time novel visual evaluation of the patient: the IDTW scores for each joint are calculated and mapped to a color table and then shown using a skeleton silhouette. In this way, the patient has feedback representing the degree of correctness of the exercise directly during its execution, without having to wait until the end of the exercise. Unfortunately, the authors did not do any tests with real patients to demonstrate the effectiveness of their algorithm. The ability to provide real-time feedback, topic of the next paragraph, is a fundamental feature in home rehabilitation, where it is essential to correct the patient as quickly as possible to prevent him/her from making harmful movements.

These are only a few examples in which DTW has been used to evaluate the performance of a patient. Almost all of these works share the same protocol, i.e., clinicians or experts record the correct execution which is then compared with the patient's exercises. Other similar articles include but are not limited to: [61] [78] [98] [99] [100].

One of the main advantages of DTW and similar solutions is its ease of use: it is sufficient to record the execution of the correct movement to perform and then compare it with the movement performed by the patient; for this reason, it is also independent of the disease or disorder treated. Although seemingly simple, this is also the main disadvantage of this type of algorithms: due to the high customization of the exercises, there could be dozens of different exercises since each patient needs a custom difficulty (which may vary over time), and it may be impossible for physicians to record all the necessary data. Moreover, pattern matching algorithms often provide only a single score representing the quality of the exercise but do not provide any information about what the patient did wrong, forcing doctors to analyze the individual exercises when they need more information.

Machine Learning Among the most advanced comparison techniques, there are those that exploit machine learning, which in recent years is spreading more and more in every area. But, although machine learning has proven to be revolutionary in some fields, it is still difficult to apply in the field of rehabilitation. To use it, an extensive training set labeled by experts is required. Furthermore, each pathology and each patient can request personalized exercises and assessments, as we have seen, so a generic system is difficult to implement. Despite these problems, however, there are some works that tried to apply machine learning in restricted rehabilitation areas.

One example is [65], authors developed a system based on Hidden Markov Models (HMM) which evaluates the executed exercises of patients after hip-replacement surgery. The model was trained based on exercises performed by patients, which movements were then classified by therapists. Authors merely say that HMMs allow discrimination between correct and wrong movements, but without giving precise results.

Another interesting work is [101]. This work described a fully immersive serious game system in which the patient is required to use a head-mounted display (e.g., Oculus Rift), a Leap Motion, and a Kinect. Their exercises have been executed by healthy subjects and these data have been used to train a Long-Short-Term-Memory (LSTM) Deep Residual Convolutional Network (RNN). The RNN evaluates patients measuring the similarities between their execution and the correct execution by healthy subjects, citing the article: "if the network gives a value of 100%, the patient is performing as a healthy subject, if the result is 80% the patient is acting at the 80% of the capabilities of a healthy subject". To evaluate the algorithm, they asked five therapists their opinion about the impairment of the patient after each session, the results are encouraging, in most of the cases, the difference between algorithm and therapists does not exceed 5%.

In [102]. authors proposed sensor-based action recognition and evaluation models. They used a multipath convolutional neural network (MP-CNN). This MP-CNN consists of a dynamic CNN and a state transition probability CNN combined to find hidden states of an exercise and extract the best features. They asked 49 healthy volunteers to record their movements using wearable sensors; each movement has been labeled as "good", "average", or "bad". This dataset has then been used to train the neural network. The classification accuracy of their model reached 79.4%.

The last work we would like to cite is [103]. As in the previous paper, using the Vicon optical marker-based tracking system (which is considerably more accurate and expensive than a traditional RGB-D camera), they recorded the performance of 10 healthy subjects completing 10 different rehabilitation exercises. Subjects were requested to complete the exercises both in a correct and incorrect way, simulating performance by patients with musculoskeletal constraints. Data have then been manually labeled with a score representing the quality of the execution. The first results are promising and demonstrate the applicability of machine learning (deep learning in this case) in the field of home rehabilitation.

Rule-based

The second approach, the rule-based approach, consists of extracting particular metrics that have been defined with the experts, usually customized on a particular disease (sometimes, however, certain rules could also be shared by several diseases). The rule-based approach allows better flexibility and control over data: adding or changing how a certain metric is extracted can be done easily and quickly.

Compared to the previous approach, the main advantages include: a) a higher computational speed, which generally allows it to be used even in real-time if needed, b) the rules do not change, they are independent of the patient, allowing the system to scale, even having a large number of patients and, c) provides more precise feedback, based on the output of each rule, it is easier to understand what the patient is doing wrong and how to correct it, compared to measuring the similarity of an algorithm such as DTW, which often does not provide enough information to understand the error the patient is making.

As a negative point, besides being suitable only for a certain disease, it can be subjective and depend on the therapist to therapist. Clinicians thus actively participate in the definition of metrics for quality assessment.

One of the most interesting works using the rule-based approach is [104]. Through collaboration with therapists, the clinical goals of low back pain rehabilitation have been identified and converted into movement analysis features. For each of the 5 exercises chosen, metrics considered representative by clinicians have been defined. A series of scores of different granularities has been defined (score for each characteristic, for each clinical goal, and an overall score), each score is calculated using a fuzzy system. The most interesting and innovative part is the possibility for therapists to modify the fuzzy rules for each patient. In this way, the evaluation is tailored to each patient. We have not found in the literature other works that allow such a high level of customization in the field of rehabilitation evaluation. The system has been tested on 20 patients with encouraging results: the evaluations obtained are consistent with those of the experts.

A somewhat similar approach is present in [105]. This system allows the experts to create a set of XML rules, which guarantee real-time assessment and evaluation of the patient's posture. The rules are based on the positions and angles between joints to define the quality of the posture. The advantage of this work is the flexibility in defining the rules, which allows for adaptation and creation of new rules also by therapists. Unfortunately, the authors do not provide any information on possible tests on patients or other subjects.

Other similar works include but are not limited to [62] [68] [106].

As will be described in detail later, we too have decided to use this approach in our work, exploiting the knowledge of therapists.

2.3.5 Real-time monitoring

We have just described, in the previous paragraph, a series of works that evaluate the quality of the exercises performed, trying to assess the patient's condition. These works very often aim to evaluate the patient "offline", providing metrics that must be analyzed by a therapist, allowing him/her to intervene when necessary. But autonomous rehabilitation, given the absence of medical staff to monitor and help the patient, can be dangerous. Failure to perform the exercise correctly, in the long run, could worsen the patient's condition rather than improve it. An automatic system for monitoring the patient during the execution of the exercise is a fundamental requirement for this type of platforms, allowing immediate and autonomous intervention without having to wait for the therapist to analyze the exercises and alert the patient.

With the terms "real-time monitoring", we refer to all those feedback and alerts, which, in real-time, allow the patient to understand that he/she is not performing the correct movement, and possibly also giving advice to correct the problem. The system should also pause the exercise/game, if necessary, and resume it only when the patient has corrected the posture. Giving warnings only at the end of the exercise is not real-time according to our definition. Moreover, monitoring should be completely autonomous. Here we do not consider the platforms where the clinician is remotely connected to the patient's system; since we are talking about autonomous home rehabilitation, we assume that the patient exercises alone, at home. In literature, there are several works in which the therapist can monitor the patient in real-time, but we will ignore them because they do not fit our constraints.

A first requirement, considered fundamental by us, is that these monitoring systems should have the possibility of customization according to the patient's needs. Often real-time monitoring has a rule-based approach, sometimes very similar to the systems we have already described for patient assessment.

In the previous paragraph, we mentioned [105], whose authors implemented a system of rules for patient evaluation, the same system was used by the authors also for patient monitoring in [77]. In this work, when necessary, they also give visual feedback describing what the patient needs to correct.

A similar approach has been used in [106]. In this case, at the end of the execution of each movement, the system provides a brief description of the correctness of the movement, giving warnings when necessary. Again, the system is based on a set of rules to define the quality of rehabilitation. Other similar rule-based systems are [67] [68] [76] [100] [107].

A different solution was used in [97]. We already mentioned this work in the previous paragraph, their IDTW algorithm was used to evaluate patients, but their algorithm has another important feature: it is faster than the classic DTW and can be used in real-time. This allowed them to control the patient's posture in real-time and to color the joints of the avatar representing the patient based on the quality of movement. If, for example, the patient is (mistakenly) bending the back, the joint representing the back will be colored red. This allows him/her to understand the mistakes he/she is making, giving the opportunity to correct them as quickly as possible.

This is an example where the analysis of the quality of the exercise overlaps with real-time monitoring, and there may not be a clear distinction between the two. However, often the evaluation of an exercise also includes other metrics, useful for the therapist to understand the patient's progress over time, which are not shown to the patient.

2.3.6 Exer-games

The traditional approach to rehabilitation can be tedious in the long run. Most of the platforms we have described in the previous paragraphs have focused mainly on one or more of the topics we have seen (patient assessment, customization of exercises, and real-time monitoring), and only a few have addressed the problem of patient motivation, which is a key factor in maintaining adherence to therapy and consequently its effectiveness. Whether or not to use the exer-games does not affect any of the other points we have seen so far, there will be no difference in the execution of the exercises, what changes is that they will be shown through a video-game, with the aim of entertaining more.

After the necessary preamble, there is some confusion around the word "exer-game". In many works, the patient simply copies the movements of an avatar, can this be considered a game? Some people say yes, we think not. Perhaps the confusion also comes from the fact that the classic elements of video-games are used (game engines, 3D models, textures, ...). But is this enough to call them video-games? No, of course not. Exer-games are used to motivate a patient, to induce him/her to play, to have fun, just like a classic video-game does. The simple action of copying the movements of an avatar cannot be viewed as a video-game, as it lacks all the characteristic elements of a game, therefore, according to our definition, it cannot be considered an exer-game.

This is not meant to be a criticism of other works, but it is a necessary premise because, in this paragraph, we will only discuss works that present some typical aspects of video-games. We will not evaluate the real effectiveness of these exer-games. This can also be very subjective: someone may not appreciate video-games at all and prefer traditional exercises. Far from us to claim that exer-games are the final solution to the problem of motivation. Indeed, as we will see in Chapter 6, where we will analyze the problem of motivation in detail, the exer-games developed so far are not without limitations.

We begin our state-of-the-art review from [108]. Four exer-games have been developed in this work, each exer-game is associated with a certain post-stroke rehabilitation exercise. Their exer-games are particularly interesting because the patient's avatar is immersed in virtual scenes of real situations, in which the patient performs a movement to reach a real goal or win a challenge. They have developed, for example, the bowling exer-game: in throwing the ball, the patient performs a particular movement of the elbow, which is also a useful exercise to improve their condition. In this way, the patient exercises and rehabilitates himself/herself without even realizing it.

Another interesting game provided by the same authors, which combines physical and cognitive rehabilitation, is "RehabQuiz". In this game, the patient is asked multiple-choice questions, and to answer he/she must physically move the arm and press the corresponding virtual button. The games were tested by 10 healthy patients and 4 experts. The system was appreciated, it was fun and easy to use. Some criticism emerged about its possible use by real patients: some stroke patients, for example, would not be able to use it as too difficult, so it would be necessary to adapt the games, features not yet present.

Other simpler games that we want to mention are [43]. Designed for post-stroke patients, they support 6 different exercises in which the patient has to move the different parts of the body to reach an object. Same principle for [42] and [63]. Most of the works used Microsoft Kinect 1 or 2. A different choice was made in [69]: authors used wearable sensors to interface with games for orthopedics rehabilitation, thanks to their greater precision.

A slightly different approach has been used in [109]. Instead of having many exer-games, each one associated with an exercise, authors have implemented a single exer-game in which the patient is asked to perform different types of movements, both with the lower and upper limbs. The game is designed for patients suffering from Parkinson's disease. Here, the patient drives a tractor, taking steps moves the tractor in the direction of the step, while moving the hands can gain objects. Authors have paid particular attention to the design of the game, also making meetings with the patients to verify the effectiveness of the design choices. Twelve levels of increasing difficulty are available. Nine Parkinson's patients tested the game, the game was appreciated, but further testing will be needed to evaluate the effectiveness.

Works analyzed so far have consisted of mini-games in which the patient performs the same action several times to generally achieve the same goal (e.g., win the game). This is nothing more than moving an exercise in a virtual environment, accompanied by typical video-game mechanics. If the game is well structured, it helps to motivate in the short run, but in the long run, it can get boring.

Unfortunately, the development of advanced exer-games with complex mechanics that ensure fun for long periods of time is difficult to achieve, especially in the academic field. Large investments, a multidisciplinary team, and tens or even hundreds of people are required to develop a complex game. Despite this, there are works that we have particularly appreciated whose exer-games are well structured and try to create an immersive and long-lasting experience.

One of these is [110]. The most important aspect of their work is the development of a complete game, as opposed to classic mini-games. The patient impersonates the main character of the game, who has to move around the world to find his/her family, to move will have to overcome challenges (e.g., climbing trees, wading rivers, ...). Each challenge corresponds to a rehabilitation exercise that must be done; all exercises are customizable by the therapist. We find that their mini-games are very well embedded in the main story; however, we have doubts about their real long-term effectiveness. Authors have developed a limited number of actions/mini-games that can be played, so once the "surprise" in playing a particular mini-game is over, the motivational drive is reduced. The game story helps to increase motivation; however, the story will end sooner or later. At that point what will the patient do? The authors do not provide this answer in the article, and they do not indicate the real duration, in terms of hours, of the story. Moreover, the platform has not yet been tested by real patients, so we will have to wait to understand its real long-term effectiveness. However, we really appreciate their attempt to create a real video-game. We believe that this is the right direction, although very complex and long to develop.

2.4 Home rehabilitation: effectiveness and results

By this point in the chapter, the reader will probably have already gained an idea of the current state of the art of home rehabilitation systems and their effectiveness. There are very few works that have involved a representative number of patients. In many works, only a few patients were recruited, often even only healthy subjects. Although the benefits of proper and continuous home rehabilitation are known and confirmed by some randomized clinical trials (RCTs) [23] [111] [112], there is still no defined protocol on how the patient should be evaluated and monitored in real-time. And as admitted by the authors of RCTs themselves, very often the number of patients is limited, and their motivation could derive a lot from the use of new technology, with the risk that with the passage of time the astonishment of novelty fades away, reducing adherence to the therapy. There is a clear need for new large-scale studies, both in terms of the number of patients and duration of testing, to verify adherence would take at least 6 months, if not more. Even once this is done, the need to define and validate common protocols will remain.

But, while the presence of some, albeit limited, RCTs is comforting as far as the effectiveness of home rehabilitation is concerned, the state-of-the-art in the validation of exer-games is far behind. Most studies are limited to tests of usability and acceptance of the platforms, often tested over short periods. Much work is to be done from this point of view. There is the need to verify their motivational drive in the long term, and possibly, also study game design solutions for the entertainment of patients.

An important note, many studies agree that an initial boost is given by the novelty of exer-games and devices used, with the passing of the years will increase more and more the number of patients grown with the technology (reaching the so-called digital natives) and this motivational drive will weaken. If simple games currently can entertain elderly people, who have never had to deal with video-games, this will probably no longer be valid in 20 years.

2.5 Summary

So far, we have cited several works based on the features that have been implemented. To give the reader a more complete idea, we summarize in a table some of the works mentioned, specifying, for each of them, if it has the key points we have described (exer-game based approach, exercises customization, real-time monitoring, and patient assessment).

The table below contains only a subset of the articles mentioned in this chapter: we ignored the older ones (prior to 2011) and focused on those dealing with rehabilitation platforms, removing, for example, all reviews, articles in which patients have done rehabilitation without any IT support, and articles that focused on validation and measurement of the accuracy of hardware devices.

The table should be intended as a starting point, if the reader is interested in a particular aspect implemented in one or more articles, we suggest to read the original works. We do not aim to summarize all the works, but only to describe some features.

Some works do not specify the disease or disorder they aim to treat; in this case, the table states “Generic” in the target column. There may also be inconsistency in the classification of exer-games, some authors present their platform stating that it is based on exer-games, but at a closer analysis in reality the gameplay is practically absent. In these cases, for us, according to our definition, they cannot be considered exer-games.

Note that the table is useful for an overview, we do not intend to make a comparison between the works. Most of the authors have focused on a particular topic, so it is normal that not all features have been analyzed.

As can be seen from the table and as we had already anticipated in the previous paragraph, most of the works have been tested only by healthy subjects. This is also due to the enormous difficulty (and cost) of recruiting a sufficiently large number of patients. Moreover, even when patients are available, it is difficult to go beyond the simple evaluation of the usability of the platform. Usability, which is certainly a valid starting point, but which should then be confirmed by real data of effectiveness through, for example, RCTs, still too limited and sporadic. In these cases, the table states "no relevant results" in the last column, it means that there is not enough data to validate the submitted work, and other tests are required to validate the effectiveness of the work proposed.

Table 2.1: *Summary of the most representative cited articles. For each article the following is represented: the rehabilitation target, if exer-games have been used, the level of customization of the exercises, if there is real-time monitoring, if they have quality assessment (Q.A.), on whom the platform has been tested, and a brief summary of the results.*

Paper	Target	EG	Cust.	RT mon.	Q. A.	Subjects	Results
[42]	MS	Yes	Supported	No	No	11 patients + control group	Improvements in the group with SGs.
[43]	Post stroke	Yes	Poor. s.	No	No	10 healthy patients	Useful tool to motivate the patient.
[60]	Shoulders rehab.	No	Part. s.	No	DTW Fuzzy L.	4 healthy subjects, 1 therapist	No results on real patients, good usability results.
[61]	Generic	No	Part. s.	No	DTW	2 healthy subjects	Platform for remote monitoring using DTW, no particular results.
[62]	Stroke	Yes	Fully s.	No	Rule based	12 patients	High adherence, effective system.
[63]	Elderly	Yes	Fully s.	Yes, not specified	No	None	Exer-games based platform with remote customization. No particular results.
[64]	Stroke	No	Supported	No	Rule based	4 post-stroke patients	Benefits for patients, other investigations are needed.
[65]	Hip replacement	No	No	HMM	HMM	2 patients and 10 healthy subjects	HMM seems reliable to find real time errors.

[66]	Generic	No	Fully s.	No	Rule based	10 healthy subjects	No particular results, they focused a lot on estimating the quality of the measured raw data.
[67]	Upper limbs	Yes	Fully s.	Rule based	Rule based	10 patients	Usable, enjoyable end effective (from patient's questionnaire).
[68]	Upper & lower limbs	No	No	Rule based	Rule based	None	Three-tier architecture with wearable sensor & mobile device, no relevant results.
[69]	Ortho-pedic rehab.	Yes	Fully s.	Yes, not specified	Rule based	42 patients	Good usability and acceptance of the system and exer-games.
[76]	Knee rehab.	No	Sup-ported.	Rule based	Rule based	4 healthy subjects	No relevant results.
[77]	Generic	No	No	Rule based	No	None	No relevant results.
[78]	Elderly	No	Part. s. & DDA	No	DTW	10 healthy people (not elderly)	DDA improves the users' score and the quality of the exercises.
[79]	Generic	No	No	Rule based	No	14 healthy subjects	System assessments 75% consistent with therapists, necessary tests on patients.
[80]	Physical rehab.	Yes	Poor. s. & DDA	No	No	4 experts	No relevant results, a more exhaustive evalua-tion is required.
[81]	Hand rehab.	Yes	Poor. s.	No	No	None	No relevant results.
[82]	Stroke	Yes	Part. s.	No	No	14 post-stroke patients	Significant correlations between game scores and standard clinical outcome measures.
[84]	Stroke	No	Sup-ported	No	Rule based	Over 20 patients	Positive feedback from therapists and patients.
[85]	Upper limb rehab.	No	Poor s. & DDA	No	No	26 healthy subjects	Good usability tests, immersive experience, more tests needed.
[86]	Upper limb rehab.	No	Sup-ported	No	No	12 healthy subjects & 6 patients	Good usability tests.
[88]	Stroke	Yes	Sup-ported	No	No	1 post-stroke pa-tient	No relevant results, other tests are required.
[91]	TBI	No	Part. s.	No	DTW	6 healthy subjects	No relevant results.
[96]	Elderly	No	No	No	DTW	21 subjects, 3 experts	Strong relationship between DTW results and expert opinions.
[97]	Generic	No	No	IDTW	IDTW	2 users and an expert	Their IDTW algorithm is very fast, and almost as reliable as DTW.
[100]	Generic	No	No	Rule based	DTW	NA	Platform designed for real-time monitoring and feedback to the patient.

[101]	Generic	Yes	Sup-ported	RNN	RNN	5 PD patients and 5 therapists	Excellent results, both in terms of usability and effectiveness.
[102]	Generic	No	No	No	Deep learn-ing	49 healthy sub-jects to create the dataset	Deep learning effective in classifying the quality of an exercise.
[103]	Generic	No	No	No	Deep learn-ing	10 healthy sub-jects to create the dataset	Promising results that demonstrate the applica-bility of deep learning in home rehabilitation.
[104]	Low back pain	No	No	No	Feat. extr.	20 patients + 20 control group	High acceptability and usability.
[106]	Generic	No	No	Yes, not specified	Rule based	3 physiotherapists, 4 adults, and 3 elderly	Good preliminary results on the basic operation of the system, positive feedback on usability.
[107]	Generic	No	Part. s.	Rule based	Rule based	5 healthy subjects	Results consistent with the views of therapists.
[108]	Stroke	Yes	No	No	No	10 healthy sub-jects, 4 experts	High usability, fun, probable difficulty of use by real patients.
[109]	Parkin-son's disease	Yes	Part. s.	No	No	9 PD patients	High usability, fun, other tests necessary for evaluating efficacy.
[110]	Motor dysfunc-tionali-ties	Yes	Fully s.	No	No	Tests in progress	Very well designed exergames, tests on patients in progress.

CHAPTER 3

Platform overview

At this point, the reader should now have a general idea of the requirements and problems that a home rehabilitation platform faces. Using the same key points described in the previous chapter, we present here a synopsis about our platform, its goals, and its architecture.

At the end of this chapter, the reader will have clear the general structure of the solution proposed, what problems have been addressed, and how we have tried to solve them. The detailed explanations on each of the points and problems mentioned will then be discussed in the following chapters.

3.1 Requirements and goals

The work conducted here is part of the development of the HoRe (Home Rehabilitation) project, carried out in collaboration with the Neurological Institute "Carlo Besta", in Milan. The goal of the project was to develop a platform to allow patients with multiple sclerosis to perform customized exercises autonomously at home. But as we will see, our solution has been developed to be flexible and also adaptable to other pathologies.

We started from the work carried out in the Rewire project, of which we maintained a few concepts and the game design of the exer-games, and further developed some features, including the motivational aspects (not only using exer-games but also designing novel solutions based on gamification and a new dynamic difficulty adjustment system) and the tools for the therapist to manage and assess patients.

More specifically, the platform should meet the following requirements:

- ***Exercises customization:*** patients suffering from multiple sclerosis can have different levels of impairment. A high level of customization of the exercises is, therefore, a fundamental requirement to enable them to carry out rehabilitation safely and effectively.

- ***Safety:*** the required platform allows autonomous rehabilitation at home, there is no real-time monitoring by the therapist, neither remotely nor in presence. It is then necessary to provide a set of tools that automatically monitor the patient in real-time, minimizing the likelihood of injury, falls, and posture errors.

- ***Patient assessment:*** therapists should have the ability to evaluate patients remotely, without having to visit or summon a patient repeatedly to the hospital. For this purpose, to speed up their work, two levels of granularity have been requested: a detailed visualization, to be able to review each exercise performed, and a general visualization, giving the possibility to analyze the patient's progress over time.

- ***Motivating:*** it should provide an environment as stimulating and fun as possible. For this purpose, an approach through exer-games, and other game design solutions, must be adopted to try to keep motivation high even in the long run.

All tools available to the therapist should be usable remotely, without having to go to the patient's home and without the need to interact with him/her. So that the therapist can comfortably manage the entire rehabilitation cycle remotely. We remark here that this does not rule out but complements periodic clinical assessment visits and periodic rehabilitation sessions carried out in the presence of the therapist.

The platform described here is designed as a means to extend the rehabilitation at home, minimizing the social impact on one side and increasing the intensity of exercising on the other, still enabling the clinicians with asynchronous supervision.

In addition to these fundamental requirements, we can also add two further secondary requirements:

- ***Inexpensiveness and usability:*** the platform should be cheap and cost-effective and, above all, easy to use, to facilitate its diffusion and proper use. Therefore, complex, expensive, or intrusive devices (e.g., IMU sensors or motion capture systems) should be avoided.
- ***Flexibility:*** to facilitate the reuse of the system, each component in the platform should be as stand-alone and customizable as possible, so that it can also be used for the treatment of other diseases or in other projects with minimal effort.

We will now see, for each of these objectives, a detailed explanation, with eventually the approach used to achieve it.

3.2 Customization: exercises and exer-games design

In defining the exercises and corresponding parameters, we have followed the guidelines identified in the Rewire project and presented in [113].

The first phase consists of identifying, with the help of therapists, the rehabilitation indexes considered interested for the disease to be treated. These indexes are necessary both for the correct modeling of the difficulty of the exercises, but also in a correct evaluation of the patient's performance. In our case, for multiple sclerosis, *stability, amplitude, speed, strength*, and *accuracy* have been identified by clinicians as reliable indexes.

Starting from these indexes, a set of exercises can be defined. Each exercise trains the patient on one or more of these indexes. This work is carried out by therapists and experts and is essential to achieve safe and effective rehabilitation: exercises should be carefully selected and suitable for the patient's condition. Each disease may have different requirements. Therefore, indexes and exercises must be defined according to the needs and types of patients.

Then, always following the guidelines illustrated in [113], primary and secondary objectives were identified for each exercise. Primary goals describe what the patient is requested to do (e.g., move to the right, ...), and they are closely related to the indexes; they are associated with a set of parameters called *exercise parameters* used to model the difficulty of the exercise. While the secondary goals describe how the exercise should be executed (e.g., constraints on the patient's posture to avoid maladaptation). Therapists can model aspects of secondary goals through a set of parameters called *monitor parameters*, which ensure that the exercise is performed correctly.

All the above-mentioned aspects are closely related to rehabilitation and have been identified thanks to the support of therapists. Once this basic knowledge has been defined, exercises can be integrated into a suite of exer-games. We would like to remind the reader that an exer-game should be a full-fledged game and should contain all the main elements of a video-game. Careful game design has a significant impact on patient motivation. The aspects related to games and their design are called *game parameters*.

Three types of parameters are therefore available. The exercise and monitor parameters are associated with the difficulty and quality of the exercise, while game parameters are related to the game and mechanics.

To facilitate the reuse of exer-games and game scenarios, accelerating development and giving more options to the patient, an exercise can be associated with one or more video-games and vice versa. The couple $<e,v>$, where e is an exercise and v a video-game, uniquely identifies an activity.

Therapists use exercise, monitor, and game parameters to adapt the exercise to the patient's current characteristics. From this set of elements, an activity is defined as follows:

Definition 1. *An activity can be represented as a tuple* $\langle e,\ v,\ p_e,\ p_g,\ p_m\rangle$, *where:*

- *e is the rehabilitation exercise,*
- *v is the video-game that will be played,*
- p_e *is the set representing the exercise parameters,*

- p_g *is the set representing the game parameters,*

- p_m *is the set representing the monitor parameters.*

An activity allows us to uniquely identify the exercise and the game that will be performed, together with their parameters. From now on, we will also use the generic term “exer-game” to refer to an activity. From this definition, we can derive the concept of *schedule*: a schedule is a set of custom activities assigned to a patient. It contains all the information needed to complete a rehabilitation session.

For the sake of clarity, Fig. 3.1 illustrates a summary scheme of the concepts just described.

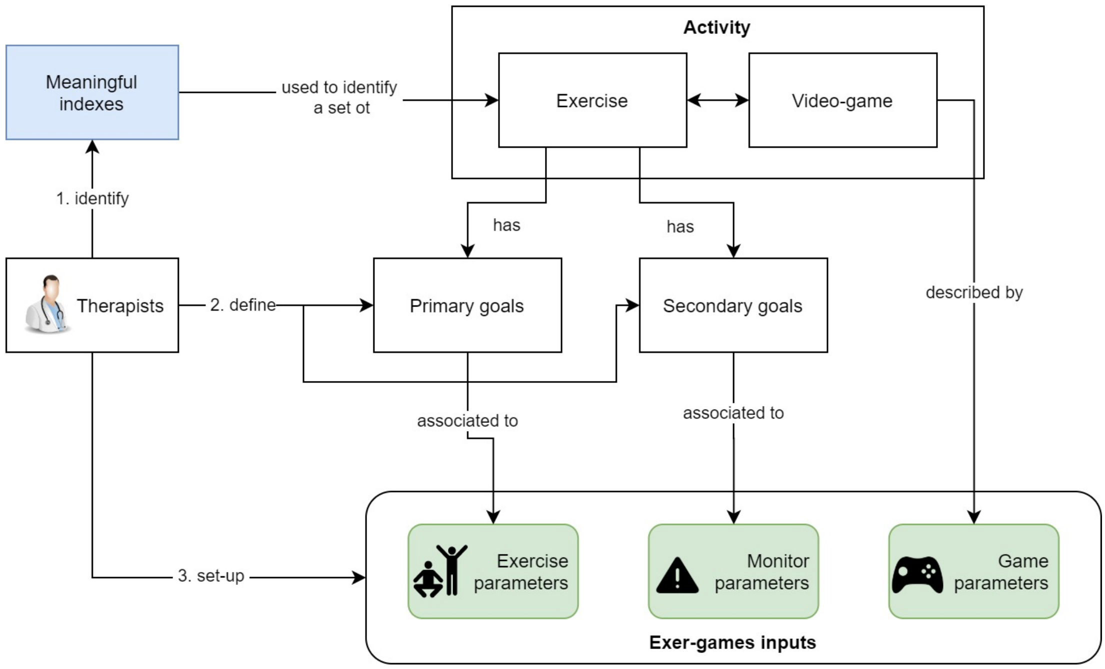

Figure 3.1: *Exercises modeling: starting from the indexes identified by therapists, a set of exercises is defined. An exercise is then associated with one or more games (and vice versa). Three types of parameters are available to therapists to adapt the rehabilitation to the patient’s needs: exercise, monitor, and game parameters.*

3.2.1 Exercises progression

The set of exercises considered should encompass the rehabilitation program that moves from less challenging exercises to more challenging ones. The need to find a framework that captures this progression was first identified by the group of de Bruin [114], who introduced Gentile's taxonomy [115] for this aim.

The taxonomy of Gentile is represented through a two-dimensional table, containing tasks of increasing difficulty, with the aim of improving the acquisition of motor skills. Gentile, in particular, for the difficulty classification of tasks defined two dimensions: the environmental context and the action function. The first refers to the conditions in which the exercise is performed (stationary or moving conditions, and presence/absence of intertrial variability). The second, instead, is characterized by the body orientation that indicates whether an action requires the patient to move (body transport) or not (body stability), and the presence or absence of an object to manipulate. Sixteen different conditions of increasing difficulty can be generated through the combination of the two dimensions, to each condition can be associated with a particular exercise, and consequently, in our case, a particular exer-game.

In this work, we preferred to use a simplified progression in the exercises identifying exercises that gradually require a greater degree of mobilization of the body segments. For postural rehabilitation, the domain addressed in MS, this goes from standing still to steps in all directions.

3.2.2 Exercises

A set of exercises has been chosen with the help of therapists, each exercise has particular characteristics that serve to train one or more primary goals. Below is the list with a brief description of all available exercises.

- ***Stand Still:*** one of the first exercises that are performed, as well as the simplest. The patient should stay as still as possible, trying to keep the pressure center in the center, avoiding overloading the unimpaired limb. It helps to improve stability.

- ***Weight Shift Lateral & Weight Shift Frontal & Weight Shift 360°***: the patient must move the center of pressure on the right or on the left (*Weight Shift Lateral*), forward or backward (*Weight Shift Frontal*), or along several directions (eight equally spaced directions in our case - *Weight Shift 360°*) to reach targets. The distance reached by the patient represents the amplitude of movement, while oscillations perpendicular to the direction of movement reflect instability.

- ***Lift Legs & Lift Legs Instantaneous***: the patient must raise and lower the legs, one at a time. In the first case, the patient has to maintain the position for a prolonged time (e.g., a couple of seconds), while in the latter, he/she has to reach a certain height, and then the leg can be lowered immediately. Also, in this case, the amplitude of movement is measured by the height reached by the leg, while the stability by the lateral oscillations made when the leg is raised from the ground.

- ***Steps Lateral & Steps Frontal & Steps 360***°: this exercise requires the patient to perform steps laterally, forward and backward, or in different directions to reach targets (in our implementation, we used eight equally spaced directions). In a similar way to the *Weight Shift* exercises, the amplitude of movement is represented by the maximum extension of the step, while the estimation of the center of mass is used to measure the oscillation during the movement.

- ***Sit to Stand***: the patient must sit down and get up from a chair located behind him/her. The main indexes of this exercise are the stability (measured during the lift and descent phase) and the lift speed.

3.3 Safety: real-time monitoring

The safety of the patient during home rehabilitation is one of the most critical points. Unlike traditional rehabilitation, where patients are always closely followed by clinical staff, who correct them in case of errors or hazards, preventing falls or incorrect postures, in our case, the patient can be completely alone. In some home rehabilitation platforms, the therapist can connect remotely and monitor the patient while performing the exercises, as if it were a video call. This solution, although technically valid and functional, would require the therapist to monitor all his/her patients, perhaps several times a week, requiring additional hours of work, greatly reducing the benefits of home rehabilitation. Moreover, it would require a fixed time to do a rehabilitation session that would greatly reduce the flexibility of this approach. Remote supervision by the therapist, although it may be useful in some cases, should at least be supported by automatic systems that help the patient in the correct execution of the assigned exercises.

To ensure patient safety, the fuzzy system described in [113] has been integrated. This system analyzes movement features (e.g., the center of pressure, joints positions and rotations, ...) in real-time. Following what has already been explained in the definition and modeling of the exercises, the behaviors deemed dangerous have been identified by the clinicians. These have been termed secondary goals [113], and from here *monitor parameters* have been derived (Fig. 3.1). By changing these parameters, the therapist can adapt the sensitivity of the monitoring system.

While the patient is rehabilitating, the system provides real-time feedback: an avatar, inspired by the Wii-Fit Avatar, representing the player is shown during the game, each body segment has a color representing the posture quality of that segment, the color ranges from green (good posture) to red (wrong posture), passing through the intermediate colors (orange/yellow), according to the severity of the posture error. In case of danger, the system can pause the exer-game and the virtual therapist pops up to advise the patient on how to avoid hazards. In the most dangerous cases, the system will close the game to avoid bad consequences. A meticulous setting of all parameters by therapists is necessary to achieve the best result and prevent the patient from posture problems.

3.4 Patient assessment

Particular attention has been given to the analysis of the results, a functionality that had not been developed in the Rewire project, to allow therapists to have the necessary means to better manage the rehabilitation process. A rule-based approach has been adopted, thanks to the collaboration with therapists, a set of rules have been defined for the extraction of metrics that allow understanding the quality of the execution of each exercise.

Compared to many other works in the literature, which provide only a detailed report for a single exercise, we have taken a step forward. Since a therapist may have a large number of patients, and a large amount of work, it is difficult to suppose that he/she can analyze each exercise performed during the week, as there may be tens or hundreds of exercises.

For this reason, we were asked to develop two separate views:

- ***A detailed view***: where the therapist can review every moment of each executed exercise, analyzing all the detailed information on all game performance, posture quality, and patient assessment.
- ***A global view***: where through summary graphs, it is possible to see the progress of the patient in the last weeks or months, showing the variation in primary goals. Should the therapist notice anything unusual from these charts, he/she may decide to review the session in question for additional information.

The combination of these two views should ensure sufficient accuracy and amount of information, but at the same time avoid the therapist having to manually control all the exercises performed.

In Fig. 3.2, it is possible to see an example of a detailed graph (on the left) and an example of a global graph (on the right). The detailed graph represents the front/back oscillation of the patient in a specific exercise, in this case, *Weight Shift Lateral* (the lower the oscillation on the antero-posterior axis, the better the quality of the exercise), while the global graph shows the lateral oscillation of the patient over a long period in as many as three exercises, allowing to group metrics common to several exercises, making it easier for medical staff to understand.

The graphs are created using the raw data of all the connected devices. In case both an RGB-D camera and a balance are present, we will be able to carry out a complete evaluation; when one of the two devices is missing, part of the information is lost, and some metrics cannot be extracted. Patient evaluation will be discussed in detail in Chapter 5.

3.5 Motivation: exer-games and game design

We have repeatedly stressed the need to provide the patient with an entertaining environment that can keep him/her motivated for as long as possible. Intensive, daily rehabilitation can be tiring in the long run, especially if there is no visible improvement.

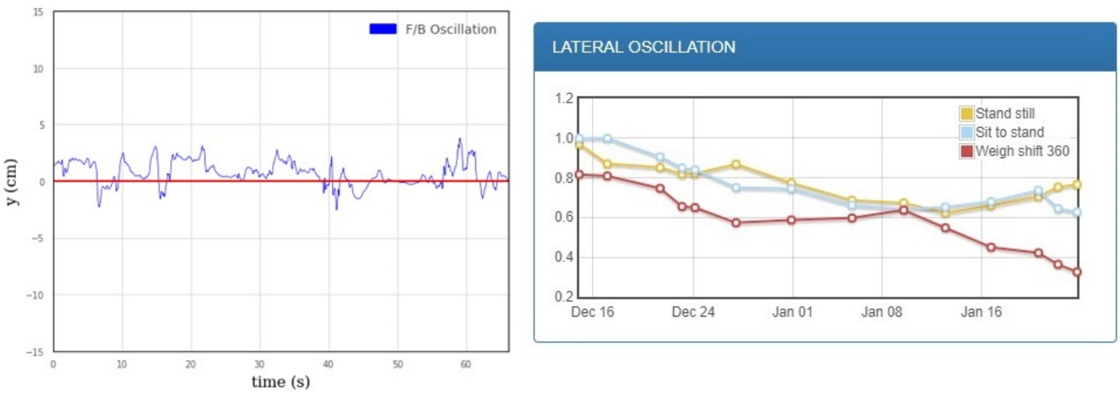

Figure 3.2: *On the left, the detailed view of the front/back oscillation in a Weight Shift Lateral exercise. On the right, the global view of the lateral oscillation of the patient in the last weeks in three different exercises.*

For this reason, we have developed a series of solutions in an attempt to stem the abandonment or reduction of adherence to therapy.

First of all, following the line initially dictated in the Rewire project, the exer-games approach has been exploited. We have revamped and modernized the games previously developed in Rewire to be more easily manageable, which implement the previously mentioned exercises. We have taken into account all the aspects of a video-game, not only the exer-games themselves, but we have also taken care of all the "secondary" aspects, such as quality and complexity of the user interface, sound effects and music, graphics and style, and simplicity of use, to provide a tool that is easy to use even for those less accustomed to technology.

Unfortunately, exer-games alone, although more fun than traditional exercises, usually due to the simplicity of their game mechanisms, could bore the patient after a while. For this reason, we also implemented additional game design solutions to try to further increase the engagement of patients:

- ***Dynamic Difficulty Adjustment***: the previous automatic adaptation mechanism [116] featured in the Rewire project has been completely redesigned and improved. It is now based on three distinct factors: the patient profile and abilities, his/her feelings, and real-time game performance. Using this information, it automatically adapts the parameters of exer-games, allowing you to adjust the difficulty according to different factors, better adapting it to the needs of the patient.

- ***Gamification***: a “game above games” has been developed, used as a glue among all activities. The patient manages a farm, by performing an activity, he/she earns points that can be used to extend the farm or by purchasing new items. This should stimulate patients to play exer-games, thus increasing adherence to therapy.

- ***Empathic Virtual Therapist***: to better support and motivate the patient, a new virtual therapist has been developed. Unlike the therapist available in the Rewire project, whose functionality was limited, the new avatar is empathic, therefore able to express different emotions, to try to establish an emotional connection with the patient. With the possibility, in the future, to detect the patient’s emotions and to automatically adapt the exer-games according to them.

Given the great attention we decided to pay to all these motivational elements, the entire Chapter 6 is dedicated to them, where all the details of the proposed solutions can be found.

3.6 Other goals

In addition to the requirements just mentioned, particular attention has been paid to many other aspects of the platform, in particular from the point of view of usability and cost-effectiveness of the system, to achieve good user-friendliness, and to ensure a possible widespread distribution to those who need it. Not to mention flexibility and possible future developments in other areas.

3.6.1 Inexpensiveness and usability

To guarantee that technology can be used by a large number of people, we were requested to use off-the-shelf (which can be easily found at a relatively cheap price), not invasive, and easily usable devices, without long and complex set-up phases. Usability, in a software of this type that must be used for a long time and several times a week, is a fundamental aspect, the system must be as minimally invasive as possible, and simple and fast to use. It is clear that no one wants to use a platform that each time requires 20 minutes of setup to be used.

With these requirements, we ignored all wearable devices (too invasive and uncomfortable to wear) and our attention fell on RGB-D sensors and balances. Through these two types of devices, we have the possibility to detect the patient's joint with good accuracy and his/her pressure center, a fundamental parameter in the stability computation.

3.6.2 Flexibility

Although the platform has been developed for patients with multiple sclerosis, from the beginning, it has been designed to be as generic as possible so that it could also work with different types of rehabilitation. This flexibility can also be denoted in the definition of the exercises and their parameters, designed to be extended to generic exercises, not only for the disorder we treat. As we will see later, also other components of the platform, such as the analysis of the executed exercises, are highly customizable and modifiable by therapists according to their needs, with the ultimate goal of allowing the use of the platform also in other areas, not strictly related to rehabilitation for patients with multiple sclerosis.

3.7 Platform architecture

As for the architecture of the platform, we have maintained an architecture similar to that of the Rewire project, with a two-tier client/server architecture, whose client is named *Patient Station* and the server *Hospital Station*.

Patient Station (PS) is the software used by the patients at their homes. It is used in combination with a set of devices capable to record patient's motion information (e.g., balance boards or RGB-D cameras). The PS includes all the exer-games and exercises needed to undergo the rehabilitation program. It has been developed using the Unity game engine.

While the **Hospital Station** (HS) is a web server, used by clinicians through a web browser, providing all the requested features previously described, such as exercise scheduling and patient assessment. HS stores information about patients, their schedules, and all the exercises performed by patients. In this way, a clinician can program a rehabilitation session and review the results from any device supporting a browser.

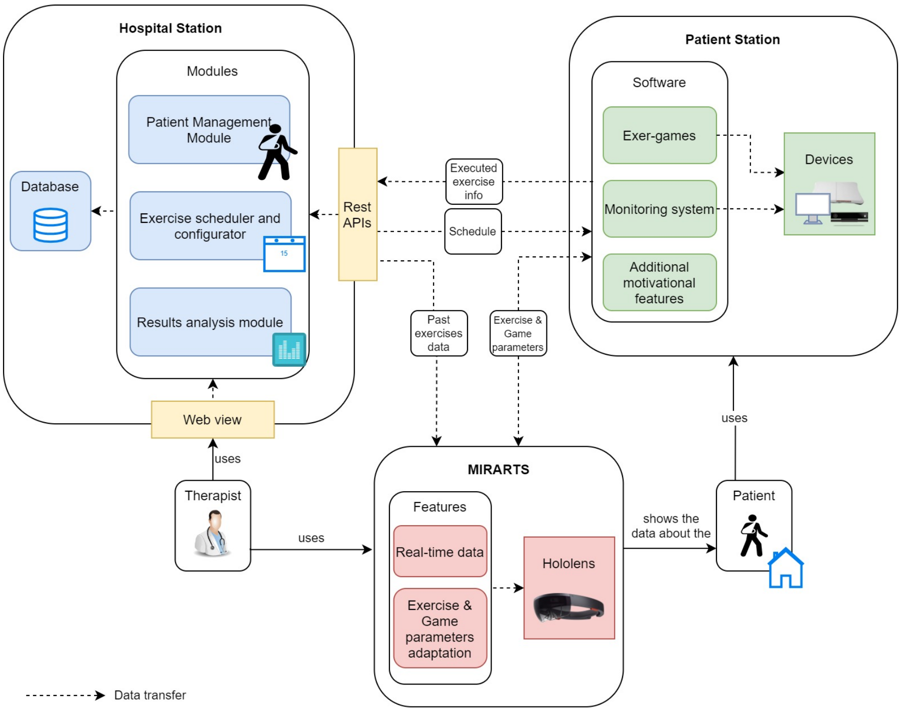

Figure 3.3: *High-level architecture of the system. The Patient Station, installed at the patient's home, guides the patient during the rehabilitation. The Hospital Station, used by therapists, allows them to manage their patients' rehabilitation programs. Finally, Mirarts, which provides support to the therapist in one-on-one sessions.*

In addition to HS and PS, also originally present in the Rewire project, we have also added a third component: **Mirarts** (MIxed Reality Adaptive Rehabilitation Therapist Station), a mixed reality platform to support the therapist in one-to-one rehabilitation sessions.

Fig. 3.3 shows the overview of the system architecture, with the main modules also illustrated.

In this picture, on the right, it is possible to see the PS, used by the patient at home, which receives the schedule containing the exercises set by the therapist. At the end of the session, all the data related to the executed exercises are sent to the HS, which will be processed, producing the predefined assessment metrics. Through the HS, the hospital staff can manage the entire rehabilitation cycle of patients (exercise planning, therapy adherence monitoring, patient assessment).

This type of architecture, developed with modularity in mind, allows the individual components to be reused in other rehabilitation areas. HS does not contain any information about the games in the PS and, in a very short time, it can be adapted to work with other games or other rehabilitation exercises, guaranteeing the flexibility required. Also the PS has been designed so that new games can be developed quickly.

At this point in the chapter, the reader should have understood the basic architecture and operation of the proposed platform, with a high-level view of the modules. Detailed information about PS and HS will be respectively described in Chapters 4 and 5.

3.7.1 Hololens integration

In addition to Patient Station and Hospital Station, we decided to go one step further: trying to take advantage of new mixed reality technologies, exploring their possible use by the therapist to increase the quality of rehabilitation in traditional one-to-one sessions with the patient. To this end, we have developed Mirarts, a visualization software designed for Microsoft's new headset: Hololens.

Mirarts provides the view of the identified evaluation metrics on the patient's posture. It has been integrated into the HS - PS architecture, not only it receives and processes data from connected devices, but thanks to the tight integration with PS, it allows the game parameters to be modified at run time, while the HS can provide in real-time the comparison between the quality of the current exercise with that of previously executed exercises. Mirarts has been designed to be used in the hospital, with or without the support of the home rehabilitation platform.

The whole Chapter 7 will be dedicated to Mirarts, with also a short introduction on augmented, virtual, and mixed reality.

3.8 Use cases

Before ending the chapter, let us see two typical use cases of the platform. The protagonists of these two use cases are Alice and Bob, two fictional characters with different backgrounds and needs.

Use case 1: Alice On one unfortunate day, Alice, a young woman, is diagnosed with multiple sclerosis. Alice has a job and does not have enough time to go to the hospital every week, several times, to perform rehabilitation. Her doctor, therefore, offers her the opportunity to undergo autonomous rehabilitation at home, which would save her a considerable amount of time, avoiding the need to travel to and from the hospital. Alice accepts, she is familiar with technology, she will have no problem using it. All the traditional examinations are performed in the hospital to verify Alice's physical capabilities. A short training period is carried out in the hospital, where the therapist teaches Alice how to use the Patient Station and how to perform the exercises correctly. Alice understands everything, and after a few training sessions, she is ready. During the training, the therapist has already tested and verified the difficulty of the exercises (also eventually using Mirarts), and, using the Hospital Station, has prepared a schedule suitable for Alice. Alice is then provided with a Microsoft Kinect and Nintendo Wii Balance Board, she already has a TV and a computer, so nothing else is needed. Alice starts doing the exercises, she understands how the platform works, follows the instructions of the virtual therapist, and performs the exercises correctly. The therapist, from time to time, checks the exercises performed, to verify the progress over time, Alice is stable, and there is no need to adapt the therapy. Periodically Alice goes to the hospital to carry out the clinically validated tests. The therapist, in this way, can verify her performance and compare it with those suggested by the home rehabilitation system. Eventually, he discusses with Alice problems or suggestions to help her in case of problems.

Use case 2: Bob Bob is an old man; he has been going to the clinic for a long time to carry out rehabilitation, but now for personal reasons, he is no longer able to make the home-clinical journey with weekly attendance. In order not to interrupt the rehabilitation path, his therapist offered him the opportunity to use the Patient Station, to try to take advantage of home rehabilitation. Bob, with some hesitation due to age and unfamiliarity with new technologies, decides to accept. Bob is taught how to use the platform; Bob's son is also taught how the system works, so he can assist his father in case of technical problems. Once he learns how it works, in addition to the two motion recording devices, Bob is provided with a computer and a new TV, because Bob's is old and cannot be connected to the computer. As soon as he starts rehabilitation at home, however, Bob is uncertain, he is afraid to perform fast or wide movements, he fears that without the therapist he might fall down; his performance is not good, he often performs the exercises in the wrong way, and the Patient Station often interrupts the game for safety reasons. Bob, however, does not want to warn his son or doctor. The therapist, after a couple of days, checks the condition of the patient, realizing that his posture is often wrong and does not achieve the required goals. She, therefore, decides to have an interview with Bob, who admits his difficulties; the therapist then chooses to reduce the difficulty of the exercises, at least in this first phase of acclimate. After a while, Bob has gained confidence, and the therapist gradually corrects the schedule, increasing the difficulty of the exercises, always monitoring Bob's performance.

These are two possible use cases that take into account two very different subjects: a young woman, accustomed to technology, and an elderly man, with little knowledge of computers. In both cases, with more or less difficulty, both users are able to carry out home rehabilitation safely.

CHAPTER 4

Patient Station

We want to begin to describe the platform from the *Patient Station* (PS). PS is the software designed to guide patients during rehabilitation sessions, and it is accompanied by a set of devices able to record and monitor the movements of the patient.

Our PS is strongly based on the work done in the Rewire project, in which an old version of the PS was already present [117]. Unfortunately, due to the now deprecated technologies that were used in the development of the old PS, we needed to develop the new platform from scratch. We have, therefore, re-implemented almost all the previously developed exer-games. Starting from this basis, we have then developed further game-design solutions in an attempt to entertain patients for longer. In this chapter, we describe the basic functioning of the new PS and its exer-games, while in Chapter 6, we will deepen all the solutions proposed for long-term motivation.

4.1 Requirements and goals

Although, as we have already seen in the previous chapter, HS and PS are closely linked, they have been developed to be flexible and to be used independently. For this reason, here we describe the requirements and goals that PS, intended as stand-alone software, without the accompaniment of the HS, must satisfy.

The PS is designed to be used at home, in a completely autonomous way (therefore, it does not provide a direct communication channel with the therapist), to guide the patient during the daily execution of the rehabilitation program, trying to keep motivation high for a long time.

To this end, it must meet the following requirements:

- ***Safe***: it should provide a system to reduce as much as possible potential harmful consequences due to incorrect posture. We would like to emphasize that the platform does not have the objective of being accessible to all patients: patients who are too compromised (e.g., severe or profound levels of impairment) or at high risk of falling cannot and must not use the PS, because it would be too dangerous and would put the patient's health at risk. PS could be able to detect falls, but not to foresee or to avoid them. For this reason, assuming its use by relatively autonomous people, it will only analyze the patient's posture and, in case, suggest how to correct it.

- ***Highly customizable***: the game and exercise experience provided by the PS must be customized according to the patient's needs and abilities. This can greatly increase the effectiveness of rehabilitation. Customization can be performed either directly from the patient or remotely from the therapist. In the HoRe project, given the serious pathology from which patients suffer, only the remote configuration is allowed by the therapist, and not by the patient; while in MoveCare, the elderly can choose the difficulty of the exercises from several predefined levels.

- ***Generates useful data***: it is necessary to record and store the patient's posture information obtained from the devices connected to the PS. It is also fundamental to also include all information resulting from interactions with games. All these data should be saved both locally and sent to the HS, where they will be stored persistently on the server. No kind of data processing is required from this point of view.

- ***Entertaining***: prolonged and daily rehabilitation can certainly bore the patient in the long run. PS should provide an interactive and fun environment, trying to limit monotony as much as possible. For this reason, exer-games are used instead of traditional exercises, together with other game design tools developed to entertain the patient.

- ***Flexible***: maybe this could be true of every software, but in our case, in particular, where there can be a lot of different patients and different clinicians with different ideas, having the possibility to easily adjust exercises and parameters according to patients' needs could be useful for the goal of developing a platform that can be applied to several rehabilitation areas.

- ***Easy to use***: we are currently focusing our attention on rehabilitation for patients suffering from MS, in reality, the platform, thanks to its flexibility, is easily adaptable, and it has also been used by the elderly in the European H2020 project MoveCare. Since, very often, these are people with very low IT knowledge, not very accustomed to the use of technological devices, the use of the platform should be as simple as possible, with clear instructions allowing the user to understand its use, to avoid frustration and possible problems arising from the poor knowledge of the system.

4.2 The Patient Station setup

The usual PS setup is illustrated in Fig. 4.1. With the term *Patient Station*, we refer only to the software used to guide patients during rehabilitation, not to the entire set of devices installed at the patient's home.

The setup includes a television (or any other monitor large enough to read at a distance of 2/3 meters), a computer running the Patient Station (a PC with a mid-range video card is enough), an RGB-D camera, and a balance board. The setup used in our pilot is composed of a mid-range desktop PC, the Microsoft Kinect 1, and a Nintendo Wii Balance Board. Although Microsoft has canceled support for Kinect, this will not affect the findings of this work. Kinect guarantees, under the appropriate lighting conditions, good reliability in recognizing the patient's joints

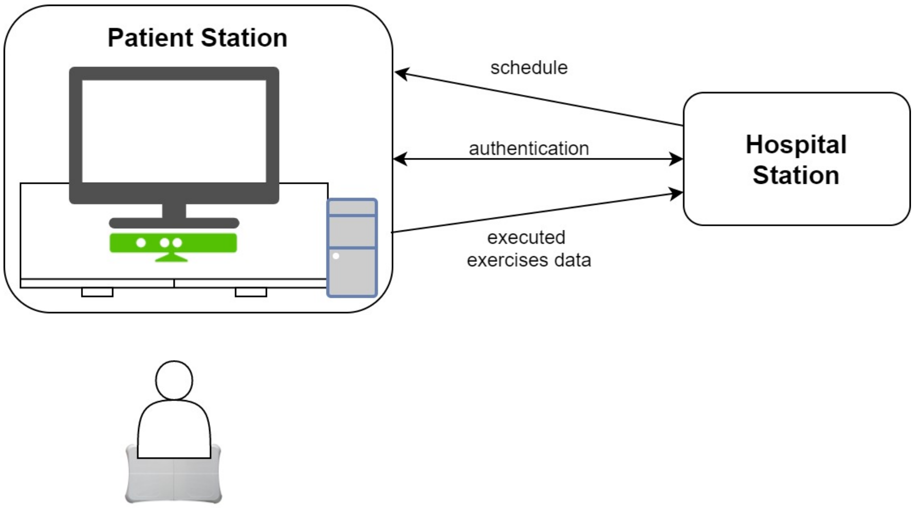

Figure 4.1: *Example of a typical Patient Station setup: television, computer, Microsoft Kinect, and Balance Board. An internet connection is also required to download the schedule prepared by the therapist and upload the data of the exercises performed.*

[21], and together with the Balance Board, capable to calculate of the pressure center (CoP), allow real-time monitoring of the position of each joint and the patient's balance. This information is used by the PS both to guide the patient during the execution of the games and by the HS to perform the patient assessment.

The Balance Board, in the case of the most compromised patients, can be dangerous and even lead to falls. For this reason, it can also be omitted, and the center of mass (CoM), used as an alternative to CoP, will be estimated by Kinect data. Currently supported devices are: Microsoft Kinect 1 and 2, Nintendo Wii Balance Board and TYMO® balance[1]. Since Kinect is out of production, integration with the Orbbec Astra camera is also underway to allow future use of the platform.

PS, although it can work independently, in our setup it also needs an internet connection to synchronize with the HS to download the list of personalized activities defined by the therapist and to upload the data of all the exercises that are played. The HS will process these data to provide therapists with the evaluation of the quality of the execution of the exercises. In this way, the patient is guaranteed to use the correct level of difficulty, and the therapist has the possibility to monitor the activities performed.

[1]TYMO® - Tyromotion, `https://tyromotion.com/en/products/tymo` (visited on 11/30/2020)

In this chapter, we will focus exclusively on the PS, HS will be described in Chapter 5.

4.3 Architectural overview

The basic architecture that we have identified to satisfy all the previously mentioned requirements is illustrated in Fig. 4.2. It is composed of four independent components, connected through the fifth component, the *Global State Manager*. The latter has the task of managing the entire flow of the application and has access to all the information necessary for correct operation: information on the patient, his/her schedule, and on the connected devices. It is the first module to be initialized, and which subsequently initializes the other components.

Below we will discuss briefly each of these modules, with the exception of Hannah, the Empathic Virtual Therapist (EVT), which will be addressed in Chapter 6. Hannah is an empathic avatar, in addition to guiding the patient in the correct execution of the exercises, it has been developed to try to create an emotional connection with the patient, with the aim of improving long-term engagement and motivation. For completeness, we could also add another component: the Farm Game. The Farm Game is an additional management game, external to the exergames, but strictly related to the physical activity of the patient, used to increase patient engagement. All the details, also in this case, will be described in Chapter 6.

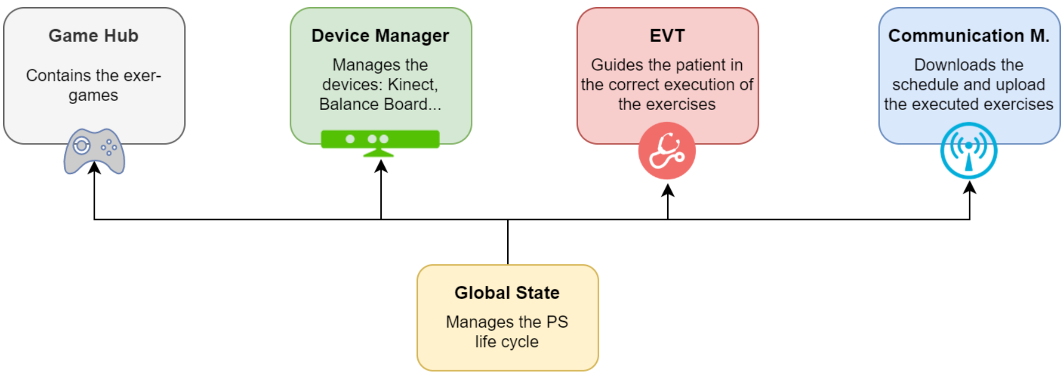

Figure 4.2: *Patient Station internal architecture: the Global State module is the main component, which coordinates and initializes the other modules.*

4.3.1 Software used

The PS has been developed using the Unity game engine. Unity is one of the most used game engines, definitely the most used in mobile and indie games, thanks to its ease of use, cost (free, in case you do not exceed a maximum threshold of earnings), the official asset store[2] (with a large amount of free or cheap assets), and a huge community, where it is possible to find help and support.

For these reasons, our choice fell on it, which is more widespread and simpler than its competitors, like Unreal[3]. Given the absence of modelers and graphic designers in the development team, most of the 3D models in the game have been downloaded from the store, while others are old models created during the Rewire project.

The programming language currently supported by Unity is C#.

4.3.2 Game Hub

The Game Hub module is the initial module which welcomes the patient and guides him/her through the various activities.

It mainly consists of two phases:

- **Calibration**: when starting the PS, all devices selected by the therapist must be connected and calibrated before starting any activity. To allow flexibility depending on environmental and lighting conditions (and minimize problems with photosensitive devices such as RGB-D cameras), it is possible to configure the distance to the TV at which the patient should be positioned.

- **Game selection**: once the calibration of the devices is completed, the patient is shown the screen with all the games available in his/her program (Fig. 4.3), which is updated every time the PS is started, if the internet connection is available. From this scene, it is also possible to access all possible additional features not included in the exer-game, like the Farm Game.

[2]Unity Asset Store, `https://assetstore.unity.com` (visited on 11/30/2020)
[3]Unreal Engine, `https://www.unrealengine.com` (visited on 11/30/2020)

Figure 4.3: *Game selection menu: from this screen the patient can select the new exer-game to play, play additional features like the Farm Game, or close the PS.*

Interaction and UI design

The interaction between the patient and the PS (but in general with many home rehabilitation platforms) does not take place via mouse and keyboard, because it would require the patient to move continuously from the gaming position (generally positioned between two and three meters from the TV, to ensure proper operation of the RGB-D camera) to the position of the peripherals. The alternative solution that we adopted consists of using the hand as a cursor (that we have called *NUI Cursor* - Natural User Interface Cursor), the movement of the hand will command the virtual cursor. It would also be possible, especially useful in the absence of an RGB-D camera, to use an air mouse, a type of device similar to a TV remote control, which allows moving the cursor.

The absence of a mouse and keyboard, combined with the use of the hand as input, requires some attention in the development of the user interface. We have established some guidelines to follow during the design and development of the platform:

- ***Interface***: since patients are positioned far from the screen, bigger cursor, texts, images, and all the user interface elements need to be larger to ensure readability. It is necessary to develop a user interface that is more similar to a tablet's interface than a PC's.

- ***Input***: the inputs are a critical part of the interaction with the platform: RGB-D cameras tend to be unreliable in hand detection, especially in sub-optimal light conditions. For this reason, the buttons and, in general, all interacting elements must be large enough to be pointed and selected in a simple way. They must also be distant from each other to avoid unintentionally selecting the wrong element. Clearly, without a mouse, there are no traditional inputs (left-click, right-click, ...). Modern RGB-D cameras are reliable enough to detect hand gestures; however, some patients may have problems with certain movements. For this reason, it was decided to simplify the interaction as much as possible, limiting it to hand movement. The click is then simulated by placing the virtual cursor over a button and holding the position for a couple of seconds. Furthermore, as soon as the patient's hand becomes the primary input device, there is a possibility that the patient may unintentionally click a button, perhaps when he/she is distracted and is not looking at the screen. To minimize this risk, the hand pointer is automatically disabled if the patient's hand is above his/her hip.
- ***Avoiding Gorilla arm syndrome***: this can be a critical part of the design. Playing for a prolonged time with the arm lifted without any support can lead to the "Gorilla arm syndrome" [118], and players start to report fatigue or pain. One of the possible solutions to avoid it is to alternate phases in which patients use their arms to control the game and phases where they can rest (in our case, this corresponds to the execution of an exer-game). A good balance between the two phases should significantly reduce pain.

These are the basic design rules that we believe are necessary to ensure an adequate experience. The interaction with the PS, although it may seem a minor topic, plays an important role in the usability and acceptance of the platform. For this reason, great attention must also be paid in the design of the game interface.

4.3.3 The Device Manager

The need for continuous patient monitoring requires the use of different types of devices. Generally, the most common are RGB-D cameras, balance boards, or wearable sensors. And since for each of the named categories, there can be several devices (e.g., for RGB-D cameras think of Kinect 1, Kinect 2, Orbbec Astra, ...), it was decided to create a module specifically designed for the management and interchangeability of these devices, so that any replacement of an obsolete device with a more recent one requires minimal effort, allowing better flexibility. This module, responsible for the entire life cycle of the devices, is the Device Manager. It deals with the connection and disconnection of the devices, but also with their calibration and the management of the recorded data, providing exer-games with a quick and easy way to access patient's movement data. In this way, if a new device is to be supported, it is sufficient to implement all the features required for its management. Two kinds of devices are available so far, depth cameras (Kinect 1, Kinect 2, ...) and pressure sensors (e.g., Wii Balance Board, TYMO, ...).

The Device Manager is also responsible for the possible aggregation or processing of data necessary for the correct functioning of the exer-games, as for the calculation of, for example, the center of pressure and center of mass, information that is not directly provided by the devices but that can be calculated from raw data.

4.3.4 The communication module

The last of the fundamental modules of which the PS is composed is the Communication Module (CM). The CM is responsible for managing all communication with the HS (or in any case with any web server that has features like the HS, and that meets the APIs of the PS). Its key features are a) the patient login, b) the download of the updated schedule, and c) the upload of all data recorded by the PS during the execution of the exercises.

Login The first fundamental step in using the platform is the creation of the patient's account, which is performed by the therapist in the HS, who then communicates the account data to the patient so that he/she can configure the PS. In this way, at startup, the PS can authenticate and receive the correct patient schedule, ensuring privacy and security for each patient; a key property, since we are also managing the transmission of personal biometric data. If the login is unsuccessful because, for example, the internet connection is missing or incorrect data has been entered, the last downloaded schedule will be used; if no schedule has ever been downloaded previously, the default settings are used for each exercise. The default settings guarantee correct functioning of the exercises at an average level. For this reason, their use with people with walking problems or suffering from other diseases is highly discouraged. Whoever takes care of the installation of the PS, should also verify that the first login is successful, so as to have at least one schedule suitable for the patient.

Schedule download Once logged in successfully, the last updated schedule is automatically downloaded before running any exer-game. The schedule is transferred in JSON format, and it includes all the exercises with the respective parameters set by the therapist.

Exercises upload At the end of each exercise, the PS produces a zip file containing all the information on the exercise performed. If the patient has logged in correctly when starting the PS, this zip file will be sent to the HS. This file is fundamental for therapists; from it, the HS can generate results and graphs representing the quality of the execution.

This zip file includes:

- *Patient username, date, and time*: used to be able to identify who perform the exercise and when (in case of no internet connection, it may have been performed days before).
- *Game and exercise performance*: game score and monitor activation percentage (i.e., the quality of the patient's posture).
- *Exercise, exer-game, and monitor parameters*: all activity parameters are sent to the HS so that they can be used during the exercise analysis.
- *Devices raw data*: each device creates a file containing the measured raw data, which will be processed by the HS, together with activity parameters.

All this information and files are compressed and sent to the HS, where they will then be uncompressed, analyzed, and stored in the HS database. The communication module also has the task of saving, locally and persistently, any files that it has failed to load, for example, due to the lack of connection. At the next startup, the PS, after checking the internet connection and logging in, it will try to send them again.

4.4 Exer-game structure

After explaining the main modules, let us now see how the exer-games are structured. As we will see, all exer-games have some parameters and functions in common, which define a basic structure that will always be followed.

4.4.1 Basic structure and requirements

In Paragraph 3.2.2, the available exercises have been illustrated, now their mapping onto the corresponding video-games will be described. Recall that there is no one-to-one relationship between an exercise and a game: it is possible that a game allows the execution of multiple exercises, and vice versa, i.e., an exercise can be mapped onto multiple games. In our case, for example, the *Weight Shift Lateral* and *Steps Lateral* exercises are mapped onto the same game. In the first case, the patient will have to move the center of pressure laterally; in the second case, he/she will have to take a lateral step to reach the target. The game is substantially identical, only the exercise changes.

Each game follows a basic structure, shared by all exer-games, also useful for the patient to get used to the platforms quickly. Let us now see the common points from which the exer-games are composed.

Trials and Repetitions When exercising (e.g., in the gym), a basic rule is to perform a series consisting of a certain number of reiteration of a movement, and, in the end, take a break and recover the energy, waiting for the next series. Exer-games are structured in this way: each of them is divided into **Trials** and **Repetition**.

A trial is the single execution of the movement required by the exercise. For example, if the exercise requires to take a step in a direction, the execution of the step is a single trial. A trial is connected to a particular goal, it can be reaching an object or a position, for example, we call this "target". If the target is reached, the trial is completed successfully (**Hit**); otherwise, it is failed (**Miss**).

A score is associated with each execution of an exer-game, reflecting the patient's performance: the score is raised (in case of hit) or lowered (in case of a miss) at the end of each trial. A set of trials is called repetition; the therapist can set the number of trials for repetition. To allow the patient a short rest, as already said, there is always a short break between two repetitions, the duration of which can also be set by the therapist. The latter can also set the number of trials per minute, to speed up or slow down the game. These three parameters are always present in every exer-game.

Monitoring system Another shared feature, configurable by the therapist, is the real-time monitoring system. When activated, it monitors the patient in real-time, interrupting the game when necessary. In addition, a score multiplier is associated with the patient's posture, the higher the quality of posture, the higher the multiplier. In this way, the patient is stimulated to maintain the correct posture as possible.

Bonus and cognitive trials To further stimulate the patient, also from a cognitive point of view, special trials are included. For example, the *Bonus trial*, generally represented through a golden target, of greater difficulty, guarantees double the points, and it is used to make gameplay less monotonous. The *Cognitive Trial* is also available. This special type of trial must be avoided by the patient (e.g., a rotten apple that should not be taken). In this way, we can speak of *Dual-task*, because in addition to the physical objective there is also the cognitive one to recognize and avoid negative targets.

In general, each exer-game is designed to entertain the patient, so another common thing is the presence of "variations", surprise elements, which aim to reduce boredom (e.g., animals running in the background). The exer-game score, which is always shown both during and at the end of the exercise, calculated based on the number of targets reached and the quality of the patient's posture, is also a stimulus for the patient to overcome himself/herself.

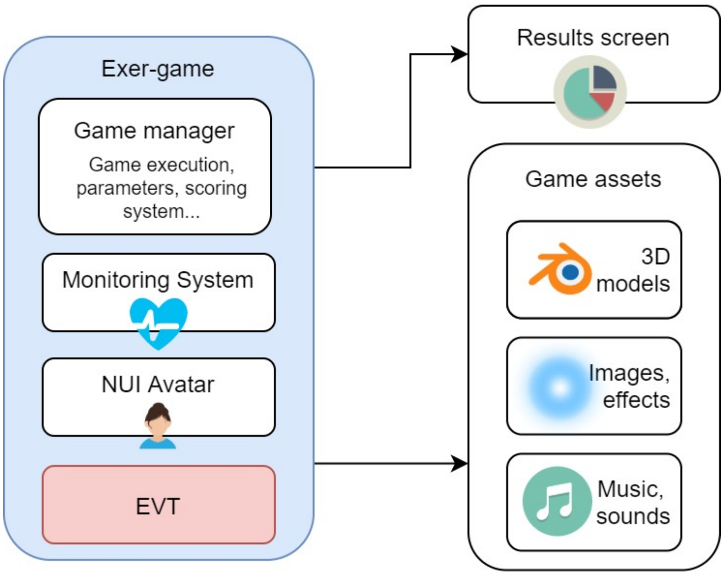

Figure 4.4: *Architecture of an exer-game with the most important components. We have tried to define a common structure shared by each game, to facilitate the learning curve of the patient.*

Attention was also paid to sounds and audio, for example, by adding motivational effects (e.g., people applauding) played at positive events (e.g., point records).

4.4.2 Components

Starting from the basic structure and design requirements just exposed, we now briefly describe the structure and components of an exer-game.

In Fig. 4.4, it is possible to see the components related to an exer-game. The main components will be analyzed individually in the following paragraphs. The main module is the *Game Manager*, which controls the execution of the game and keeps track of all the parameters necessary for correct execution. It also deals with the creation of the scene and the game itself, and to do this, a certain amount of assets is needed, which can include images, 3D models, animations, particle effects.

In each game, the player is represented through an *avatar*, which can be humanoid, in the presence of the RGB-D camera, or an object, if it is not possible to detect the patient's joints.

The patient's joints and posture are constantly monitored thanks to the third component: *the monitoring system*. The monitoring system is present only inside an exer-game.

Outside the exer-games, we do not know what the patient is doing, and not having a global system capable of identifying postural problems of a generic position, it is not possible to know what rules to apply.

In case of incorrect posture, Hannah, the EVT, intervenes by giving advice. The accurate description of Hannah will be described in Chapter 6, dedicated to long-term motivation. As well as being a fundamental part of the exer-games and ensuring patient safety, as we will see, it is also an important element of motivation for the patient.

Finally, at the end of each exercise, a screen with the *Summary Results* of the exer-game played is shown (Fig. 4.5).

NUI avatars

One of the most important elements is the patient's avatar, called **NUI (Natural User Interface) avatar**. The origin of this name is because it is controlled by the connected NUI devices, RGB-D cameras, balance boards, wearable sensors, and so on. The avatar is of particular importance because it allows the player to identify himself/herself within the game, increasing the immersion and improving the experience.

When an RGB-D camera is present, a humanoid avatar is used. This avatar is animated according to the patient's movements, e.g., if the patient raises an arm, the avatar will also move congruently.

While, if it is not possible to access this information, and only the information from the Balance Board is available, an avatar that can be controlled via the center of pressure will be used. In this case, the avatar changes according to the type of game, and can represent, for example, a basket that moves sideways, or a stick that it moves horizontally and vertically.

At the end of the chapter, all games with screenshots attached are presented, where it is possible to see the different types of avatars.

The Monitoring System

The **Monitoring system** is the component responsible for ensuring the safety of the patient.

We used the system previously developed in Rewire (see [113] for details). This system includes a set of "monitors". A monitor controls a particular movement of the patient (e.g., the angle of the back) and warns the patient, also pausing the game in case of need, if he/she is performing a wrong movement.

Each exercise can have different types of monitors, which have been identified with the help of therapists, and they are tailored for patients with multiple sclerosis. A monitor has as input the information coming from the connected devices, this information is then processed through a rule-based approach, defined ad hoc for each monitor.

The output of a monitor is a value that represents the quality of posture related to the specific movement for which the monitor has been programmed. Each monitor has four threshold values with which the output is compared:

- *Green threshold*: if the output is below this threshold, the patient's position is correct; no action will be taken.
- *Yellow threshold*: the posture is incorrect, but it is not harmful to the patient, the exercise can continue.
- *Red threshold*: the game is interrupted; the virtual therapist appears, giving instructions on how to correct your posture. When the posture is corrected, the game can restart.
- *Danger threshold*: the patient's posture is so dangerous that the game is completely stopped and is no longer restarted.

The output color will then be applied to the patient's avatar, highlighting the part of the body that is having an incorrect posture.

The Results Screen

At the end of each exercise, a graph representing the patient's recent performance in that particular exercise is shown (Fig. 4.5). The graph shows the trend of the points earned. It has no rehabilitative value, nor does it aim to show the patient a clinical measure of his/her progress. It is designed as a self-assessment tool (although without clinical value) to encourage and motivate the patient.

The results screen is divided into two parts:

- On the left, some basic posture information is shown, such as the percentage of activation of the monitors, accompanied by a silhou-

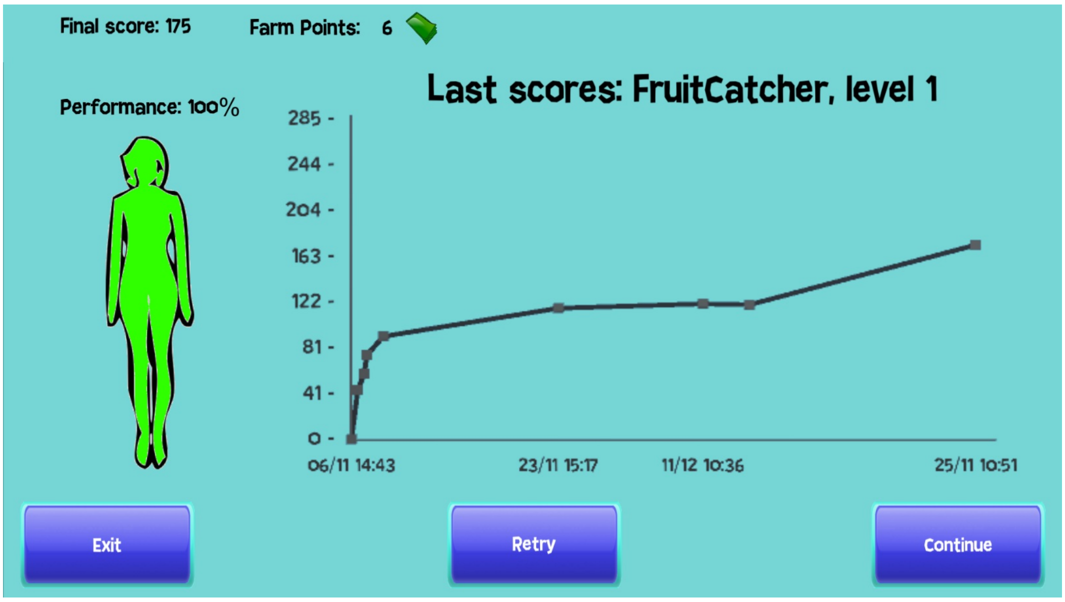

Figure 4.5: *The Results screen shown at the end of the execution of each exer-game. It shows a summary of the quality of the exercise just performed. It is possible to see both the quality of the patient's posture (left side of the interface) and the graph showing the scores obtained in the last executions of the exer-games (right side).*

ette whose color varies from green to red, to make it easier for the patient to understand the quality of his/her posture.

- On the right, the graph representing the trend of the Hit percentage for the exercise just played is drawn. For each day, the maximum percentage of Hit is shown to encourage the patient. In this way, negative performances will have no impact on the graph.

4.5 Developed games

The reader should now have a clear understanding of the application flow, the structure of the exer-games, and their characteristic primary elements. To conclude the chapter, let us now briefly see the list, with attached images, of all available exer-games. All the games presented here have been inherited from the Rewire project. The same game-design that proved successful with post-stroke patients has been maintained.

All games can be played with both Kinect and Balance Board. A subset of games has been adapted to work even only with the Balance Board and implemented in the MoveCare project.

4.5.1 Bubble

In *Bubbles* game (Fig. 4.6 on the left), the patient is personified by a stick inside a cauldron. The goal is to burst the bubbles that are generated in the eight directions. This game is associated with *Weight Shift Lateral*, *Weight Shift Frontal*, and *Weight Shift 360°* exercises. Due to the absence of a human-looking avatar, the game is also playable using only the Balance Board. In this case, the monitoring system, based on the patient's joints, cannot be used (this version of the game has been used in MoveCare). In the case is the Balance Board to not be present, CoM estimated using the data provided by Kinect is used to move the stick.

4.5.2 Scarecrow

Scarecrow game (Fig. 4.6, on the right) is associated with the *Stand Still* exercise, in which the patient is requested to stay as still as possible. Both the movements of the joints recorded by the Kinect and the oscillations of the CoP recorded by the balance board are used. Some Kinect unreliable joints (e.g., the hands) are excluded to prevent inaccuracies of the device from compromising the patient's performance. Compared to the other games, where a single trial is easily identifiable, here a trial is represented through a period of time, ended this time if the sum of the movements is less than a determined threshold set by the therapist, a Hit will be obtained. The game can also be used with a single device; a version playable only with Balance Board is included in MoveCare.

Figure 4.6: *On the left, Bubbles: associated with Weight Shift exercises, the patient is requested to move the CoP to reach the targets. On the right, Scarecrow: associated with Stand Still exercise, the patient has to stay as still as possible to attract birds.*

4.5.3 Pump the Wheel

Pump the Wheel game (Fig. 4.7, on the left) is associated with *Lift Legs* exercise. The goal of the game is to inflate the wheel of a tractor. To do this, the patient uses a pump, activated with the movement of the legs. By raising and lowering the legs, alternating right leg and left leg, once the patient reaches a certain height threshold defined by the therapist, the pump is activated, and a Hit is obtained. In doing so, patients must also maintain a good level of balance, avoiding moving too much left and right. This game is played only with Kinect, without Balance Board, for safety reasons.

4.5.4 Animal Hurdler

In *Animal Hurdler* (Fig. 4.7, on the right), the patient must raise his/her legs to avoid animals walking towards him/her. This game is associated with the *Lift Legs Instantaneous* exercise. Also here, as in the previous exercise, the therapist defines the minimum height the patient has to reach, which will reflect on the size of the animals: the larger the animal, the greater the height required to enslave it. The difference with *Pump the Wheel* is that here the patient must maintain the position with the leg raised for a longer time, waiting for the animal to leave. As in the case of the previous exer-games, also this game is played without the Balance Board.

Figure 4.7: *On the left, Pump the Wheel: associated with the Lift Legs exercise, the patient must raise and lower the legs simulating the inflation of the tractor's wheel by means of a pump, activated with the movement of the leg. On the right, Animal Hurdler: the patient must dodge some animals, to do so he/she must alternately raise his/her right leg and left leg.*

4.5.5 Fruit Catcher

In *Fruit Catcher* game (Fig. 4.8, on the left), the player has to catch apples that fall from the tree above him/her. To catch them, patients need to move under the apple, which will be taken from the basket placed on the avatar's head representing the player. Two exercises are associated with Fruit Catcher: *Weight Shift Lateral* and *Steps Lateral*. In the first case, the patient, standing on the balance board, will have to move his/her CoP to the right and left, while in the second case, the patient will have to take a single step in the direction of the apple. A version playable only with Balance Board is available to MoveCare users, where the player's avatar has been replaced with a basket. Also from the figure, it can be seen that part of the player's avatar is colored red. It means that at that moment the patient was assuming an incorrect posture, presumably due to excessive rotation of the back.

4.5.6 Firefighter

In *Firefighter* (Fig. 4.8, on the right), the patient has to extinguish the flames that are generated around him/her in 8 directions. To do this he/she must take a step, with one leg, and place his/her foot above the flame, which after a certain period of time, set by the therapist, will be extinguished. This game is playable only through Kinect and without the Balance Board, which could cause the patient to fall. It is generally associated with the *Steps 360°* exercise, but it can also be associated to Steps Lateral or Steps Frontal.

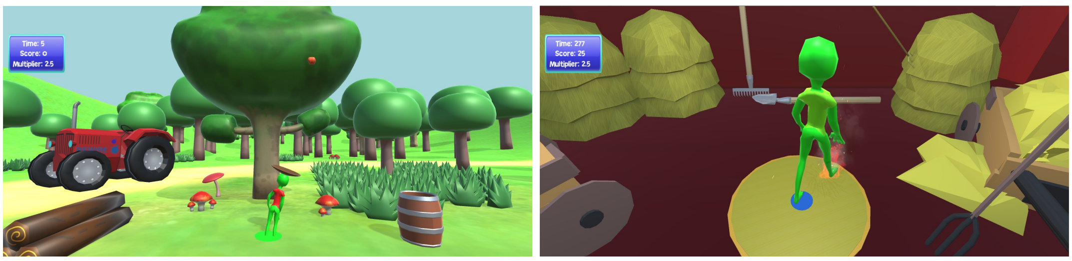

Figure 4.8: *On the left, Fruit Catcher: by moving the CoP sideways (Weight Shift Lateral) or taking a step (Steps Lateral), the patient must catch some apples that fall from the tree. On the right, Firefighter: the patient must extinguish the flames that are generated around him/her by taking steps and placing a foot over the flame.*

4.5.7 Horse Runner

In *Horse Runner* (Fig. 4.9, on the left), the patient's avatar is riding a horse, which runs along a predetermined path. The path and world of the game change with each execution of the game to increase variability. The exercise associated with this game is *Sit to Stand*. Along the way many trees and jars of honey are positioned, near a tree the patient must sit and avoid it, while he/she must get up when he/she is about to approach a jar of honey to take it. Also in this case, a version playable only with the Balance Board is available in MoveCare; to compensate for the absence of the camera, the player's avatar automatically gets up and sits down according to the weight loaded on the balance.

4.5.8 Hay Collect

Finally, *Hay Collect* (Fig. 4.9, on the right) game is associated with the *Weight Shift Lateral* exercise. In this game, the patient must drive a tractor to collect hay. He/she can move the tractor by turning right and left by moving the CoP in the desired direction. There are also some rocks in the hay field, positioned just before the hay, which must be avoided. Playable only with Balance Board, it is only available in MoveCare because it is considered too dangerous for patients with multiple sclerosis.

Figure 4.9: *On the left, Horse Runner: in the saddle of the horse, the patient must collect honey and avoid the branches of the trees, getting up and sitting down when required. On the right, Hay Collect: the patient controls a tractor by moving the CoP to collect hay and dodge rocks.*

CHAPTER 5

Hospital Station

The next topic we will address is the Hospital Station (HS), the system designed to be used by clinicians and therapists to manage all the phases of the rehabilitation cycle. In the hospital, clinicians work with patients and can see and analyze their physical condition, making them perform exercises suited to their abilities to make rehabilitation more effective and safe. They can also evaluate the patient's progress with their eyes and possibly modify the exercises or their difficulty according to the patient's needs. In home rehabilitation, this does not happen.

The therapist may not see the patient for several weeks as the patient exercises independently at home. For this reason, it is necessary to provide therapists with a tool that allows them to administer personalized exercises and remotely monitor the patient's progress. The software that takes care of this task is the *Hospital Station*.

5.1 Requirements and goals

The HS tries to bridge the gap between traditional rehabilitation and home rehabilitation, providing all those tools necessary for the therapist to make decisions about the patient, both as regards the scheduling of the exercises and for the analysis of the progress. It also provides the opportunity to verify adherence to therapy, which is a critical point in home rehabilitation; the greater the intensity and frequency of rehabilitation, the greater will be its effectiveness [119]. Often, the absence of a therapist and the total autonomy of the patient can lead to a decrease in motivation that reduces adherence, and this should be avoided.

The HS has been designed to be used in different areas, not only in postural rehabilitation. It can also be used with software other than PS. The general requirements it should fulfill are the following:

- ***Patient's management***: therapists should be able to take charge of new patients, their data (and any notes on their status), and their discharge.
- ***Exercise scheduling***: to increase the effectiveness and safety of rehabilitation, it must be possible to program highly personalized exercises for each patient, to schedule exercises suited to the abilities of each patient.
- ***Therapy adherence***: the adherence of the patient must be constantly monitored. The therapist must be able to easily verify that the patient is carrying out the rehabilitation program and be notified when this does not happen.
- ***Exercise analysis***: therapists should be able to verify the quality and correctness of the exercises performed by the patient, having both a detailed tool for the analysis of each exercise and an overview to quickly check the patient's progress.
- ***Flexibility***: flexibility is strongly needed. On the one hand, it should be easily possible to use HS in areas other than postural rehabilitation; on the other hand, regardless of the area of use, it should be easy to modify both the parameters of each exercise, as well as the graphs and the data that make up the patient's evaluation.

The HS is designed to be used exclusively by medical personnel. It is an instrument that can become relatively advanced and not easy to interpret or use. Therefore, the same ease of use required by the PS is not required.

5.2 Architectural overview

In Fig. 5.1, a representation of the internal architecture of the HS is shown. The main modules are three: a) the *Patient Management module*, b) the *Exercise Scheduling module*, and c) the *Results Analysis module*. These modules satisfy the requested features described above, providing the possibility to manage patients, schedule their exercises, and analyze their progress. We will then see each of these three modules in detail in the following paragraphs. Each module can be added or removed from the HS, depending on the therapists' needs. Secondary modules, not relevant from the scientific point of view, but necessary for proper operation, such as, for example, the notification system, will be described very briefly.

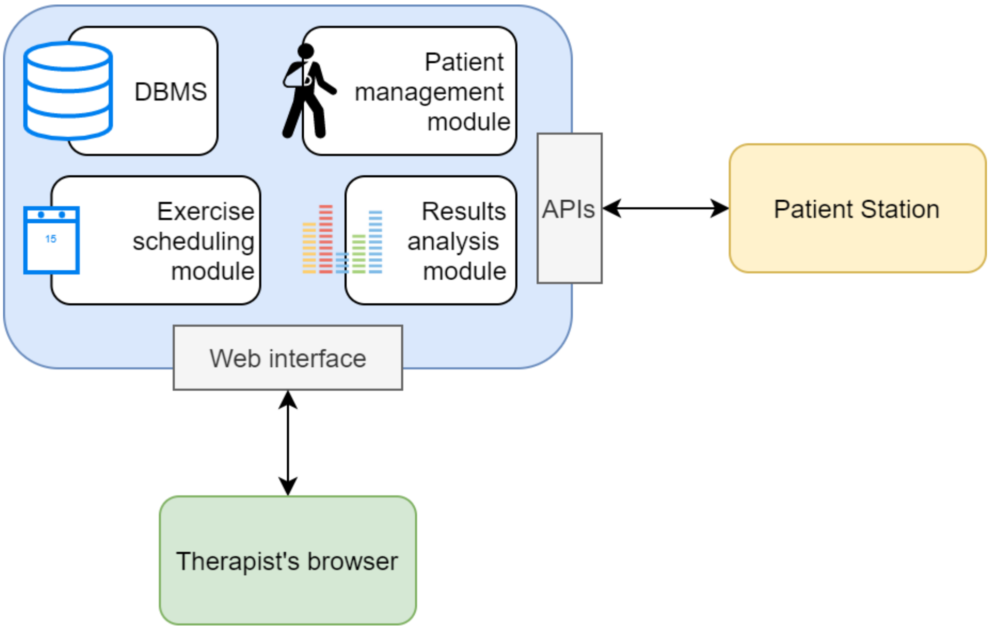

Figure 5.1: *HS architecture. Through a set of APIs, it communicates with the PS, with which it exchanges information concerning the schedule defined by the therapist and the exercises performed by the patient. While the therapist, through the web interface, accesses the HS services. Inside the HS, it is possible to see the main components necessary to provide the required features.*

5.2.1 Software used

Access to HS must be practical, easy, and fast. For this reason, it was decided to develop a web server that would offer all the functionality via the browser. Given these premises, the choice of the technology to use fell on the Django Project framework[1].

Django has many advantages. It supports Python, one of the most popular general-purpose languages, which allows integration with many libraries widely used in scientific field (e.g., numpy, matplotlib, ...). Django is also designed for fast prototyping, suitable in our case, where requirements have changed often. It is also very popular with an active community in case of need, and it lends itself well to modularization and code reuse.

In Fig. 5.2, a screenshot of the HS homepage is shown.

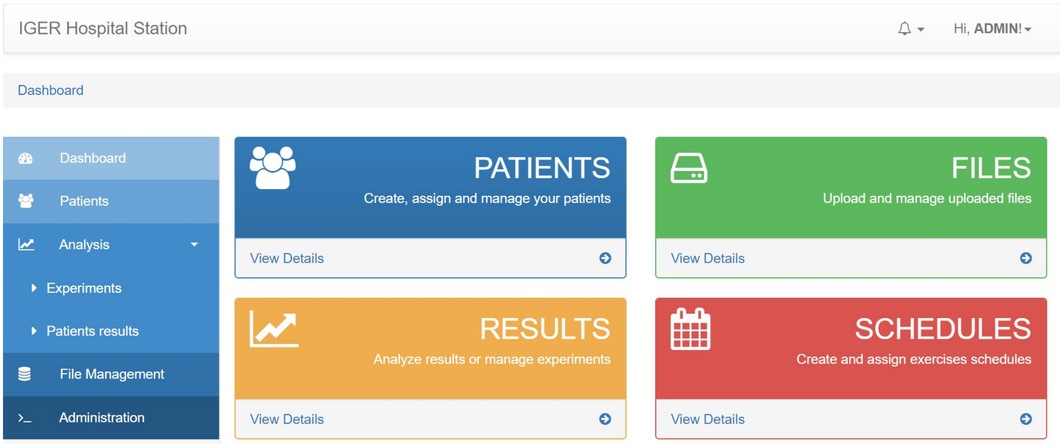

Figure 5.2: *HS homepage. From this page, the therapist can access all the main features of the HS, i.e., Patient Management module, Exercises Scheduling module, and Results Analysis module.*

5.3 Patients Management module

Let us start the description of the modules starting from the simplest: the *Patient Management module* (PMM). This module is used for the management of your patients, both for basic information such as biographical data and some slightly more complex features.

The main critical aspect of this module is data management and privacy. For this reason, to ensure the privacy of each patient, a two-tier authentication system is used. At the lowest level, there is the patient's account, which through the PS can only request its schedule and upload the exercises performed but has no other type of access to the HS. At

[1]Django Project, `https://www.djangoproject.com` (visited on 11/30/2020)

the upper level, there are the therapists accounts, which have access to all the features of HS. A therapist only manages his/her own patients; it is obviously not possible to see the information of patients in charge of other clinicians.

Then, above this system, the three main functionalities of this module have been developed, presented below.

- **Add a new patient**: when a new patient is taken care of by the therapist, it is possible to add him/her through this form. The therapist will fill in the patient's data and create his/her account, through which the patient can then connect using the PS. If necessary, in addition to personal data, the therapist can also change the password of the patient's account. Once the account is created, the therapist can start scheduling the exercises.

- **Discharge of a patient**: when a patient no longer needs to perform rehabilitation, he/she can be discharged; in which case his/her account will be hidden from the pages for scheduling the exercises and analyzing the results. However, it will always be visible in the PMM, in a separate section, ready to be reactivated if the patient needs to be taken back into charge.

- **Share a patient**: sometimes, it may be necessary for a patient to be followed by several therapists or for a therapist to ask a colleague for a consultation. In these cases, it is possible to temporarily or permanently share a patient with other doctors. New therapists will have full access to patient information, such as the patient's schedule and exercises performed.

5.4 Exercise Scheduling module

The second module we are going to describe is the *Exercise Scheduling monitor* (EMS). The EMS is mainly used for two functions: the scheduling of customized exercises for each patient and the monitoring of adherence to therapy.

The module is based on the concept of *Schedule*, which has already been defined in Paragraph 3.2. Resuming that definition, a schedule is a set of activities, where each activity is a pair <*exercise, game*> with all the related parameters.

Here we extend the definition of schedule, adding start and end dates, and mode. Through the starting and ending dates, it is possible to program multiple schedules in different periods, but only one schedule at a time can be activated. In this way, therapists can program different schedules for different periods and also have the assurance that a past schedule, perhaps no longer suitable, is not performed by the patient.

The schedule mode can be *Open*, in which the patient can play all the exercises as many times as he/she wishes, or *Close*, in which he/she can play only once for each exercise.

5.4.1 Schedule editor

To allow the patient to benefit from personalized exercises, adapted to his/her abilities, and that guarantee safety, the *Scheduler Editor* has been implemented. It gives therapists the possibility to create a new schedule or modify/delete an already existing schedule.

For each schedule, it is possible to define the set of activities that should be performed and, for each activity, all the parameters necessary for the correct definition of the difficulty.

In Fig. 5.3, it is possible to see the main page of the schedule editor. On this page, all the available activities are shown. On the left side, it is possible to see the games currently not included in the selected schedule; on the right side, the activities currently present in the schedule are shown. Therapists, through drag and drop actions, can add or remove activities. The activities are configured manually by the therapist, who is aware of the patient's status and can set the parameters to maximize the effectiveness of the rehabilitation.

The therapist, in the profile setting page, can decide whether to configure the editor with an exercise-based approach or with the video-game approach (as in the figure). In the latter, as shown in the figure, the editor, on the left, shows the set of video-games still available, and the therapist is required, for each exer-game, to choose which exercise will be associated (opposite behavior for the other approach).

In the box of each activity already scheduled (on the right side of Fig. 5.3), in the lower part, it is possible to see a set of shortcut buttons.

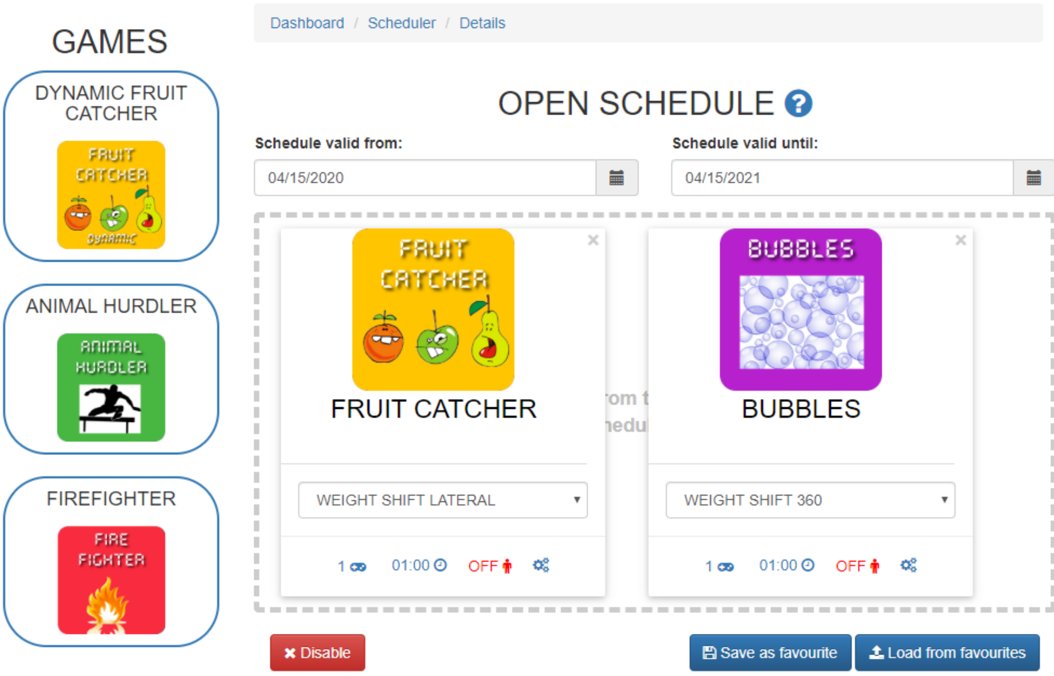

Figure 5.3: *The schedule editor. On the right panel, the activities currently contained in the schedules are shown. The other available video-games are visible on the left panel. Therapists can add or remove activities as they wish.*

These buttons allow to:

- *Change the difficulty*: five predefined levels of difficulty are selectable: each level of difficulty is associated with a set of parameters. In case of need, the therapist can decide to use these levels to speed up the scheduling. Each level is customizable: once chosen, the therapist can proceed with the usual tuning of all parameters.
- *Set the duration of the exercise.*
- *Enabling or disabling the monitors.*
- *Open advanced settings*: clicking on this button opens the *Advance parameters configurator*, through which it is possible to manually modify every single parameter (Fig. 5.4).

On the right side, it is also possible to see the fields containing the starting and ending dates, and, in the bottom, from left to right, the buttons to enable or disable the schedule and to save or load a schedule from favorites.

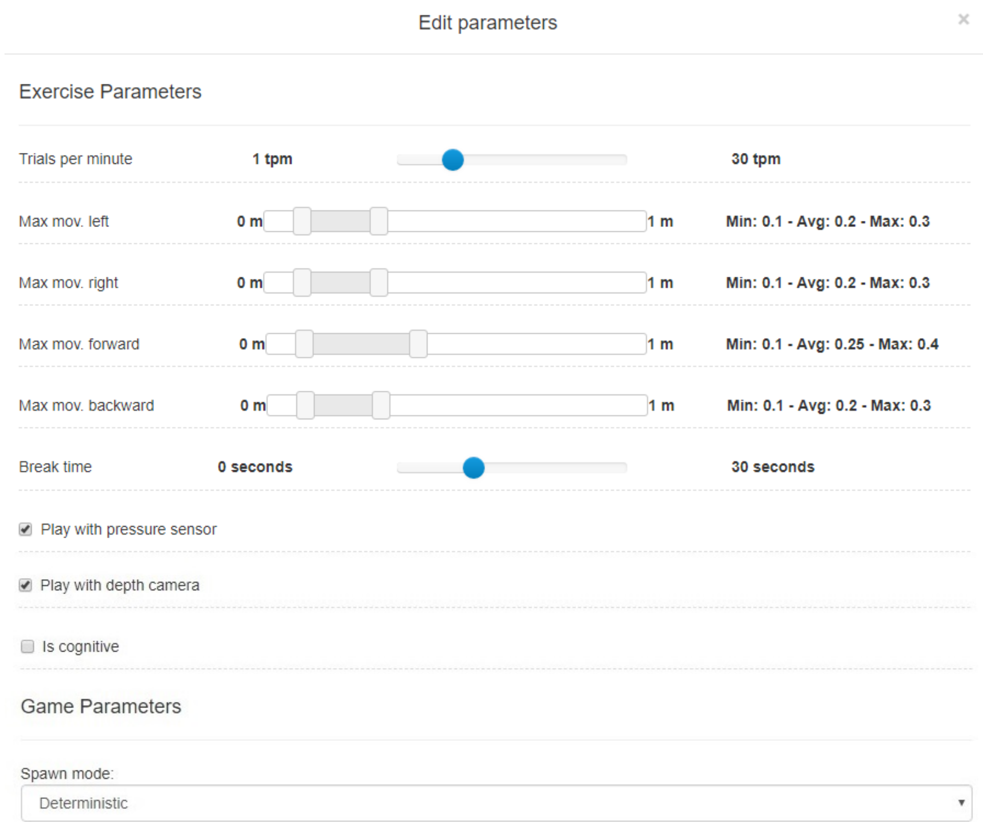

Figure 5.4: *Parameter configuration dialog. In this window, it is possible to change all the parameters (exercise, exer-game, and monitor) for a certain activity. For some parameters, it is possible to select a continuous range of values. During the execution of the exercise, the parameter will be automatically adapted, remaining within the range defined by the therapist, to suit the patient's condition.*

This latter feature has been requested by therapists and can be useful when two or more patients have similar abilities. The therapist can add a schedule in the favorite list and load it in the profile of the other patient who needs the same schedule. Each favorite schedule has a name and description to assist the therapist in identifying the desired schedule.

The level shortcuts allow therapists to quickly select a set of predefined parameters; however, sometimes they may need to manually modify some parameters and fine-tune the difficulty. This can be done using the advanced parameter configuration (Fig. 5.4).

From this dialog, therapists can set all the parameters for a particular activity. The parameters can be set via drop-down menus, checkboxes, or sliders.

Static and dynamic parameters

It is possible, for some parameters, to select a range instead of a single value (e.g., *Max mov.* parameters, in Fig. 5.4). These parameters are called "dynamic parameters". Unlike the others, which are called "static parameters", the dynamic parameters may vary during the execution of the exercise or between two consecutive executions. This allows automatic modification of the difficulty in real-time. It is used to better adapt the difficulty, and consequently the fun, of the patient. It is a mechanism that involves both HS and PS, and which will be discussed in detail in Chapter 6.

5.4.2 Tracking patients activities

The second important feature of this module concerns the monitoring of the patient's activity, which has a key role in the rehabilitation program. The scheduling module provides two different views to control patient adherence data: a *calendar view* and a *list view*.

Calendar view

Through the *calendar view*, therapists can see for each day of a month if the patient has played, partially played, or not played the scheduled activities, providing a clear picture of the rehabilitation adherence of the patient. In Fig. 5.5, it is possible to see an example of the calendar view. We can guess that the schedule was created on January 15 but that it was downloaded by the patient only two days later when the status went from ND (not downloaded) to P (played). From then on, the patient played three days a week, as requested by the therapist.

Although not yet available, it is easily possible to integrate this calendar with the notification system, alerting the therapist if the patient is skipping too many sessions to allow timely intervention.

List view

The second monitoring view, the *list view* (Fig. 5.6), shows all the basic information of the schedule, such as starting and ending dates as well as the exer-games contained and the number of times an exer-game has

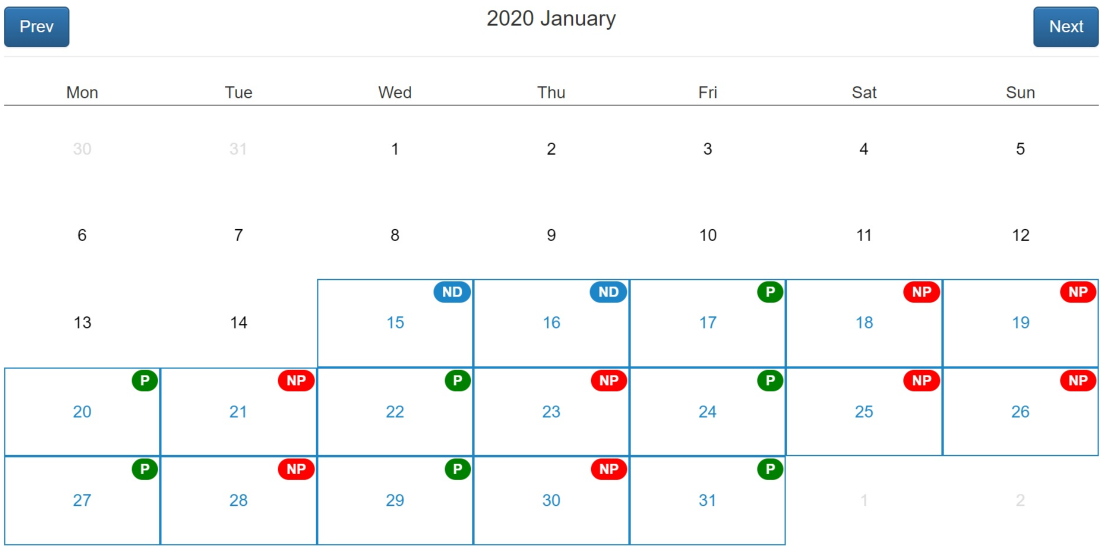

Figure 5.5: *Calendar view. It shows for each day if the patient follows the schedule, helping the therapist to verify adherence to the therapy.*

Figure 5.6: *List view, with the list and the number of played games.*

been played. It also shows the status of the schedule (played, partially played, or not played) of the last week.

Under the current schedule, all the previously played schedules are available. If necessary, clinicians can re-open an old schedule and reactivate it. Future schedules are also shown in a dedicated tab.

5.5 Results analysis module

The last module we deal with is the *Results analysis module*, surely the most complex and critical module. Designed for patient assessment, this module allows therapists and clinicians to analyze the exercises played by patients.

Since the rehabilitation sessions inside the hospital could be infrequent, a tool for remote patient assessment is needed to verify the patient's progress. Rehabilitation therapy, the set of exercises and their difficulty, is decided according to the patient's ability. With proper therapy, the chances of success and effectiveness of rehabilitation increase significantly. For this reason, providing a reliable evaluation system is a crucial point in a home rehabilitation platform.

For each exercise, it must therefore be possible to verify its quality in detail, estimated using some evaluation indexes that have been defined with the therapists.

But, clearly, a therapist could have dozens of patients, and there may not be the possibility and the time to evaluate all their exercises. For this reason, the platform must also provide the long-term trend of the patient's performance to allow a quick (but more approximate) analysis.

This module presents two main difficulties to face: finding the indexes that best represent the patient's state and how to show them.

We will first start by describing the basic architecture of the module, and then we will see how these indexes are shown to therapists. The module has been designed to be flexible and reusable. Particular attention has been paid to ensure that it can be used in different rehabilitation fields. To achieve this, it is easily possible to add or modify new indexes, allowing to extend the analysis of an exercise with new evaluation metrics.

5.5.1 Module architecture

Due to the complexity and size of the module, it has been logically divided into three components: the results generator, the results aggregator, and the results visualizer. Architecture is illustrated in Fig. 5.7.

The Results Generator Module (RGM) It analyzes all the information (e.g., devices raw data, game events, monitors, ...) of a certain exercise to produce graphs and tables representing its quality. This information will then be used by the Results Visualizer Module to produce a page showing the metrics which will be available to the therapist.

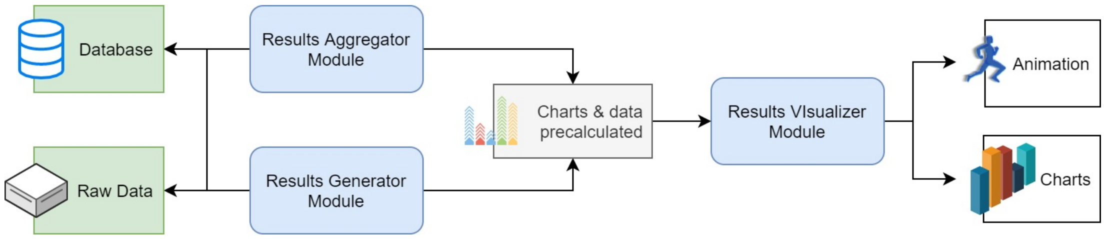

Figure 5.7: *Results analysis module: architectural overview. Results Aggregator and Results Generator modules, using the information stored in the HS, generate a set of charts and other data representing some metrics about the executed exercises. This data will be used by the Results Visualizer Module to provide to the therapist with a picture of the patient's status.*

The Results Aggregator Module (RAM) It analyzes all the exercises performed so far by a patient (using also the results previously calculated by the RGM) to produce aggregated metrics representing the patient's trend in the long-run.

The Results Visualizer Module (RVM) Finally, using the pre-calculated result created by RGM, it creates a web-page containing all the metrics needed to understand the quality of an exercise.

Let us have a look at each of these three modules in detail now.

5.5.2 Results Generator module

In Chapter 2, we saw two possible approaches for patient evaluation: template-based and rule-based. In our case, it was decided to use the latter approach. Thanks to the collaboration with therapists, a set of rules for the extraction of metrics representing the most important features for each exercise were defined. These metrics allow therapists to analyze each exercise in detail. Generally, such a detailed view is rarely used, mainly when the therapist notices that something is wrong, and then proceeds with a detailed check. But, precisely because it is used in important and/or critical situations, it is essential that it is reliable and offers the therapist all the information he/she needs.

RGM is activated upon receiving a new exercise, and it generates one or more *Result objects*. A Result object can be a graph or a piece of textual information that is used to represent the quality of the exercise. Since an exercise can have several and different metrics to evaluate it, there can be many results for every kind of exercise. The Result Objects will be used later by the results visualizer module to create a page containing all the information deemed useful by the therapists to obtain a correct evaluation of the patient.

To generate the Result objects, our module uses a set of *Output parameters* (OPs) objects. An OP is used to extract a single metric from the devices' raw data. Every OP is associated with a Python method (i.e., our extraction rule) that will be executed having in input the raw data to generate the desired results. An exercise can have one or more OPs (usually at least three or four), according to the therapists' needs. Once a new exercise is received by the HS, the methods associated with the corresponding OPs are executed, generating a set of results with associated data (e.g., images representing the graphs).

In case of need, using OPs, it is easily and quickly possible to add further metrics or modify existing ones. If and when the therapist needs new information, a new OP will be defined and implemented by the developers.

Defining an OP For clarity purpose, let us see an example of OP. In the *Weight Shift Lateral* exercise, one of the metrics deemed useful by clinicians is the so-called *Maximum Excursion* (MXE). MXE is represented by a percentage describing how close is the patient to the goal set by the therapist. In this exercise, the patient is required to move on the left and on the right to reach pre-defined thresholds. The maximum amplitudes reached by the patient in the two directions divided for their thresholds are the desired MXEs (right MXE and left MXE). The patient's CoP, calculated on the data coming from the Nintendo Balance Board (or in its absence the CoM estimated by the patient's joints), is used to determine the MXE. To extract this metric, we must then define an OP and write the corresponding Python code necessary for data analysis. Example code for the extraction of this metric is represented in Algorithm 5.1. In this code, we extract the minimum and the maximum values of the CoP, which correspond to the maximum left and right shifts achieved. We then divide them by the thresholds set in the schedule (MaxMovementRight and MaxMovementLeft parameters), obtaining the MXE in the two directions.

```
@outputParameter
def Weight_Shift_Lateral_MXE(exercise_data, index_of, label='TEXT'
                                , dictionary = None):
    # Initialization of the dictionary representing the result
    # type: type of output (Text, Image, Animation, ..)
    # index_of: choosen between (Nothing, Amplitude, Stability,
                                    ..), used to aggregate data
    # id: id of the output parameter
    results = {'type': type, 'index_of': index_of, 'id': 'WSL_MXE'
                                    }

    # Getting thresholds (using activity parameters)
    # MaxMovementRight & MaxMovementLeft represent the amplitude
                                    of the movements required
                                    by the exercise
    right_threshold = self.GetParameter("MaxMovementRight")
    left_threshold  = self.GetParameter("MaxMovementLeft")

    # Computing MXEs as the maximum and minimum values of the CoP
                                    along the y-axis.
    copY = []
    for frame in exercise_data.frames:
      copY += [frame.wiibbdata.copY]
    right_max = max(copY)
    left_max = min(copY)

    right_MXE = right_max / right_threshold * 100
    left_MXE = left_max / left_threshold * 100

    # Adding MXE information to results
    results['output']['rightMXE'] = right_MXE
    results['output']['leftMXE'] = left_MXE

    return results
```

Code Listing 5.1: *Example code for the extraction of the MXE in the Weight Shift Lateral exercise.*

This is a simplified example: calculating the minimum and the maximum values may not be reliable or representative of the patient's status. The OP currently in use, it first calculates all the maximum distances temporally close to a trial (i.e., we are calculating the distance only when we are sure the patient is moving to reach the target), and computes the average between all the maximum distances, to obtain a more reliable value. The example shown here is only for guidance, to let the reader understand how fast and easy it is to add or modify an OP. Clearly, nothing prevents the definition of methods much more complex than the one just mentioned, even perhaps using information from other exercises performed recently or using advanced algorithms.

In this example, the result of the method is a dictionary containing the information we want to show (textual information in this case). In other cases, for example when the output parameters need to be shown as a figure, the method will generate a picture that will be stored on the HS, and it will return a dictionary containing the path to the generated picture.

Emotions analysis Until now, we have exclusively talked and treated metrics related to the physical performance of the patient through the analysis of raw data of the connected devices. Which is logical because the primary objective of the platform is to allow physical rehabilitation.

However, also the psychological aspect should not be underestimated. In one of our preliminary experiments, using Microsoft's Face API[2], PS monitored perceived facial expressions (e.g., happiness, sadness, anger, ...) and sent this information to HS at the end of the exercise. We then defined a special OP to show the relevant emotions during the execution of the exercise. This information can be useful both to monitor the patient from a psychological point of view (to eventually try to detect pathologies, such as depression) and to verify how emotions change during the execution of the exercise. For this second purpose, facial expressions were detected both periodically (e.g., every 10 seconds) and in conjunction with particular events, such as Hit, Miss, or other game events.

5.5.3 Results Visualizer module

At this point, we should have understood how the results are generated. But how are they shown? Showing them to therapists is not a secondary issue, and in our experience, there have been many discussions about how to make it easier for therapists to understand the graphs.

We would like to emphasize that therapists can often evaluate their patients' performance only through HS (hospital or home visits may be very sporadic), so they must have all the information they need, and it must be presented as clearly as possible so as not to be misunderstood.

[2]Microsoft's Face API, `https://azure.microsoft.com/en-us/services/cognitive-services/face` (visited on 11/30/2020)

We have just illustrated the example of the MXE calculation, which is shown as textual information, but this is not the only possible visualization type. There are four different categories that are associated with four different visualizations:

- **2D-3D animations**: mainly used to show the patient's skeleton and CoP (or CoM), they represent an animation which lasts for the entire duration of the exercise, implemented using three.js[3] (Fig. 5.8). This information can be particularly useful, as it allows the therapist to visualize all the movements performed by the patient during the exercise through a 360° 3D visualization. Through a progress bar, clinicians can move the time of the execution, allowing them to analyze the corresponding information for that time. Play, pause, stop, and speed features are also available to manage the animation.

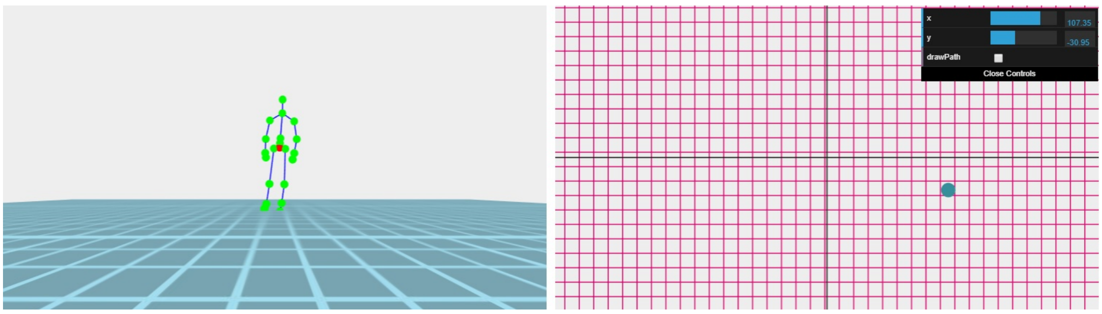

Figure 5.8: *On the left, the 3D animation widget showing the patient's skeleton and CoM estimated by the Kinect (red sphere); on the right, the 2D animation showing the CoP calculated by the Balance Board.*

- **Textual information**: this type of result is used to show precise information, such as averages, minimum and maximum values, i.e., anything that can be represented through a short text string. All textual information is grouped and shown in the form of a table, with the corresponding name associated with the OP (Fig. 5.9). All exercises always have at least two entries in the table: Hit and Monitor percentages. Remember that the percentage of Hit represents the number of successful targets, while the percentage of monitor represents the average quality of posture.

[3] Three.js, `https://threejs.org/` (visited on 11/30/2020)

INFORMATION	
HIT:	1.00
MONITOR:	0.14
MXE FORWARD:	114.62% ± 57.31%
MXE RIGHT:	103.52% ± 53.97%
MXE BACKWARD:	115.29% ± 43.76%
MXE LEFT:	98.99% ± 56.11%

Figure 5.9: *Textual results of a Weight Shift 360° exercise. In addition to the Hit and Monitor percentages (present in every exercise), it is possible to see the MXE achieved in the four main directions. This type of information is also useful because it allows the therapist an easy comparison with other executions of the same exercise.*

- **2D charts**: simple charts displaying a data series calculated for the entire exercise duration (e.g., the stability of the patient). Useful because they allow understanding the trend of a certain metric during the execution of the exercise. They are created using the flot.js[4] library (Fig. 5.10). This type of graph is now obsolete and no longer used, in favor of the next type of output: the *Advanced images*.

- **Advanced images**: previous 2D charts have some limitations: they cannot be customized enough when advanced information is requested (e.g., for calculating the convex hull of the CoP). In these cases, high-customizable images (e.g., Fig. 5.11) showing all the needed information are created using matplotlib[5] library. In these images, for example, it is possible to add lines or circles representing the objectives to be achieved. Another feature of this type of results is that it also allows the overlap of multiple exercises. The therapist can choose, through a drop-down menu, to superimpose the same graph of one or more exercises, to check the patient's progress.

Each exercise has its own page containing all its metrics. Therapists can browse through the various exercises, divided into game sessions (i.e., the set of games played from the start of the PS to its shutdown).

[4]Flot.js, `https://www.flotcharts.org/` (visited on 11/30/2020)
[5]Matplotlib, `https://matplotlib.org/` (visited on 11/30/2020)

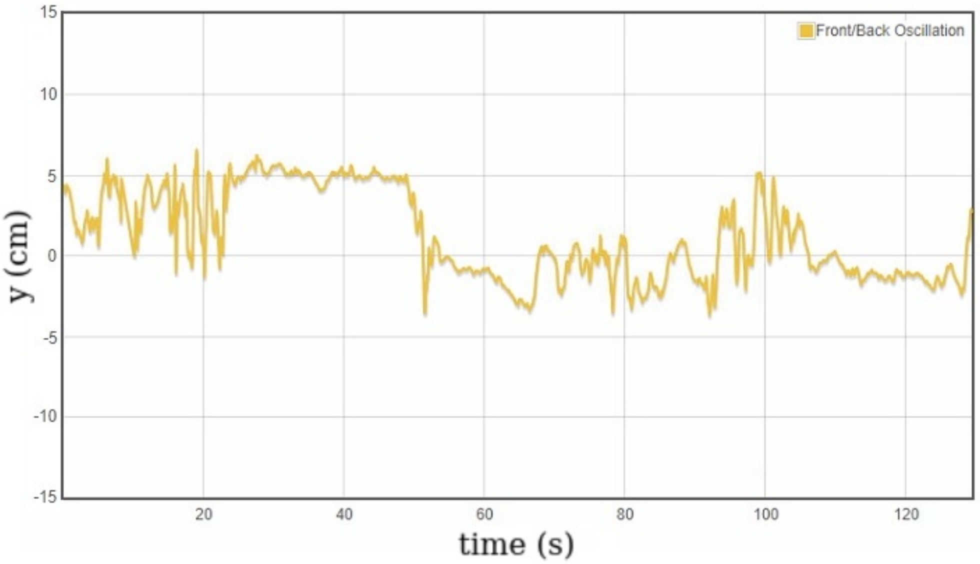

Figure 5.10: *Example of a chart showing the stability of the patient in a Weight Shift Lateral exercise. In this case, the patient's stability was good throughout the exercise, with no significant oscillation noted.*

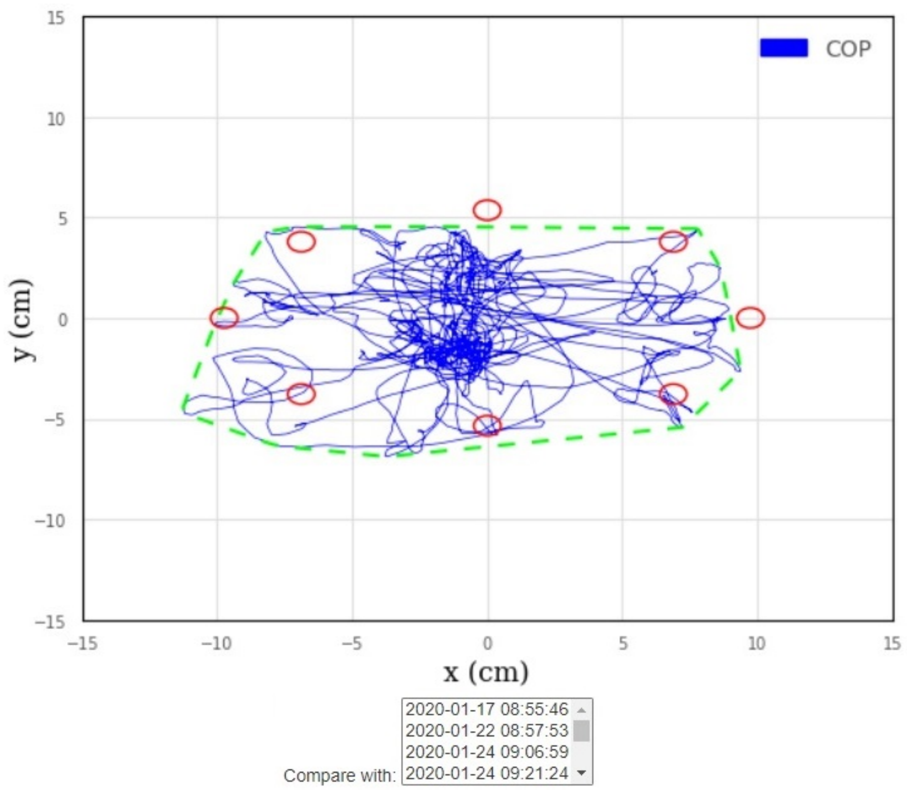

Figure 5.11: *Image generated for the Weight Shift 360° exercise: in every direction, the point required to reach is shown as a red circle. The green convex hull represents the area covered by the patient during the execution of the exercise. This type of results can also be compared with previous executions of the same exercise.*

Multiple Sclerosis: calculated metrics

For each exercise, the metrics that best represent the quality of the exercise and the patient's skills have been defined. These metrics aim to evaluate the patient according to one or more of the following rehabilitative dimensions: amplitude, stability, accuracy, force, and speed.

These indexes have been defined and studied for patients with multiple sclerosis; before applying them to other diseases, validation by hospital staff is required.

- ***Stand Still***: evaluation is in terms of stability of the position (calculated as the area covered by the CoP, the smaller is the area, the greater the stability) and accuracy of the pose, computed as:

$$A = \sum_{i=0}^{m} |J_{i,j} - J_{i,j-1}| \tag{5.1}$$

  where $J_{i,n}$ is the position of the i-th joint in the j-th frame.

- ***Weight Shift Lateral/Frontal/360°***: the distance the patient is required to cover with his/her CoP in each direction determines the movement amplitude. Accuracy is given by the average distance between the patient CoP and the center of the target. The smaller the distance, the greater the accuracy. Stability can also be evaluated. It is calculated as the standard deviation from the ideal straight line that should be followed.

- ***Lift Legs & Lift Legs Instantaneous***: amplitude is associated with the height of the raised foot. Speed is determined by the raised leg speed during the movement, and stability is calculated through antero-posterior oscillations when the leg is raised.

- ***Sit to Stand***: here, too, the lateral stability during movements and the speed at which the patient stands up is calculated.

- ***Steps Lateral/Frontal/360°***: amplitude, speed, and accuracy are evaluated. Amplitude and accuracy are calculated in the same way as *Weight Shift Lateral/Frontal/360°* exercises but using the foot position instead of the CoP. While speed is determined by the average speeds required to move the foot from the center position to the target position.

5.5.4 Results Aggregator module

So far, we have seen a series of graphs and information that accurately describe in detail the quality of a single exercise performed by a patient. But a therapist could have dozens of patients, if he/she had to supervise every single exercise in such a detailed way, autonomous rehabilitation would lose any advantage, requiring the therapist a comparable amount of time to traditional rehabilitation.

The detailed view of a single exercise is certainly a useful feature in some cases; for example, if the therapist wants to check if the patient is performing an exercise correctly or if he/she suspects some kind of problem. But often such a high level of detail may not be necessary.

For this reason, a module has been developed to aggregate the data of a single patient into a limited number of graphs, containing only the most representative information regarding the patient's performance. These graphs represent the trend over time (even weeks or months) of the patient's physical capabilities.

It was not immediately clear which was the best method for the definition of these aggregated graphs. For this reason, the HS supports two alternative views. The first approach developed is based on the use of OPs, the same that produce the graphs in the detailed visualization: a subset of OPs considered most representative has been selected, and if an OP is shared by several exercises, they are combined into a single graph. This approach has not turned out to be as useful as expected, at least with patients with multiple sclerosis, so we moved to a second approach, where different exercises are no longer combined into one series, but more series are produced for a single graph, so the therapist can more easily get an idea of the exercises that are not being performed properly.

General approach to data aggregation in the HS

Initially, after a few meetings with therapists and after defining the detailed evaluation metrics for each exercise, it was decided to use the rehabilitation indexes (amplitude, accuracy, stability, strength, and speed) as metrics to represent the patient's performance over time.

Each OP can be associated with one of these indexes. For example, in the *Weight Shift Lateral* exercise, the movement amplitude can be associated with an OP that calculates the average between the right MXE and the left MXE, which is a good representation of the patient's overall amplitude. Similarly, in other exercises, such as *Steps Lateral*, it is possible to calculate the amplitude of movement in completely different ways (in this case, by measuring the amplitude of movement performed by the patient's feet).

So, the original idea is to calculate, for example, the amplitude of movement of the patient, starting from the amplitude obtained from different exercises. Obviously, a problem immediately arises, different exercises have different scales: how can I combine the amplitude of movement obtained in *Weight Shift Lateral*, where I cannot perform steps, with the one estimated in the *Steps Lateral* exercise?

The solution we proposed was to calculate the trend of a specific OP for a single type of exercise and normalize it. Taking into account a single type of exercise, it was sufficient to calculate the value of the OP for each day on which the exercise was played (possibly averaging if several exercises were played on a given day). And finally, once the series for all the different type of exercises including that particular OP has been obtained, it is possible to perform the average between the series, now feasible thanks to the normalization.

At this point, theoretically, it is possible to create a graph that represents the patient's abilities with respect to a rehabilitation index. This graph should at least give an indication of the patient's trend, whether it has improved or deteriorated over a given period. As we will see now, however, there are some problems.

MS specific approach to data aggregation

It was immediately clear, after showing therapists a first version of the aggregated graphs, that this type of visualization was too general and did not allow a sufficiently clear evaluation of all rehabilitation aspects. By combining the indexes of different exercises, it became impossible to evaluate the patient in a particular exercise, and some problems inherent to a specific exercise may not be identified. A trivial example: a patient may have improved his/her amplitude of movement in *Weight Shift Lat-*

eral and worsened it in *Steps Lateral*. From a single trend, it would be impossible to get this information. For this reason, it was necessary to find an alternative system for the calculation of global graphs, something that would aggregate the information but still allow a clear, quick, and simple evaluation of the patient's status.

So, it was decided to create more trends that could better highlight some individual aspects for each exercise. In addition to the global Hit % graph, we were asked to group exercises in two categories: those for static balance (i.e., exercises in which the patient does not have to take steps) and those for dynamic balance training (i.e., exercises in which the patient takes steps).

Three relevant aspects were chosen for each category, for static balance exercises we can estimate:

- **CoP area**: calculated from *Stand Still, Weight Shift Lateral, Weight Shift 360°*.
- **Lateral oscillation**: from *Stand Still, Sit to Stand, Weight Shift 360°*.
- **Front/Back oscillation**: from *Weight Shift Lateral, Weight Shift 360°, Stand Still*.

While for dynamic balance exercises:

- **Velocity**: from *Lift Legs, Lift Legs Instantaneous, Steps Lateral, Steps 360°*.
- **Lateral oscillation**: from *Lift Legs, Lift Legs Instantaneous, Steps 360°*.
- **Front/Back oscillation**: from *Lift Legs, Lift Legs Instantaneous, Steps Lateral, Steps 360°*.

We then produce a time series for each exercise of the category, so that the therapist is able to see which exercises the patient performs worse by looking at these six graphs.

An example of lateral oscillation for static exercises is visible in Fig. 5.12. The graph shows the lateral oscillation in the three static exercises available through the PS.

Figure 5.12: *Graph representing the global lateral oscillation. The graph shows the trend of lateral oscillation in those exercises in which lateral oscillation is a representative metric for the quality of the exercise.*

With this visualization, it is easier for therapists to verify the patient's performance in every single exercise, measured through the most representative rehabilitation indexes (amplitude, stability, ...), without falling into excessive generalizations, which could prevent the evaluation of all the parameters necessary to determine the patient's progress. In case of need, all detailed results for each exercise are always available.

5.6 Notification system

We conclude the chapter with a brief description of the last component of secondary importance: the *Notification System*.

The notification system allows therapists to be notified when particular events occur. Currently, the notification is only visible within HS, and the events that are notified are only when a new exercise has been performed and when an invitation to share a patient is received.

However, we plan to enhance this system both to notify events in a more immediate way (e.g., sms, e-mail, or push notifications) and to alert of other more important events. In case, for example, of a fall, or other problems detected by Hannah, the therapist should be notified immediately.

CHAPTER 6

Patient engagement and motivation

Patient's motivation plays a key role in the outcome of the rehabilitation program: a motivated patient will be more inclined to follow the program assigned by the therapist. Unfortunately, for some diseases, there is a slow but steady decline. Rehabilitation, in these cases, aims to slow down this decline as much as possible, to allow a better quality of life for the patient.

Given this premise, it is clear that even the most motivated patient, after weeks or months of sessions, can lose motivation, given the apparent lack of improvement. Providing a stimulating environment during the execution of the exercises can certainly help. To this end, exer-games can contribute, but only in the short term. Once the patient has fully understood the mechanisms, the novelty factor will slowly fade away, and the patient will begin to get bored.

In this chapter, we will start with some simple theoretical notions about motivation, and we will continue describing the features that have been implemented to try to increase patients' interest and, consequently, motivate them during the execution of the exercises.

6.1 Motivation

Before illustrating the game design solutions we developed to stimulate the patient, we want to start this chapter with a first theoretical part on motivation. Motivation is a crucial element for the patient; it can be defined as “the psychic process that initiates, guides, and maintains human behavior” [120]. Let us start with a couple of theories to make the reader understand how it is related to video-games and consequently with the effectiveness of rehabilitation.

6.1.1 Self-determination theory

The first key point we would like to mention is the Self-Determination Theory (SDT) [121]. STD can help us to understand how human motivation and behaviors work: it tries to explain why some individuals are highly determined and committed to fulfilling their duties (high self-determination), while others have a passive, almost indifferent behavior (low self-determination) [122].

It also introduces the concepts of intrinsic and extrinsic motivation. In a self-determined person, the motivation comes from inside (intrinsic motivation), in contrast with low self-determination, in which behaviors are guided from the outside (extrinsic motivation). Probably every one of us knows at least one person who immediately does what he/she has to do, without any external incentive and, at the same time, we all know at least one person who must be encouraged, motivated, before doing what duty requires.

Self-determination theory is strictly related to motivation: when performing an activity, both intrinsic and extrinsic motivation influence the development and enjoyment of that activity.

Intrinsic motivation comes from internal desires, like a duty, a sense of pleasure, the desire to learn, or any other internal satisfaction; in our case, the wish of a better condition is a strong motivation to perform rehabilitation. On the contrary, extrinsic motivation occurs when an individual acts mainly in response to external forces, influenced by others, or rewards (e.g., money). There is also a further third type of motivation, usually less known, the amotivation, which is basically the absence of motivation [123]. The combination of these three types of motivation defines the interest in a particular activity. Understanding how these different types of motivation work in games and video-games and how they are related to fun can help to develop better games with more entertainment capabilities. In fact, although born as a theory for a generic activity, SDT can also be applied to video-games (e.g., [122] [124]).

6.1.2 Short and long term motivation

Intrinsic and extrinsic motivation are also related to short and long-term motivation. As stated by Ryan and Deci [125], people with strong intrinsic motivation tend to be motivated for longer and have better performance and creativity.

Short-term motivation generally concerns a single game and is more related to the fun and enjoyment experienced in that short period of time. Instead, long-term motivation is related to keep high the player's motivation during multiple sessions spread over several days or even weeks or months. The latter is more complex to achieve. In our case, the effort required to produce a set of exer-games that allows keeping the patient entertained and motivated over a long time is huge.

This problem is shared by every game. Every video-game has its own life cycle: no video-game publisher expects their own game to be played forever. Our goal is to try to extend the life cycle as much as possible: if the patient gets bored after a few days, adherence to therapy may soon begin to decrease, and our goal will not be achieved.

Popular and famous games present a large set of actions that can be performed within the game: different levels, world exploration, multiplayer. These elements, if well designed, can entertain the player for a long time. This obviously requires the work of tens or even hundreds of people generally for months, an enormous amount of work.

The scenario is even more complex as far as exer-games are concerned. Exer-games have several constraints to meet compared to traditional video-games, which limit their longevity. For example, they have to be usually used with devices that are not compatible with mouse and/or keyboard (e.g., Kinect or Balance Board); this requires the development of user interfaces designed specifically for the type of devices used, and the interaction between the user and the computer can be limited and complex. Furthermore, an exer-game is closely related to a rehabilitation exercise, and the design of the games must be designed around the exercises to be performed by the patient.

Fortunately, there is also a positive side: most patients are driven by intrinsic motivation and the desire to improve their physical condition, this can help to balance or reduce possible game-design deficiencies. Starting from this primary need that motivates the patient, the use of games and other attractive features, can also stimulate extrinsic motivation, for greater effectiveness.

6.1.3 Fun and Flow theories

The last theories we would like to present, well known by game designers, are the theories of fun and flow. Currently, there is not a clear definition of "fun", although several studies had tried to define it [126] [127] [128]. It is also hard to measure and to formalize: few heuristics have been proposed, and there have been some attempts to vary some game mechanics to increase the player's engagement.

[129] represents one of the first works with the objective of measuring fun in a quantitative way. Iida et al. introduced a metric to evaluate the fun for the variants of the chess game, using the average length of the game and the number of possible moves.

In [130], an attempt was made to measure the fun of Pac-Man games in mathematical terms through some heuristics. To validate their estimation, the authors have recruited several players who were asked an estimate of the difficulty of the level played and how much they enjoy playing. Results show that the mathematically estimated fun is not always consistent with what was expressed in questionnaires, and some contradictions have emerged. Further tests are necessary.

A slightly different approach was used in [131]. Instead of mathematically estimating the fun, psychophysiological measurements (i.e., facial electromyography, galvanic skin response, ...) were used to try to identify the player's level of immersion in a first-person shooter video-game. Again, questionnaires were used to measure the player's subjective immersion. A good correlation between objective and subjective measurement was obtained, demonstrating the goodness of the work.

For readers who want to go deeper into the subject, an interesting review is [132].

These works are generally based on one of the most important theories in this field: the *Flow Theory* [133]. In this work, Csikszentmihalyi administered questionnaires and interviewed thousands of people. His work did not directly concern video-games; his study started from all of those people who spend a large amount of time on difficult activities that do not provide external rewards (e.g., money, status, ...), continuing with "ordinary" people who do not perform this kind of activity. He defined the concept of "flow", which describes the optimal experience as "so gratifying that people are willing to do it for its own sake, with little concern for what they will get out of it, even when it is difficult or dangerous" [133].

The state of flow is a state of mind in which the player is totally focused on the activity, losing control of time and self-identity, concentrating only on the current activity. To achieve this state of mind, some elements are necessary (e.g., a challenging task to complete, clear goals, immediate feedback). It has been shown that among the various benefits of flow is also the reduction of pain [134]. It may be surprising to know that also reading is one of the most enjoyable activities [133].

Csikszentmihalyi identified a series of elements that help people enter the flow state; these elements are often exploited by video-games to try to entertain players more. One of these key elements, for example, is the challenge difficulty, which should be matched to the player's skills [135]. This is why a system for automatic adaptation of the difficulty has been implemented.

In the next paragraphs, we will describe some features that have been implemented in the PS to increase the motivation, both intrinsic and extrinsic, of the patient, in an attempt to increase interest in the games and enter the flow state. Some images and contents of this chapter have been previously published in [136] [137] [138].

6.2 Procedural Content Generation

Game content is a crucial aspect of a video-game and greatly influences its longevity. Having the possibility to, for example, explore a big world or use a lot of different items or characters is an important factor in keeping players engaged [139].

Unfortunately, the work required by manual content production is huge and unscalable [140] [141]. Since modern video-games are increasing in complexity, the effort required by content generation is growing more and more, and content production is becoming the bottleneck in game budgets and product time-to-market [142]. For this reason, in the latest years, automatic content generation, also called Procedural Content Generation (PCG) [143], has begun to spread. PCG can be applied to several different elements in video-games, such as textures, sounds, environment (rocks, trees, props, ...), story, level, and so on.

The first commercial games implementing PCG have appeared around 1980. At that time, PCG was a useful technique to reduce the size of the game (e.g., The Sentinel [144] had 10,000 levels stored in a few kilobytes or Elite [145], able to generate an entire universe with thousands of planets in only 32 Kb). Examples of modern video-games that use PCG include, but are not limited to: Diablo [146], Minecraft [147], and No Man's Sky [148], just to name a few.

PCG is not only used in modern commercial games but also in serious games; a couple of examples are [149] and [150], in which PCG has been used to generate levels for patients during the rehabilitation.

In the PS, currently, PCG has been mainly exploited for the dynamic generation of the game world in "Horse Runner" and "Animal Hurdler" exer-games. Here, the entire world (i.e., topology, environment elements, and water) is generated at the beginning of the execution. The generation process is made up of four distinct parts (Fig. 6.1).

1) Topology creation Starting from a completely flat ground, the topology of the environment is generated. Perlin noise function [151] is used for the generation of a procedural texture that is applied to the terrain, terrain vertices heights are modified according to the texture pixels.

2) Base texturing Once the basic terrain topology has been generated, textures can be applied. First, a biome is randomly selected. The biome defines the environmental characteristics (e.g., snowy mountains, desert, meadow, ...), each environment has a predefined set of textures that will be then applied to the terrain following some basic rules (e.g., rock texture on sloping walls, snow at high altitude, ...).

3) Path Generation The next step is the generation of the random cyclic path that will be followed by the player's character. We start by defining

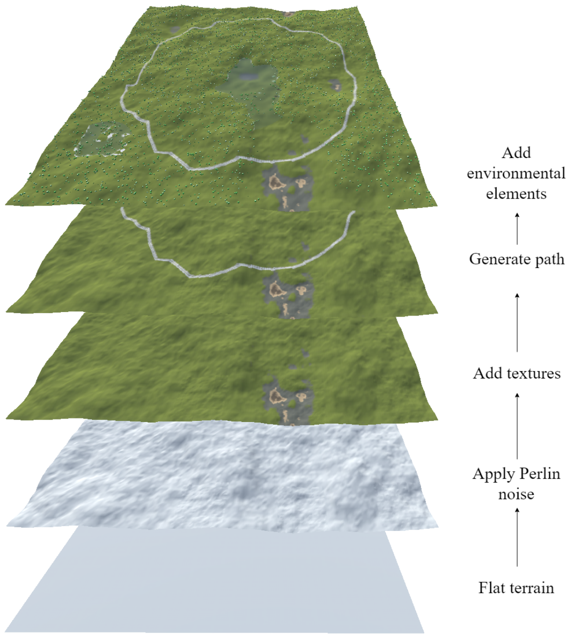

Figure 6.1: *Starting from completely flat terrain, the Perlin noise function is applied to generate the basic topology of the environment, to which textures are added based on the characteristics of the terrain. In the end, environmental elements are added.*

a center of the path, then a set of points around the center, at a random distance, is generated. These points are used as control points of a B-spline curve [152], which will represent the path.

4) Environmental elements The last step is the generation of environmental elements, such as trees, rocks, rivers, or lakes. These elements are randomly generated and positioned on the terrain at a sufficient distance from the path to prevent them from interfering with the gameplay.

This process allows us to procedurally generate a different world in each game, allowing the gameplay to vary slightly. In the exer-games, PCG was also used in other secondary areas (e.g., the automatic generation of the garden visible in the background).

The possibility to have a different experience each time can certainly help motivate the patient, and it is worth the work, especially in exer-games, where the mechanics are limited, and the game risks becoming boring easily.

Currently, however, these solutions are not enough in the long term. In the future, we aim to further improve PCG by including also story generation. In this regard, a preliminary work is illustrated in [153].

6.3 The Empathic Virtual Therapist

As we will see in Chapter 8, among the aspects that have been most appreciated by patients, there is Hannah, the empathic virtual therapist present in the PS. In the latest years, empathic avatars have been increasingly spreading, especially in applications related to rehabilitation or behavior-change therapies [154] [155] [156], showing to be able to increase patient engagement [59]. They have also proved particularly useful in interactions with patients with psychological disorders, such as depression [157]. Patients who could dialogue with an empathic avatar, who adapted the facial expression based on the user's emotions, reported a better attitude in talking with the avatar than filling out a classic questionnaire. Also in the area of exercise, Shaw et al. [158] developed a virtual coach for exercise. In the case of a cooperative coach, adherence to patient therapy increased compared to a competitive coach.

Hannah was already present in the Rewire project, with the task of welcoming patients, following them in all the various phases of the game, such as device synchronization or messages of encouragement or warning, in case of incorrect posture.

The old version of Hannah (Fig. 6.2, on the left) had no empathic functionality and was also very limited from the point of view of facial animations. For this reason, Hannah has now been recreated and improved using Adobe Fuse[1] to create the 3D model, which was animated through *Mixamo*[2]. The new Hannah (Fig. 6.2, on the right), unlike the old avatar, is now able to understand the patient's emotions, adapting her behavior according to them, trying to establish an empathic connection with the patient to increase engagement and acceptance of rehabilitation therapy.

Hannah is always present throughout the rehabilitation session. She appears the first time during the connection of the devices and is always present in every phase of the game. Her two most important features are:

- ***Exercise support mode***: during the execution of the exercise, Hannah appears to make suggestions to the patient (e.g., how to correct posture) or to encourage or congratulate him/her.

[1]Adobe Fuse, `https://helpx.adobe.com/it/support/fuse.html` (visited on 11/30/2020)

[2]Mixamo, `https://www.mixamo.com` (visited on 11/30/2020)

Figure 6.2: *On the left, Hannah used in the Rewire project; on the right, the new model currently in use. The new model is much more detailed, with a much greater number of vertices in the face, allowing her to express different emotions, which is not possible with the old avatar.*

- ***Direct mode***: the patient can consult Hannah in her office. It is possible to have a conversation with her and express feelings about the exercises, such as boredom or frustration. Hannah will try to understand and help the patient, adjusting the difficulty of the exercises if necessary.

To establish an emotional connection with the patient, Hannah has available a set of input channels to try to deduce the patient's emotions, and a set of output channels to show empathy.

The input channels currently are the user's performance during the execution of a game (the score and posture quality) and the answers that are given during the conversation in Hannah's study. Based on this information, Hannah reacts by modifying the output channels, her facial expression, and voice responses accordingly. Hannah can express the following emotions: happiness, sadness, surprise, and anger. These emotions are a subset of the emotions defined by Ekman [159], the remaining emotions (fear, disgust, and contempt) have not been considered useful in our case.

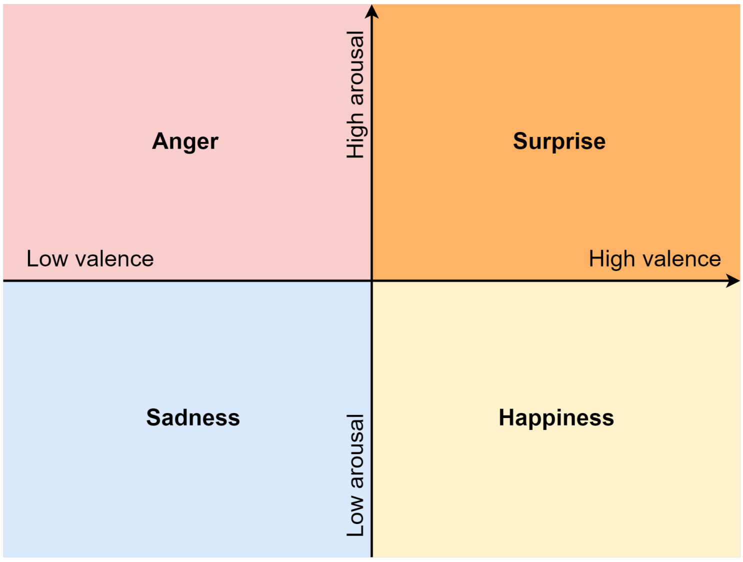

Figure 6.3: *A generalization of the Core Affect model proposed by Russell: the value of valence and arousal determines the emotion experienced.*

6.3.1 Interpretation of the patient's emotions and reactions

We will now illustrate the basic operation of the new empathic avatar at a high level.

The model presented by Russell [160] was used, with the concepts of valence (i.e., the degree of pleasure of an event) and arousal (i.e., the level of excitement of the individual). The combination of the values of these two elements shapes the different emotions of an individual. A generalization of the Core Affect model proposed by Russell is shown in Fig. 6.3. In the case of Hannah, valence and arousal are updated each time an event occurs. For each event e, we have defined an i_e value that represents its impact. The impact of an event can vary from -1 (very negative event) to +1 (very positive event). To give a couple of examples, a good performance in an exercise is a moderately positive event (e.g., +0.5), while if the patient complains of being frustrated because of exergames, it is a very negative event (e.g., -0.8).

Update of the emotional state

We have selected the algorithm proposed by Pontier [157] for the update of the valence, based on a decay factor $\delta \in [0, 1]$ (i.e., the speed with which the valance returns to the value of the initial state) and a change speed factor $\sigma \in [0, 1]$ (i.e., the speed with which a new event impacts on the valence). Every time a new event occurs, the new valence value is calculated according to the following formula:

$$v_t = v_{t-1} + Decay + Change$$
$$Decay = (v_0 - v_{t-1}) \cdot \delta$$
$$Change = \frac{\sigma \cdot i}{1 + i(v_0 - v_{t-1})}$$

Where i is the impact of the new event, v_0 is the initial value of the valence, and v_{t-1} is the previous value of the valence.

We have further adapted this formula to update the arousal based on the frequency of the event in the short term. We have provided the EVT with a Q queue of a fixed size which remembers the last n events (if it is full, the oldest event will be discarded). When a new event is received, the relative frequency f_r of this new event is calculated with respect to the content of the queue, the higher that event occurred recently, the higher the relative frequency will be. This value will then be used to reduce the impact of frequent events. In particular, the impact of the new event is multiplied by $(1 - f_r)$.

We have also added two conditions useful especially in the early stages, when the queue is not full. If $sgn(v - 0.5) \neq sgn(i_e)$, we require that $i_a \geq 0.5$, otherwise it must be $i_a \leq 0.1$. These values allow avoiding exaggeratedly high impacts in the beginning when the queue contains few elements. The complete procedure is illustrated in Algorithm 1.

The new values of valence and arousal, at the end of the update after receiving a new event, are the input to a fuzzy system, based on Mamdani's model [161]. This system produces a vector $e \in \mathbb{R}^4$ whose components are values in the range [0,1], each representing the intensity of a specific emotion, calculated through a set of fuzzy rules (e.g., if both valence and arousal are very low, then the sadness is very high). Their output is defuzzyfied using the Center of Gravity defuzzyfication function.

Output channel: face and voice

Once the new emotion has been calculated, Hannah's facial expression is adapted to react to the emotion experienced. This is done by applying

Algorithm 1 Update of *valence* and *arousal*.

Input: The interaction event, described by an id and an impact (id_e, i_e).
Parameters: The valence and arousal growth and decay factors $\sigma_v, \sigma_a, \delta_v, \delta_a$; the event queue Q.
Output: Valence and arousal after the new event, v_t and a_t.

$enqueue(Q, id_e)$
if $|Q| > n$ **then**
  $dequeue(Q)$
Let $i_v = i_e$
if $sgn(v_{t-1} - 0.5) \neq sgn(i_v)$ **then**
  Let $i_a = \max(|(1 - f(id_e, Q)) \cdot i_e|, 0.5)$
else
  Let $i_a = \min(|(1 - f(id_e, Q)) \cdot i_e|, 0.1)$
Let $decay_v = (v_0 - v_{t-1}) \cdot \delta_v$
Let $update_v = \frac{\sigma_v \cdot i_v}{1 + i_v(v_0 - v_{t-1})}$
$v_t \leftarrow v_{t-1} + decay_v + update_v$
Let $decay_a = (a_0 - a_{t-1}) \cdot \delta_a$
Let $update_a = \frac{\sigma_a \cdot i_a}{1 + i_a(a_0 - a_{t-1})}$
$a_t \leftarrow a_{t-1} + decay_a + update_a$
  return v_t, a_t

the Facial Action Coding System (FACS) [159] developed by Ekman. This tool allows encoding facial expressions in a set of Facial Action Units (FAU). A FAU is an action associated with a facial muscle (e.g., raising or lowering inner brows). Ekman has associated each human expression (e.g., happiness, sadness) with a set of FAUs to activate. For example, to show happiness it is necessary to raise cheeks and pull lip corners. Thanks to Adobe Fuse, the avatar is provided with a set of blend shapes that roughly correspond to human facial muscles. We have therefore mapped each emotion with a set of blend shapes (as identified by Ekman) and the corresponding activation value. This allows us to simulate the activation of facial muscles, as in an individual. In case Hannah is experiencing two emotions with the same value (i.e., happiness and surprise or sadness and anger), the blending between the key shapes of the two emotions will be performed. In other cases, the blending is not performed to avoid unpleasant or unrealistic effects.

The voice response also changes according to the emotions, supporting the patient when he/she is sad, for example.

Currently, Hannah's tone of voice does not express emotions, as the Text To Speech (TTS) system in use does not support this feature. To solve this gap, in the future, more advanced systems such as Acapela[3] or Google TTS[4], which provide Emotional TTS, will be used.

This is the basic operation of EVT, which should give the reader the minimum information to understand how it works. More information can be found in [137].

6.4 Dynamic Difficulty Adjustment

As stated by Czikszentmihalyi in his theory of flow [133], a fundamental requirement to achieve the flow state is the difficulty of the game, which should match the ability of the player. A game should alternate more excited moments when the difficulty is greater and the player is more anxious, with other moments of calm (with lower difficulty), but without ever getting bored (Fig. 6.4).

To find the Flow channel suitable for the players, it is necessary to modify the difficulty so that it is adapted to their skills, which can change over time (generally, they improve as the player learns the game mechanics). One of the possible ways to find an adequate level of difficulty and adapt it according to the player status is Dynamic Difficulty Adjustment (DDA) [162].

A DDA system automatically adapts the difficulty of the game to better suit the player's abilities. DDA has been used in a large number of video-games in the latest years. The two best known and studied examples are probably Half-Life [163] and Left 4 Dead [164].

In [165], tensor factorization has been exploited to create a model of the player used to predict his/her performance over time. This prediction is used to adapt the game parameters to align the player's game performance with that desired.

In [166], the game is adapted according to the emotional state of the player. Authors analyzed physiological signals to infer the player's anxiety, difficulty is then adjusted in function of the anxiety level.

The need to adapt the difficulty becomes more necessary in serious

[3] Acapela Group, `https://www.acapela-group.com` (visited on 11/30/2020)

[4] Google Cloud Text-to-Speech, `https://cloud.google.com/text-to-speech` (visited on 11/30/2020)

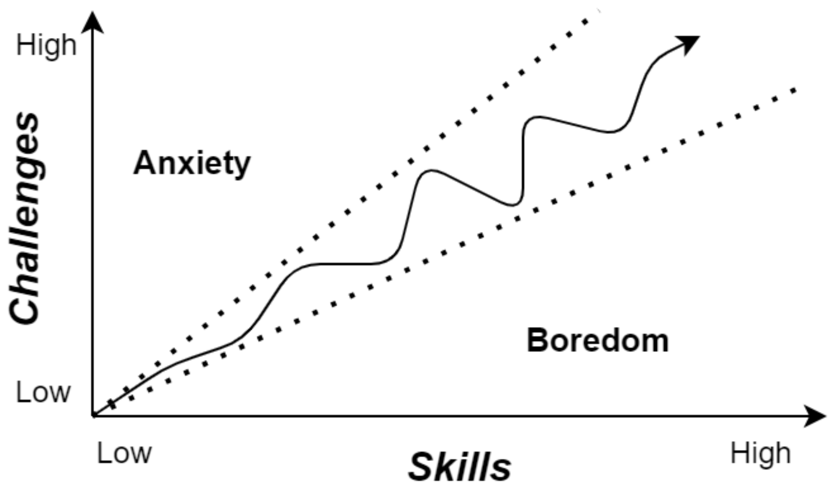

Figure 6.4: *The game's difficulty should be well balanced between anxiety and boredom. Too anxiety or boredom could decrease the engagement.*

games and exer-games. Patients could have different skills and learning abilities [167]. A certain degree of difficulty could not be suitable for some patients due to their limited physical or cognitive abilities.

In [168], a prediction of the player's skills and how they will evolve is made. Based on this prediction, the difficulty of some exer-games for upper-limb rehabilitation of stroke patients is adapted. The experiments show an improvement in the amplitude of movement by the patient in sessions with DDA enabled. In [169], exer-games for Parkinson patients have been presented. Each game has three parameters: speed, accuracy, and range of motion, which reflect the patient's hand control capability. At the end of the game, the three parameters are adapted according to the patient's performance. For example, if the patient was unable to reach the most distant targets, the range required by the game is lowered.

Given these premises, we decided to implement a DDA mechanism in the PS (with also the support of HS). DDA in exer-games has a double advantage. On the one hand, it better adapts the difficulty according to the patient's skills; on the other, it allows the therapist to save part of the long and complex scheduling work. As we have seen, our exercises and exer-games are characterized by various parameters. In the absence of an automatic adaptation mechanism, the therapist should constantly monitor the patient's status and adjust the parameters accordingly. This would take a great deal of time, which the therapist may not have.

We started from the DDA-related part of the work described in [116], where a Bayesian framework has been designed and implemented. This framework takes into account the level of difficulty set by the therapist and the current patient's performance, modifying the difficulty to tend to a predefined success rate. We extended the solution they proposed, providing a system based on three different modules:

- an *off-line adapter* which runs on the HS, using the data of the previously executed exercises, it creates a model representing the patient's physical capabilities.

- an *emotional adapter*, based on the outcome of the conversations between the patient and Hannah. Hannah tries to retrieve information about the patient's feelings regarding the difficulty of the game and, if necessary, can adapt it.

- an *on-line adapter* is finally used to adjust the difficulty according to the current state of the player in a particular game in terms of score and quality of posture.

These three modules, which can also work independently, are combined, taking into consideration all the factors (both physical and psychological) that, in our opinion, can influence the patient's performance.

To ensure safety during rehabilitation, parameters adaptation is restricted to constraints set by the therapists through the HS, who best know the patients and are able to set boundaries that allow avoiding risks.

6.4.1 The proposed model

We will be as general as possible in the description of the model, which can also be applied in other rehabilitation domains and other platforms. We start by defining E, the set of exercises available through the platform (e.g., *Stand Still*, *Weight Shift Lateral*, ...), and G, the set of games that are associated to these exercises. We recall that every activity can be uniquely identified by the couple $\langle e \in E, g \in G \rangle$.

The set of these devices needed to record the player's performance (e.g., Microsoft Kinect, Orbbec Astra, Wii Balance Board, ...) is D.

To allow customization, as already described, each activity is characterized by a series of parameters (exercise, game, and monitor parameters) which can be defined as follows.

Definition 2. *(Exer-game parameter) An activity parameter p can be defined as a tuple* $\langle D_p,\ m,\ M,\ z\rangle$*, where:*

- $D_p \subseteq D$ *are the devices necessary to measure the physical skill related to the parameter.*
- m *and* M*,* $m \leq M$*, are the minimum and maximum value that can be assumed by the parameter, defined by the therapist inside the HS.*
- $z \in [m, M]$*, the current value of the parameter.*

When $m = M$, the parameter is called *static*, and it cannot change during the execution of an exercise. Otherwise it is called *dynamic*, and it can vary between m and M. A parameter can be shared by different exer-games.

While an exer-game can be defined as follows:

Definition 3. *(Exer-game) An exer-game eg can be represented as a tuple* $\langle v,\ e,\ P,\ D',\ C\rangle$*, where:*

- $v \in V$ *is the video-game that will be played.*
- $e \in E$ *is the rehabilitation exercise.*
- P *is an ordered list of parameters, as defined in Def. 2.*
- $D' \subseteq D$ *is a set of devices required to play, it is defined as the union of the devices required by each parameter.*
- $C(.)$ *is the set of functions which map patient's current ability into game parameters.*

Note that this definition extends and differs slightly, but does not contradict, the previous definition of Activity (i.e., exer-game) we gave in Chapter 3. This change was necessary to allow a greater generalization of the model and its correct operation in the DDA system.

According to Def. 3, it can be noted that the difficulty of an exer-game depends exclusively on the values of the parameters associated with it.

So, given a generic exer-game eg, its difficulty can be defined through the weighted combination of the values assumed by its parameters:

$$f(eg) = \sum_{i=1}^{n=|P|} w_i P_{i_z} \tag{6.1}$$

$$w_i \in \mathbb{R} \; \forall i$$

where P_{i_z} is the value assumed by the i-th parameter of the exer-game, while w_i are patient-specific weights, and they depend on the patient's residual abilities. Finding the values of the variables w_i, and consequently, the objective value of the difficulty of an exer-game (given a particular patient), is practically impossible, and even useless, considering that it could change over time. Our goal is, therefore, not to find the value of the function f given a certain exer-game, but only find a set of initial parameters that guarantee a good level of difficulty, which is then dynamically adjusted at run-time.

To achieve this, the DDA system will be initialized with a set of parameters based on the patient's profile and on the outcome of the dialogues with the EVT, then the system will adapt these starting values according to the patient's performance during the execution of the games. This can be summarized in this way: if the game is too easy (i.e., low hit percentage), increase the difficulty; if the game is too difficult (i.e., high hit percentage), lower the difficulty. All the details about every phase of this process will be described in the next paragraphs.

It is up to the therapist to define which parameters can vary and their variation intervals. In this way, the DDA system will continue to work with a set of parameters that has been approved by the therapist, guaranteeing a good level of safety.

6.4.2 Patient's profile

As we have seen in Chapter 5, to assess patient progression, the therapist, through the HS, has the access to a series of metrics that define the quality of the patient's exercise. These summarize the actual patient capabilities in quantitative terms (e.g., maximum lateral movement amplitude, maximum speed, ...).

These metrics are also exploited by the DDA system: we first mapped the most important exercise parameters on the patient's physical capabilities, which will be estimated through the metrics calculated by the HS. This association will allow us to find an initial set of values by analyzing the performance of the patient in the previously executed exercises.

Let us take the *Fruit Catcher* game as an example, associated with the *Weight Shift Lateral* exercise, whose goal is to move the CoP laterally. It is easily understandable that the amplitude of movement required by the game is directly related to the patient's ability to move sideways, therefore to the maximum extension of the CoP recorded by the Balance Board. So, the minimum and maximum values reached by the CoP along the X-axis will then be stored. This is an example of a parameter that is strictly linked to physical ability, in some cases the correspondence may not be so direct. Always in *Fruit Catcher*, the "Spawning time" parameter represents the fraction of time elapsed from when the apple is visible to when it falls; the lower this time, the greater the speed the patient is requested to have to catch the apple. The metric linked to this parameter can be the average or the maximum speed of movement of the CoP. A physical parameter can be linked to different exercises. The CoP amplitude, for example, is also required by *Bubbles* (*Weight Shift 360°* exercise), which also requires the patient to move laterally.

The use of the physical parameter allows to abstract, avoiding a direct association with an exer-game. Every time a new exercise is played, all the physical metrics related to its parameters are updated. Since the patient's skills may change over time, only recently played exercises will be considered. Physical values will be used by the off-line adapter to determine the set of initial parameters suitable for the patient, to achieve it, the $C(.)$ functions (Def. 3) will be used.

6.4.3 Off-line adapter

The Off-line adapter is installed in the HS, and it is executed every time a new exercise is received. Its fundamental task is to update the patient's profile analyzing the new exercises.

Each time the HS receives a new exercise, the Off-line adapter extracts the assessment metrics from the exercise received and updates the patient's profile. To do it, it analyzes all the exercises recently performed (e.g., in the last 10/15 days) to create a reliable profile based on recent information. For each parameter, a function that takes as input the raw data of the devices and estimates the patient's physical capacities has been defined. This function can also take into account outliers and safety thresholds.

These values are then sent to the PS when the patient is preparing to play. The information received by the PS is just the physical limits that are necessary for the correct execution of a certain exercise.

Since the HS is game-agnostic, it is not aware of the concept of "exer-game" and its mechanics; to be able to convert the real-world information contained in the patient profile into game-world information, we use the $C(.)$ functions described in the exer-game definition (Def. 3).

Every parameter p has its own converting function c_p. Always taking the *Fruit Catcher* exer-game as an example, the avatar representing the patient has a basket on the head, increasing the width of the basket will help the patient to catch apples. It means that the maximum movement suggested by the HS will be approximately increased by an amount equal to the width of the basket divided by two. As can always be seen from Def. 3, the parameters of an exer-game are an ordered list, the conversion functions must be applied to preserve the order. This is necessary to manage the dependency between parameters.

Let us clarify better with an example: in *Fruit Catcher*, we first calculate the maximum distance that a patient can reach for both sides, then, given the two distances and his/her speed, a suitable spawning time is calculated. It is not always possible to perfectly define a converting function, but the off-line adapter is not interested in achieving that; since the difficulty level will be further tuned by the online adapter, which can remove this inaccuracy.

6.4.4 Emphatic Virtual Therapist

In commercial video-games, the difficulty level is changed manually or automatically based on the player's skills without worrying about his/her physical or psychological condition. In home rehabilitation the situation is different, the patient may, for example, experience pain even when the difficulty is reasonable. In these cases, having an automatic tool that understands the patient's needs and mood can be useful.

This could also be helpful in the presence of psychological disorders such as depression. Also, any misconfiguration of exer-games could lead to frustration and negative emotions; this should be identified and corrected as fast as possible.

To this end, in the PS, it is possible to have a conversation with Hannah. She will try to understand the emotions experienced by the patient, and eventually change the difficulty of the exercises and/or advise the therapist that something is wrong. This can be done by visiting Hannah's virtual office (Fig. 6.5): during these conversations, the EVT asks questions to the patient, who can answer by selecting one of the predefined sentences. EVT is implemented using Dialogflow[5], a Google Cloud Service for creating chat-bots.

Based on the patient's answer, the EVT can provide different outcomes. For example, if the patient is bored because exercises are too easy, the EVT can propose to increase the difficulty of some exercises; on the opposite, if the patient is feeling pain, the EVT can decrease the difficulty and warn the therapist if necessary. Hannah has access to the parameters of the exercises recently played, based on patient feedback, she calculates the new values that will be suggested in subsequent games.

Hannah plays a key role in the patient's motivation, as she tries to understand the patient's emotions, which are sometimes underestimated. The level of difficulty of the games is subjective: some patients may prefer a higher or lower level depending on their character. In addition to fully automatic systems that rely exclusively on the analysis of objective data from the devices, we believe that taking into consideration also the patient's emotion is also important to adapt the therapy.

6.4.5 On-line adapter

Off-line adapter and EVT are two different methods to resolve the same problem: find the best starting value for each parameter. It is so necessary a way to merge their outputs, giving each one the right importance. Off-line adapter monitors only exercises played in the last days. Assuming that the patient is following the schedule and playing at least a couple of sessions every week, a good number of executed exercises will be available. If the patient is playing for the first time or only a small

[5]Dialogflow, `https://www.dialogflow.com` (visited on 11/30/2020)

Figure 6.5: *In Hannah's office, it is possible to have short conversations, through which the patient can express his/her mood and thoughts about the exercises.*

number of exercises is available, the adapter will not be able to suggest the starting values, and it will be ignored.

EVT is quite different: it is not possible to assume that the patient talks with her frequently, so the decisions made by the EVT should have limited power in time; if several days have elapsed since the last time the player spoke with her, her decision should have little importance.

The final value for each parameter p_i will then be calculated as follows:

$$p_i = \begin{cases} \frac{1}{2}(m_{p_i} + M_{p_i}) & \text{if } n_{EVT} \geq t_{EVT} \ \wedge \ n_{HS} < t_{HS} \\ p_i^{HS} & \text{if } n_{EVT} \geq t_{EVT} \ \wedge \ n_{HS} \geq t_{HS} \\ p_i^{EVT} & \text{if } n_{EVT} < t_{EVT} \ \wedge \ n_{HS} < t_{HS} \\ \frac{n_{EVT}}{t_{EVT}} p_i^{HS} + (1 - \frac{n_{EVT}}{t_{EVT}}) p_i^{EVT} & \text{otherwise} \end{cases}$$

Where p_i^{HS} is the value suggested by the off-line adapter and p_i^{EVT} is the value of the same parameter suggested by EVT. Their estimates are weighted based on the reliability and recentness of their data: n_{EVT} is the number of days since the last time the patient spoke with the EVT, and n_{HS} is the number of rehabilitation sessions recently played. t_{EVT} is the threshold above which the input of the EVT is considered not reliable (e.g., 10 days), and t_{HS} the threshold under which the input from the HS was considered not reliable.

When both the off-line adapter and the EVT suggest reliable values, a weighted average between them is computed.

If a reliable input is obtained only from one module, that input is retained. In the case that both off-line adapter and EVT do not have enough information, the mean between the minimum and maximum values (set by the therapist in the HS) for each parameter will be used. This should always ensure a minimum level of safety.

These initial values, suggested by the combination of the Off-line adapter and the EVT, will then be further tuned in real-time, depending on the quality of the patient's exercise.

The goal of this adaptation is to remove errors produced by possible inaccuracies of the off-line adapter and EVT, taking into consideration the patient's status on that particular day. For example, if the patient is sad or feels pain, he/she could perform worse. The off-line adapter cannot recognize it since it works analyzing a large set of previously executed exercises, and EVT cannot help either if the patient has not talked to her.

To avoid too frequent changes in the difficulty, the adaptation takes place between two consecutive repetitions. The inputs of the online adapter are the following:

- R_h: repetition hit rate,
- R_m: repetition monitors activation rate,
- R_t: repetition trials information,
- G_h: global hit rate,
- G_m: global monitors activation rate,
- G_t: global trials information,
- f_a: evaluation function.

Hit rate and monitor rate are concepts already mentioned, they describe the patient's performance based on the number of successfully completed trials and the quality of posture.

f_a is the evaluation function, using all the other parameters, it returns an array d, where d_i represents the variation of the parameter p_i. Potentially, every dynamic parameter can be modified at the end of a repetition.

The implementation of f_a can vary greatly: it can depend on the exergame and how inputs parameters are used. The simplest algorithm could be using only R_h and increase or decrease the difficulty of all parameters according to a couple of thresholds. For example, if R_h is under the lower threshold, the difficulty can be decreased; otherwise, if it is higher than the upper threshold, it will be increased.

Finally, R_t and G_t are the information of the trials performed, they include all the parameters used for their generation. The latter allows a better adaptation of the parameters. Take, for example, *Fruit Catcher*. Suppose that on a given Repetition the patient has successfully achieved half of the objectives, with such a low percentage, it makes sense to lower the difficulty level. But what if the patient had failed all the targets in a certain direction? It means that we should decrease the required distance for that side and probably increase the distance for the other side (since he/she reached all the targets in that direction).

The monitors' information can also be used to analyze the postural quality of the patient: a high level of difficulty could force the patient to worse his/her posture to reach targets. This is probably a behavior we would like to avoid, f_a can take this into consideration and balance difficulty also according to this information.

To achieve it, one of the possible functions we suggest to use is the following:

$$p_i = \alpha \; FPA(R_h, R_m) + (1 - \alpha) FMA(G_h, G_m) \tag{6.2}$$

$$\alpha \in [0, 1]$$

Where:

- FPA is the *Fully performance adapter*: it uses only the information regarding the hit percentage, ignoring the monitors' values.
- FMA is the *Fully monitor adapter*: safer from the rehabilitation point of view, it completely ignores the hit rate, and it uses only monitor information to adapt the difficulty.

Therapists can decide the α value to determine how much importance to give to the patient's posture for each exercise.

We implemented two possible algorithms for FPA and FPS: a linear adapter and a fuzzy adapter. The linear adapter adjusts difficulty increasing or decreasing the parameters by a fixed quantity, regardless of the percentage of hits or monitors: under the lower threshold, the difficulty is decreased; above the upper threshold is increased. While the fuzzy adapter uses a more complex algorithm to calculate the new percentage: if the percentage is much lower than the lower threshold, the difficulty is greatly increased; the same thing happens with the upper threshold. In both of them, R_t has been used to discriminate the parameters to change.

This DDA system, thanks to the three different factors taken into consideration (patient performance and ability in the last sessions, psychological aspects, and run-time performance), should be able to adapt the difficulty better, compared to other systems that take into account individual aspects. In addition, these three components are completely independent and optional, each of them can work independently or in combination with the other components, facilitating the reuse of the system even partially.

Unfortunately, due to timing problems, it was not possible to include this system in the trial with patients or the elderly. Further trials will be necessary to verify its effectiveness and usability.

6.5 The Farm Game

Until now, we have described a few solutions to increase the patient's engagement when playing the exer-games. In this last component, we changed approach, aiming to add a common background and a connection between exer-games. We call it "the Farm Game", it is a central hub in which patients are required to play the exer-games if they want to increase the value and productivity of their virtual farm. In this way, exer-games are now a part of a bigger game, and they become sub-games, which are played for an actual reward that can be appreciated inside the Farm Game, not just for rehabilitative purposes. This should help to find additional motivation, both intrinsic and extrinsic, which hopefully will extend the longevity of the platform.

An important consideration: we added the Farm Game to entertain the patient more, but since the goal of the platform is allowing to perform rehabilitation, playing exer-games must be a mandatory activity; otherwise, the Farm Game could become a distraction from the original purpose. This implies that Farm Game must be designed so that patients are "forced" to play exer-games if they want to progress in it. In this way, if they appreciate the Farm Game, they will not feel the burden of having to perform the exercises because they will get other types of rewards.

On the other hand, the central hub should not be intrusive with respect to the rehabilitation exercises: if the patient does not like to play and he/she does not want to spend time playing the Farm, he/she should be able to do it without negative rewards in the exer-games, so the exer-games behavior must not change.

6.5.1 Gameplay

Let us now describe how the Farm Game works. In particular, we will focus on the design issues necessary for its proper relationship with the exer-games. During the development of the Farm Game, the guidelines described in Chapter 4 have been followed for a correct design of the user interface. Particular attention has been paid to "Gorilla arm syndrome" [118], preventing the user from excessively long sessions in which the use of the arm is required.

The Farm Game is in some ways similar to the famous FarmVille[6] game: the patients can build their own farm by spending points that they have gained playing exer-games. In this way, patients are encouraged to exercise more if they want to progress in the Farm Game. In Fig. 6.6, it is possible to see the main view of the game.

To balance the time spent in the Farm Game and the time spent practicing, a careful economic system has been developed. Two different currencies are available: *Farm Points* (FPs) and *Coins*. FPs are gained by playing exer-games, while coins are used to increase the farm's value and can be obtained only by selling resources (i.e., plants and farm animals), which can be purchased with FPs.

Let us start by describing the actions and features available through the Farm Game:

- *Create a new container for resources*: players can buy a block of

[6] FarmVille, `https://www.zynga.com/games/farmville` (visited on 11/30/2020)

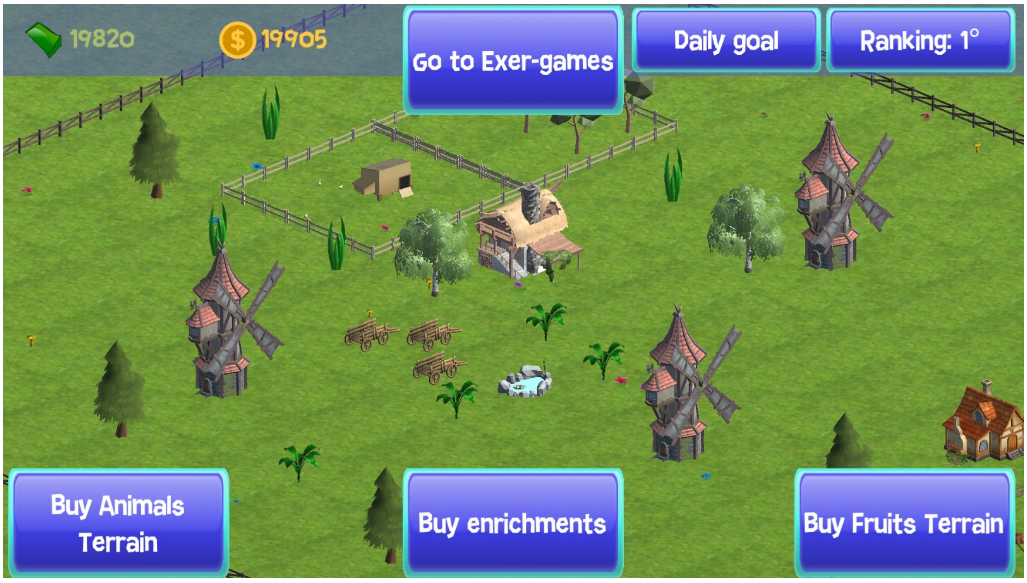

Figure 6.6: *Main view of the Farm Game. As it is possible to see, all the buttons are large in size and are spaced apart for ease of selection. From this interface, the player can perform all the main actions of the game.*

land, where they can grow animals or plant fruit trees. From now on, we will use the word "resource" to identify animals and plants. Each block is called a *container*. Containers can only be purchased using coins. Each container can only contain one type of resource, up to 9 units. By paying coins, it is possible to convert a container allowing it to contain a new kind of resource.

- *Buy a new resource*: once a container is available, by paying a certain amount of FPs, the player can buy a new resource, which will be added to the selected container. Every plant and every animal has a growth level, their level increases when the patient plays an exer-game. From the moment the patient buys a new resource, he/she needs to perform four exercises to make the animal or plant grow.

- *Sell a resource*: once the final stage of an asset is reached, the player can sell it at the market, earning coins. The market has been programmed to simulate a real market: the number of coins earned when selling a resource depends on the type of resources sold and their demand. If a player always sells the same type of resource, the earned coins will continue to decrease because the demand for that resource decreases. This is intended to encourage the conversion and creation of new types of containers.

- *Buy an enrichment*: if the player wants to increase the beauty of his/her farm, he/she can buy an "enrichment", a purely decorative object that allows to beautify and increase the value of the farm. To buy an enrichment, a certain amount of coins is needed. It has been shown that the possibility of customization in video-games increases the enjoyment of the player [170].

- *See the daily goals and the ranking*: further information will be provided in the following paragraphs.

FPs are the main core of the game. They can only be earned by playing exer-games: the higher the quality in the execution of the exer-game, the higher the FPs patient earns. Without them, it is not possible to buy animals or plants, which are necessary to buy containers and decorations. The logical flow and functioning of the two coins are shown in Fig. 6.7. In this way, the two coins are well balanced, and the only way to continue is to play the exer-games. To prevent the players from ending up completely without resources, they are initially provided with two empty containers.

6.5.2 Exer-games and Farm Points

Since the only way to earn FPs is to exercise, patients need to play exer-games if they want to advance their farm. To also stimulate good exercise performance, the amount of points earned depends on their performance and other factors, such as the duration of the game or the difficulty of the exercise. In this way, we encourage proper execution of the exercise to obtain more FPs.

At the end of each exer-game, the patient will earn a number of FPs according to the following formula:

$$r = r_{base}(1 + \frac{t \cdot b}{10}\ (\alpha\ p_{hits} + (1 - \alpha)\ p_{monitors})) \tag{6.3}$$

$$p_{hits}, p_{monitors} \in [0, 1]$$

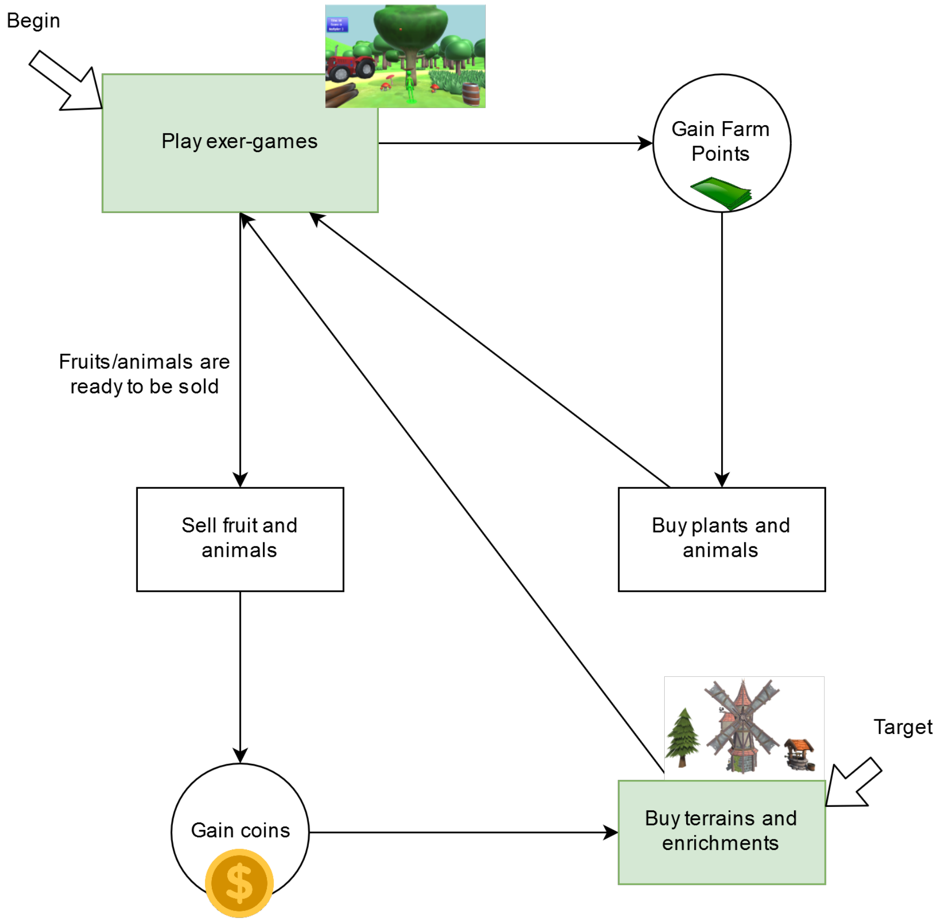

Figure 6.7: *The game flow of the Farm Game. The game mechanics have been designed to induce the patient to play the exer-games, the primary goal of the platform.*

Where:

- r_{base}, called Base Reward, is an integer value that is proportional to the level of difficulty set by the therapist through the HS.
- t is the duration of the exer-game, measured in seconds.
- p_{hits} is the percentage of correct trials (i.e., the Hit percentage).
- $p_{monitors}$ is the fraction of time during which no monitors have been triggered.

While the bonus value b is computed as follows:

$$b = \begin{cases} rel \cdot 0.5 & \text{if } s_{ratio} < 0.5 \\ rel \cdot 1.5 & \text{if } s_{ratio} > 1 \\ rel \cdot s_{ratio} & \text{otherwise} \end{cases} \quad (6.4)$$

$$s_{ratio} = \frac{s_{current}}{s_{best}}$$

$$rel \in [1, 5]$$

Where:

- rel is a parameter that is set by the therapist. It represents the relevance of that exercise for a particular patient. Some patients may need to perform certain types of exercises to improve their condition. As can be seen from the formula, the higher the value of rel, the greater the number of points that are earned; in this way, we try to encourage patients to play that set of exercises which are more useful for them.
- $s_{current}$ is the score of the exercise that has just been played.
- s_{best} is the highest score that the player has ever obtained in that exercise.

In other words, players receive a greater reward if they are able to beat their high score, even better if this happens in a particularly relevant exercise.

6.5.3 Gamification elements

To increase the extrinsic motivation of the players, we have also integrated some well-known elements of gamification. Talking about "gamification" in our field might be slightly inappropriate since it is defined as "use of game design elements in non-game contexts" [171], but we are applying it to a set of exer-games (i.e., in a game context). However, the definition of gamification has several nuances: in our case, we do not have a complete video-game, which is played just for the sake of being played. We are always in the field of serious games, which by definition is the application of video-games for non-entertainment purposes; with this assumption becomes clearer the need to use all possible mechanisms to entertain the user. For these reasons, we included:

- *Daily goals*: three random goals are generated every day (e.g., play at least three games, play a specific game, buy an enrichment, ...).

When the patient achieves a goal, he/she is rewarded with additional Farm Points. This approach can be improved by customizing it according to the needs of each patient. For example, we could encourage the player to play exer-games with greater relevance, generating goals that target those particular games.

- *Awards for particular events*: the patient will be rewarded with additional points upon reaching particular events (e.g., getting a new high score, playing consecutive days, ...).
- *Leaderboards*: it has been shown that leaderboards and badges can be used as extrinsic motivation strategies to enhance the player motivation both in traditional video-games and in educational/learning contexts [172]. In the Farm Game, we developed a virtual leaderboard: whenever the patient buys something, he/she will gain a certain number of ranking points according to the value of the purchased item: the more items are bought, the more ranking points will be gained. The leaderboard includes 10 players: 9 virtual players and the real patient. Virtual players have been programmed in such a way that the real patient is usually between the first and the fourth position since players usually perceive themselves more autonomous and competent if they are in the first positions [173].

6.5.4 Customization

Several studies proved that customization can help to increase the sense of autonomy and control [170] [174], and improving the game experience [175]. 24 different decorations are available in the Farm Game, and they can be added to the scenery. To give a greater sense of progress in the game, only a small set of decorations is available at the beginning; the others require to reach a certain ranking point, thus stimulating the patient to play to unlock new items.

6.6 Discussion

We close the chapter with some final considerations. We have shown here a few solutions, PCG, DDA, the EVT, and the Farm Game, that can entertain the patient. The effectiveness of these techniques, which

Figure 6.8: *Example of decorations available in the game. Assets shown have been downloaded from the Unity Asset Store.*

can be improved, and eventually extended (maybe even improving the mechanics of the exer-games themselves, for example), also depends a lot on the type of patients being treated.

If we are talking about the elderly, people with usually a lot of free time, they are more likely to be very effective. As the older person will have more time available, and will not have to go to work. While if we are treating patients of working age, and maybe with a family, it is more logical to think that they will minimize the time spent in front of the PS, maybe limiting themselves to the exercises planned by the therapist, without doing additional activities. Furthermore, there may be patients who do not like to play or who prefer traditional rehabilitation. In these cases, clearly, the solutions we have proposed will not be effective at all.

Getting to the gist of it, there are no universal solutions that can entertain the patient forever. What we have presented here are some solutions that we believe can work with some types of patients, but still in a limited time. Even if their effect is limited, it may be worth exploiting them because even a minimal increase in patient adherence can have important results.

CHAPTER 7

Mirarts

The architecture seen so far, with the patient practicing at home and the therapist controlling remotely, is quite common in literature. In this chapter, we try to go one step further, applying the new technologies of augmented reality and mixed reality to rehabilitation. The use of these technologies, in the coming years, could transform rehabilitation, providing therapists with a range of quantitative information to which they previously had no access.

To this end, exploiting Microsoft Hololens[1], a recent mixed reality headset, we developed Mirarts, a novel application to support the therapist during traditional one-to-one rehabilitation sessions. Mirarts provides, in real-time, quantitative information similar to that provided by the HS. It has also been integrated into the PS/HS architecture, allowing the real-time adaptation of exercises, and the analysis of patient performance in the long term.

Some images and contents of this chapter have been previously published in [176].

[1]Microsoft HoloLens, https://www.microsoft.com/en-US/hololens (visited on 11/30/2020)

7.1 Virtual Reality, Augmented Reality, and Mixed Reality

In recent years, thanks to the continuous improvement of computational capability and miniaturization, new types of devices have been created. Among these, virtual, augmented, and mixed reality devices are increasingly known and popular among the general public.

Although they all seem very recent concepts, *Virtual Reality* (VR) and *Augmented Reality* (AR) have begun to spread since the 60s. At the time, they were obviously primordial devices, very different from what we mean today. The computational capability of the time (and subsequent decades) was certainly not sufficient to develop marketable devices. We need to get to the present day, from 2010 onward, to start seeing the first diffusion of these technologies. However, at the time of writing, although several devices of this type are available on the market, they remain niche products, mainly due to a not particularly cheap price and a reduced number of applications and games available. Nevertheless, the trend is improving, and we hope for greater diffusion of these devices in the coming years.

VR and AR, in a way, could almost be seen as opposite concepts. On one hand, a complete immersion in the game world losing all contact with the real world; on the other hand, the user continues to interact with the real world, to which virtual elements are added. The concept of AR has evolved over time compared to its original concept, and now very often takes the name of *Mixed Reality* (MR). To unravel any confusion, we now see a brief history of these technologies.

VR begins its real diffusion starting from about 2012, when Oculus shows the first prototype of its visor: the Oculus Rift DK1. The first version available to the public will be released only 4 years later, in 2016. This type of technology aims to immerse the user in a completely virtual world (hence the name - virtual reality), completely replacing the visual and sound perceptions of the real world with those of the virtual world. The user will therefore lose the conception of what is happening around him/her (with potential safety issues if he/she is asked to move). This type of devices is mainly designed for entertainment and gaming, thanks to its immersive nature, much better than other gaming devices that currently exist. However, it is beginning to spread to other areas.

It is not difficult to find VR devices even in museums, aquariums, or similar places, where they have the most educational purpose. Also in literature, interesting works start to be found. Just to cite a couple of examples: VR has been used to support post-stroke [85] and Parkinson's disease rehabilitation [177].

AR, on the other hand, does not replace the user's visual and auditory senses but can supplement them with additional information. This type of technology lends itself less to video-game use, as the user remains aware of the real world. Therefore, it becomes difficult to develop complex video games; however, there are numerous small games, often for smartphones, that use AR to entertain the user. This type of technology can be useful in various areas, as it provides the user with a source of information to which he/she would normally not have access. Initially, the AR was conceived as simple static information on the monitor (mainly text or simple 3D models), with which the user could not interact.

For this reason, after the development and distribution of Microsoft Hololens, the concept of Mixed Reality (MR) has been introduced. This new term identifies a new category of devices that do not just show static information on the screen, but information and objects (such as 3D models, for example) are placed within the real environment, and the user can interact with them. MR can therefore be seen as a natural evolution of AR, which is no longer limited to showing objects superimposed on the real world, but these objects are truly part of the world.

7.1.1 Mixed Reality and Microsoft Hololens

To date, the only true Mixed Reality device is Microsoft Hololens. The technology is still immature. Microsoft's only competitor is (or maybe it is better to say was) Magic Leap, which after 9 years of development and 3 billion investments turned out to be a colossal flop, and to be forced to lay off half of its employees in 2020. Other devices, which define themselves as MR devices (e.g., Samsung HDM Odyssey, Dell Visor, Lenovo Explorer), are in fact VR devices, equipped with cameras that can simulate the eyes, but their real MR applications are almost non-existent.

Given this necessary premise and an environment everything but rosy, we managed to get the first version of Microsoft Hololens (Fig 7.1), with

Figure 7.1: *Hololens 1 headset, developed by Microsoft and sold from 2016. It has now been replaced by the most recent model: Hololens 2.*

the aim of applying it to the domain of rehabilitation. Developed in 2016, equipped with a depth camera, four “environment understanding” sensors (gray-scale cameras), a color camera, and an ambient light sensor, is able to perceive and reconstruct the environment around the user. The depth camera also allows to detect obstacles, walls, or floors, and developers can use this information in their applications. At the beginning of 2019, the second generation of Hololens has been presented by Microsoft, featuring new hand and eye tracking, allowing users to better and more naturally interact with virtual elements.

Hololens is not a device designed for the general public. Its cost is very high (over $3,000), and there are many limitations. The biggest is the very narrow field of view, which greatly limits the experience. In the case of Hololens 1, moreover, prolonged use is not recommended due to the poor ergonomics of the device, and also the interaction with the software is not particularly comfortable. Hololens 2 has partially solved these problems, expanding the field of view, and improving ergonomics and interaction. However, it remains a niche device designed for some areas of the business world; before a few years will not be available to the consumer world. This can certainly be seen as a partial failure, considering that Microsoft itself presented Hololens also focusing on gaming and the consumer world. The hope is that the development will continue and will not have the same end as Magic Leap.

Despite all these limitations and problems, the first works exploiting Hololens are beginning to spread in the literature. The peculiar characteristics of the mixed reality and the device make it inclined to be applied in different areas, such as engineering, education, tourism, or medical. In [178], authors successfully used Hololens to provide assembly instructions; they integrated Vuforia[2] to increase accuracy using marker-based tracking.

In medical fields, Hololens has been used during autopsy [179], providing remote supervision, annotation, 3D image viewing, and manipulation. Always remaining in the medical field, in [180], authors used Hololens in endovascular interventions, showing the 3D view of the vascular system without the need for radiation, avoiding X-ray exposure. Other works in medical fields include [181] [182] [183].

These are just a few examples. Many of these works are very limited to date, and lack real results. Surely even the prototype state of the device does not contribute to large scale experiments. In the future, we hope that new devices will spread on the market, more advanced than the current models. In spite of everything, however, its application to so many different domains bodes well for its greater diffusion and applicability in the coming years.

7.2 Mirarts: Mixed Reality applied to rehabilitation

After this brief introduction to these new technologies, let us now see how Hololens has been integrated into the PS/HS architecture.

We have developed Mirarts (MIxed Reality Adaptive Rehabilitation Therapist Station), an application for Hololens to support the therapist. Mirarts has been developed with the aim of being used in the hospital by the therapist, in traditional one-to-one sessions. To this end, it has two main features:

- ***Provide quantitative data***: it provides the therapist with a series of objective metrics on the patient's performance. Through these metrics, the therapist can make more informed decisions to increase the effectiveness of rehabilitation.

- ***Adapt exer-games difficulty***: it can be used in combination with the PS, allowing to adapt the difficulty of the games in real-time to analyze how the patient reacts.

[2] Vuforia, `https://developer.vuforia.com` (visited on 11/30/2020)

The idea is to allow the therapist to have a series of additional information such as stability or amplitude of movement, with which therapists can base their choices in the definition of rehabilitation therapy.

As we already mentioned in the introductory chapter, currently, this type of rehabilitation is based a lot on the experience and judgment of the therapist, who must analyze both the physical condition of the patient and the psychological one. Having a tool that provides objective metrics could be helpful in the decision-making process. It would mean integrating the experience of the therapist with the objectivity of modern devices. In this way, the human factor would not be ignored (a key factor in rehabilitation) but enhanced.

Currently, there are already several validated tests that can provide objective metrics (e.g., Smart Balance Master[3] or GAITRite®[4]), but they are long and complex tests that can be performed from time to time. Having a less precise evaluation tool than clinically validated tests, but usable on a daily basis could be an important step forward.

7.3 Application architecture

Let us start the description of Mirarts starting from the architecture and how it has been integrated with HS and PS. The complete architecture is shown in Fig. 7.2. Note that the operation and communication between HS and PS are identical to those described in the previous chapters and therefore are not shown in the figure.

In this configuration, Mirarts receives information from both PS and HS:

- From the Patient Station, it receives the raw data of all the connected devices, through which it can calculate metrics representing the quality of the exercise. Through the PS, Mirarts also get all the parameters of the current exer-game, with the possibility of modifying them at will.

- From the Hospital Station, it receives the data of the previously executed exercises, allowing to compare the performance of the ex-

[3] Smart Balance Master, `https://www.mossrehab.com/smart-balance-master` (visited on 11/30/2020)

[4] GAITRite, `https://www.gaitrite.com` (visited on 11/30/2020)

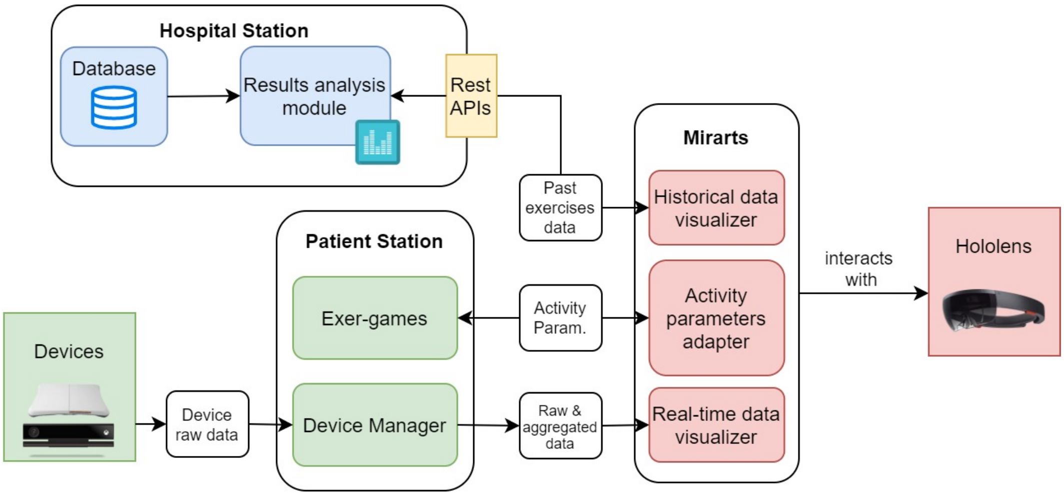

Figure 7.2: *Complete platform's architecture: Mirarts is connected to both PS and HS. All information relating to the activity currently in progress is exchanged with the PS, while the HS provides advanced metrics to compare the performance of the current activity with that of previous activities.*

ercise that the patient is carrying out with one or more exercises of the same type performed in the past. In general, the HS can also be used to perform computationally intensive calculations that should not be feasible using only Microsoft Hololens due to low computational power and limited battery power.

From this architecture, we could interpret Mirarts as a kind of portable HS, which in real-time provides the metrics representing the quality of the exercise that is being performed. These metrics are calculated thanks to the data of the devices sent by the PS. The latter, moreover, having a good computational capacity (compared to Hololens, which has a limited battery and CPU), can also already provide aggregated data to limit Hololens tasks.

The architecture just described, allows Mirarts to interact with the platform as completely as possible, also modifying the functioning of the exer-games. Actually, Mirarts can also work without HS and/or PS. Note, always from Fig. 7.2, that Mirarts is composed of 3 distinct modules. Each of the three modules can be present or absent, adding or removing functionality to Mirarts. In the simplest configuration, in fact, Mirarts can also be used almost alone. This configuration is designed to be used in individual sessions and traditional rehabilitation (i.e., without exer-games). However, since Hololens 1 does not have real-time body tracking, a desktop application that implements the PS's Device Manager module and interacts with Kinect and/or Wii Balance Board and forwards the data to the Hololens is needed. If and when a mixed reality device with an integrated RGB-D camera that offers real-time skeleton tracking will be developed, it will be possible to avoid the use of other external devices, improving the usability and ease of use of Mirarts.

7.4 Features

We now briefly describe the additional features made available through Mirarts. Many of the calculated metrics are similar to those calculated by HS and PS, so we will not dwell long.

Assuming that Mirarts has access to the raw data of Kinect and Wii Balance Board that are sent by the PS, the following information is provided to the therapist:

- ***Basic game information***: information strictly related to the game, such as the hit percentage, the monitor activation percentage, or the current duration of the exercise, is available.
- ***Monitor information***: through the data coming from the PS, Mirarts shows any posture errors through a skeleton that is displayed in front of the patient so as not to overlap his/her, avoiding vision problems. The same color system used in the PS monitoring system is also used in Mirarts to indicate the error the patient is making.
- ***CoP and CoM visualization***: along with the skeleton, we also provide therapists with the capability to see the CoP and CoM of the patients. CoM is positioned on the skeleton to make it easier to check, while the CoP is projected to the ground, near the patient's feet.
- ***Exercises metrics***: Mirarts calculates some metrics that represent the quality of the exercise (for example, stability, precision, ...) and shows them at run-time. The metrics are the same as previously described in Paragraph 5.5.3. Similar to the results shown by the HS, these metrics can be shown as a graph or as simple text information (for example, the maximum amplitude reached). Mirarts, compared to HS, provide additional features:

Figure 7.3: *Mirarts main view. On the left, it is possible to see the graphs showing the trend of the CoP during the execution of the exercise. On the right, in addition to a series of summary metrics (top box), it is possible to change in real-time the main parameters of the exercise (bottom box).*

- The CoP amplitude is shown near the patient's feet. It is represented by an n-gon, a polygon with n sides, and is calculated at run-time from the CoP position in each frame. The CoP area is also shown and calculated once per second.
- Load cells data of the Balance Board: Mirarts, through vertical bars positioned around the patient (Fig. 7.3), shows the values in kilograms recorded by the Balance Board. Aggregate data are also available (e.g., left cells versus right cells or upper cells versus lower cells), depending on the type of exercise.

• **Parameters updating**: through a dedicated panel always visible, the therapist can view the current values of the game, exercise, and monitor parameters, and modify them if necessary. Due to space limitations, only the most representative parameters are present. Some secondary parameters (e.g., the pause between two repetitions or the number of tests per minute) are not available.

To be able to see all this information correctly, when Mirarts starts, it is necessary to calibrate the device, indicating the location of Kinect, so that the correct position of the patient can be calculated.

The interface developed has been studied to be non-invasive and easily visible to the therapist. For this reason, all data is displayed around the patient, without interfering between therapist and patient. In this way, the therapist can continue to observe the patient without distracting himself/herself by looking at other monitors. Information and graphics are designed to be accessible at a distance of about 2 meters or less, and they rotate autonomously towards the therapist to be always readable. Automatic font size adjustment could be easily added to improve the readability of the information even at longer distances.

7.4.1 Historical data

Sometimes the therapist may need to compare the current exercise with a previous one to see if the patient has improved or worsened. As with the HS, there is a similar mechanism here. During the execution of an exercise, the therapist, using his/her credential, can connect to the HS to retrieve historical data from the exercises performed previously.

This data is shown in the graphs together with the data for the current exercise, so it is possible to compare the current execution with those previously performed. Through a set of buttons, therapists can retrieve the data of the exercises performed in the last N days or the last M exercises. Since it is not possible to show a series of data for every single exercise performed, the average trend is calculated by the HS. It first selects the subset of exercises required by the therapists, then it calculates (if not already stored and calculated) the required metric for all selected exercises and normalizes the duration of these exercises so that they can be compared. Finally, it computes the mean (or other functions, like minimum or maximum) between the metrics. Once the data set has been calculated, it will be sent to the Mirarts and drawn in the graph.

A current limitation of this method is that it can produce results that are difficult to interpret in some cases, e.g., if the time of the trials of the exercises under consideration differs. Think, for example, of two executions in which at the same time the patient moves to the left, while in the other one is still standing at the center.

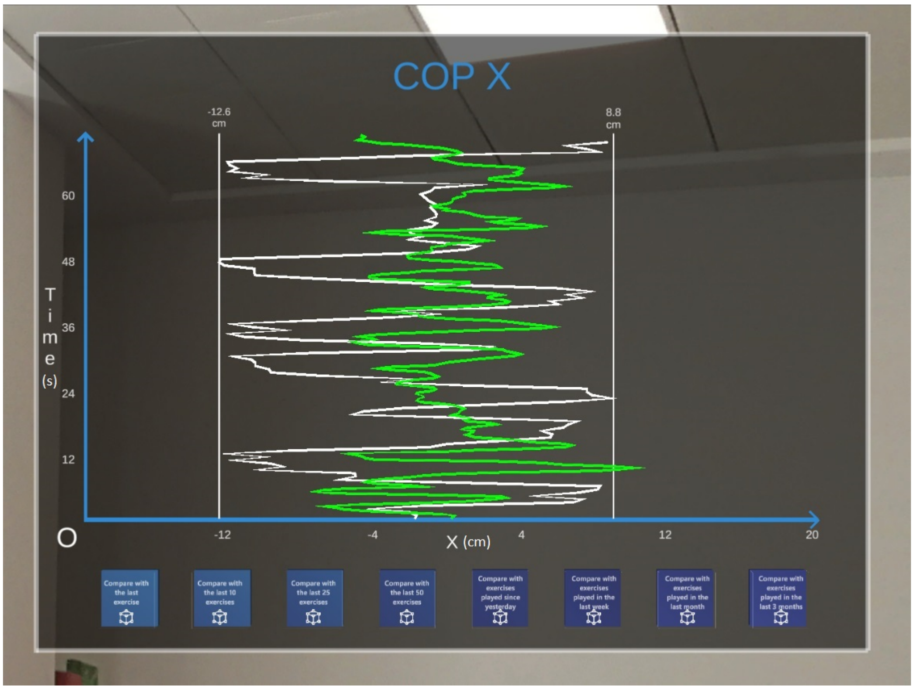

Figure 7.4: *Example of comparison between the lateral shift of Weight Shift Lateral calculated in the current exercise (white line) with the average calculated in past exercises (green line).*

This problem is currently only partially solved through the use of other aggregation functions such as maximum or minimum. In the example of *Weight Shift*, in fact, the therapist might be more interested in the maximum amplitude of movement obtained, to compare it with the current amplitude. However, this solution is not always possible. Further work will be needed, such as trial alignment, to provide more representative graphs.

7.4.2 Exercise results

At the end of the execution of an exercise, a summary is presented to the therapist in a dedicated view. In this view, the therapist can see:

- Exercise and game basic information such as the duration, and hit and miss percentage.
- All the graphs containing the metrics to evaluate the quality of the exercise.
- A set of snapshots.

Figure 7.5: *Example of exercise results. For each snapshot, the basic game information (% Hit,% Miss, ...) and summary parameters (e.g., maximum amplitude requested, ...) are shown. In this way, the therapist can evaluate how the patient's performance has changed when the parameters have been modified.*

The last point, the snapshots, are a new important feature provided by Mirarts. A snapshot can be defined as an "interval of time in which the values assumed by the parameters do not change". So, every time the therapist changes a parameter, a new snapshot is created. For every snapshot, we calculate the basic game information and other metrics. To better understand the advantages of this approach, see Fig. 7.5, where an example summary screen is shown.

This figure provides summary data at the end of the *Weight Shift Lateral* exercise. In this exercise, the amplitude of movement requested by the patient (laterally, to the right and to the left) represents the difficulty of the exercise. Thanks to the visualization through snapshots, it is possible to understand the progression of the patient's performance according to the change in the difficulty of the exercise. For example, initially, requiring a 11 cm lateral shift, the patient obtained 94% Hit, which could mean that the difficulty of the exercise is too low. For this reason, at a certain point, the therapist changes the difficulty, requiring 15 cm of shift, and the percentage of Hit collapses, reaching only 56%. This change can be interpreted as excessive difficulty, compared to the patient's ability. Therefore, the difficulty in the third snapshot is reduced, leading to a better percentage of Hit. The adaptation of the parameters is decided by the therapist, who both based on the performance of the game and on his/her experience and knowledge, decides if and how to adapt the difficulty.

The possibility of real-time adaptation of parameters and the display of snapshots are intended to provide an additional tool for patient assessment. From our experience, we have noticed that it is not always easy to change the difficulty of an exercise in the correct way, and this may take time and several attempts. Beyond this, Mirarts is also designed as a stand-alone tool, even for traditional rehabilitation, to support the therapist, who now has more information, previously difficult to access, on which he can base his/her decisions.

7.5 Discussion

Before closing the chapter, we want to make some considerations about the use of these technologies in rehabilitation.

Unfortunately, it has not yet been possible to test Mirarts with patients and therapists, so no usability data are yet available. Furthermore, Mirarts is still in a prototype phase, and tests and meetings with clinicians will be necessary to understand which direction to go and how to develop it. However, we can already make some observations regarding the use and application of Hololens 1 and mixed reality in general, as a support tool for the therapist. The feeling is that this technology is still immature. Unfortunately, we could not try Hololens 2 yet, but as for Hololens 1, there have been several problems. Already during the development of Mirarts (e.g., poor documentation, little support, not working features, ...). The device itself has many limitations, and it is not adapted to prolonged use (it is very heavy and unbalanced); besides having a very narrow field of view, which forces to rotate the head to see all the information.

Unfortunately, even the absence of real-time skeleton tracking forces the simultaneous use of an RGB-D camera (and consequently of a computer to connect it, with attached software for data extraction), requiring a not particularly comfortable setup.

We hope that in the coming years, new better MR devices will be developed (and Hololens 2 is probably already going in this direction), from which we can benefit more, because, to date, there are still many issues to be resolved before we can make the best use of this technology.

CHAPTER 8

Results

After having illustrated the functionality of the platform, we now see some preliminary results from its use in two pilot projects. PS and HS have been used to support patients with multiple sclerosis, while a subset of PS games has been used to entertain and train the elderly in the MoveCare project. Finally, we end by illustrating an ontology that tries to summarize all the work done, starting from the definition of exercises and related metrics up to the creation of exer-games. This ontology describes all the main components of home rehabilitation that we believe are fundamental and wants to be a guide in the development of this type of platforms. Unfortunately, also due to the COVID-19 pandemic, it has not yet been possible to test the functionality and usability of Mirarts on real patients. We hope to be able to test it as soon as possible.

8.1 HoRe project - Pilot

PS and HS were used for the first time within the HoRe project, in collaboration with the Neurological Institute "Carlo Besta", in Milan. The aim of the project was to verify the feasibility of using a home platform for the care of patients with multiple sclerosis.

8.1.1 Preliminary activities

In the initial phase of the project, it was planned to use the old Patient Station developed in the Rewire project. But after the first series of meetings, it was immediately clear that it would be difficult to maintain and upgrade according to the clinicians' guidelines. For this reason, it was decided to develop the new version of the PS, described in this work, and make it immediately compliant with the requirements.

Before the trial with patients began, there was a close collaboration with clinicians for the validation of games and metrics for patient assessment. An iterative work was required for the definition of the metrics for patient evaluation and their visualization. Some meetings were necessary before arriving at a result deemed satisfactory by the clinicians.

From the safety point of view, at the request of the therapists, for the most compromised patients, we implemented the possibility of playing without the Wii Balance Board, estimating the CoM from Kinect data, to avoid possible falls due to the balance. Often, what seemed clear and useful to us computer scientists were not particularly representative and helpful to doctors. For this reason, it was decided to try to present metrics in a similar way to others with which therapists are already comfortable (e.g., like those produced by Smart Balance Master[1]).

8.1.2 Inclusion criteria

A list of inclusion criteria that patients must meet to participate in the pilot is given below:

- No fall or near-fall in the last year.
- Absence of other neurological pathologies or pathologies that may affect participation in the study.
- No corticosteroid drugs taken in the month prior to enrollment in the study.
- Absence of seizures events.
- No pregnant or lactating women.

[1]Smart Balance Master, `https://www.mossrehab.com/smart-balance-master` (visited on 11/30/2020)

These criteria are necessary to ensure patient safety. Any problems or pathologies could lead to falls or unrepresentative results.

8.1.3 The pilot

13 patients participated in the trial. The entire recruitment process, including assessment of the patient's initial status, was performed by therapists. For each patient, there were two distinct phases. Initially, each patient is asked to go to the clinic a couple of times a week for training for about a month. During this time, the clinical staff assesses the patient's status, identifying the set of parameters that best suit the patient. The patient is also taught how to use the supplied software and hardware so that he/she can use it correctly and safely. Unfortunately, at the time of patient training, the development of Mirarts was not yet finished, so it was not possible to use it.

Once the training period is over, the workstation is installed at the patient's home, where he/she will be asked to perform the scheduled exercises three times a week for at least 7 weeks. Therapists will monitor patients' activity remotely via HS, modifying therapy when necessary.

At any time during the test, patients could communicate with therapists about any problems with the platform.

8.1.4 Patient Station: usability and acceptance

In Table 8.1, it is possible to see a summary of the use of the system (i.e., the number of exercises performed) for each patient. Each exercise lasts 2 minutes, so the total duration is above 100 hours. Patient 8 and 12 dropped out after less than a month for a variety of reasons (e.g., small house and uncomfortable use of the platform, problems with the interaction with the exer-games, insufficient time to dedicate, ...); this explains the low number of exercises played (only 63 and 80 respectively).

Patients during the trial were asked to play each game at least once in every session. Impressive is the number of exercises performed by Patient 13, who, also probably facilitated by the lockdown that occurred in Italy from March 2020 due to COVID-19, played almost every day from the end of February until June, well beyond the minimum number of sessions required per week.

Table 8.1: *Platform usage data. For each patient, the number of executed exercises is shown.*

Patient	Exercises
P1	114
P2	106
P3	177
P4	398
P5	422
P6	119
P7	176
P8	63
P9	187
P10	221
P11	136
P12	80
P13	1019
TOTAL	**3138**

Table 8.2: *Average score (from 0 to 4) with standard deviation of the six aspects of the TSQ-WT questionnaire. 11 patients have completed the questionnaires (the two patients who dropped out of the project have been excluded).*

Aspect	Average score $\pm$ SD
Benefit	3.51 ± 0.38
Usability	3.02 ± 0.35
Self-concept	3.33 ± 0.60
Privacy	3.16 ± 0.71
Quality of Life	2.69 ± 0.48
Wearing Comfort	2.22 ± 0.35

We also administered the Tele-healthcare Satisfaction Questionnaire - Wearable Technology (TSQ-WT) questionnaire [184]. TSQ-WT evaluates six different aspects of the platform: *Benefit, Usability, Self-concept, Privacy, Quality of Life,* and *Wearing Comfort*. Results are shown in Table 8.2. Patients recognize the *Benefit* of the platform (3.51 out of 4), which has the highest score, followed by *Self-Concept* (the emotions felt by the use of the platform, such as feeling happy, sick, or old) and *Privacy*. Good scores also in *Usability*. The lowest scores have been in *Wearing Comfort*, probably due to the balance board, that has to be moved at the beginning and at the end of each session, and *Quality of Life* (the effects felt in the daily life, e.g., feeling better).

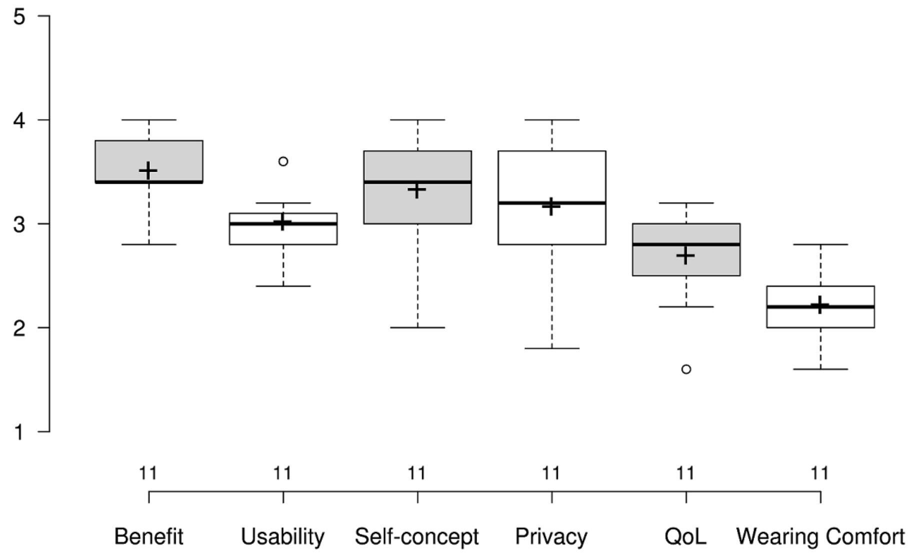

Figure 8.1: *HoRe questionnaires box plot.*

In general, the scores are satisfactory and the platform has been appreciated. The low score in wearing comfort will probably make us rethink the use of the balance board, evaluating more comfortable alternatives.

Overall, therefore, patients have liked the exer-games and have maintained a good adherence to the therapy. Among the most positive things that have been reported, a note of merit should be given to Hannah, the virtual therapist. According to the patients, she was helpful during the execution of the exercises, and they appreciated her advice.

Given that some questions on usability were already present within the questionnaire, we did not consider it necessary to use other questionnaires such as the System Usability Scale [185].

Self-efficacy tests

Multiple sclerosis, which can cause a slow but continuous worsening of patients' physical and cognitive conditions, can also lead to disorders such as anxiety [186] or depression [187]. Patients see their future uncertain and often fear that they will not be able to overcome the challenges that the disease poses to them. Some aspects of the patient's personality can help to better respond to challenges. One of these aspects is self-efficacy. Self-efficacy represents the patient's belief in overcoming the problems they face. Individuals with a high level of self-efficacy will be more capable of facing complex challenges and will be less likely to give

Table 8.3: *MS Self-Efficacy tests results.*

Patient	Pre-rehab score	Post-rehab score	Change
Patient 4	52	55	+3
Patient 5	52	54	+2
Patient 6	37	40	+3
Patient 7	35	37	+2
Patient 9	61	61	+0
Patient 10	41	46	+5
Patient 11	44	44	+0
Patient 13	38	37	-1
Average ± SD	45 ± 9.13	46.75 ± 9.00	+1.75 ± 1.58

in to obstacles and changes [188].

We, therefore, decided to try to measure the self-efficacy of patients, before and after the use of PS, to try to understand if there could be significant changes through the use of a home rehabilitation system.

The Self-Efficacy Scales are one of the most widely used tools to try to estimate an individual's self-efficacy. We decided to use the Multiple Sclerosis Self-Efficacy Scales (MS-SES) [188]. The questionnaire proposed by the authors has been carefully translated into Italian to allow full understanding by patients. MS-SES consists of 14 questions. For each question, the patient expresses his/her degree of agreement on a 6-point Likert scale (from "Strongly Disagree" to "Completely Agree").

Table 8.3 shows the results of the questionnaires before and after using the PS. We decided to introduce the questionnaire starting from the second group of patients, so the results of the first three patients are absent (in addition to the two patients who dropped the pilot before the end). At a significance level $\alpha = 0.05$, according to the Paired T-Test, the difference between the two samples is statistically significant, with an effect size $d = 0.88$. Nevertheless, given the small number of patients, we prefer to perform further tests on larger samples to be able to confirm this result.

It can be noted that 5 out of 8 patients improved their score, two kept the same score, and only one worsened slightly. The only one who had a lower post-score than the pre-score as well as the lowest post-score of all (on a par with Patient 7), is curiously Patient 13, who is the patient who most enjoyed PS and performed a much higher number of exercises than all the others. It is, therefore, not clear the association between the score with the effort put during rehabilitation. But, as mentioned earlier, it is unrealistic to speculate on such a small sample of patients.

Patient Station: weaknesses

During the pilot, patients did not report any critical problems using the PS, the associated devices, and during the execution of the exer-games. The only serious problem that has been found sometimes is the uncomfortable use of the hand as a tool for interaction with the PS. In the wrong lighting conditions (e.g., too much light), in fact, Kinect has difficulty correctly identifying the position of the hands (and sometimes even the feet, which can cause inaccuracies in the exercises that require the tracking of the feet). Several times patients reported difficulties in selecting the buttons. This could be frustrating in the long run, reducing patient motivation. Some minor issues were also identified during the pilot and promptly corrected.

7 of the 13 patients had the Farm Game available as an optional game. However, except in sporadic cases, it was not used. It is possible to interpret this scarce use for a couple of reasons: 1) the patients recruited consist of people of working age, who often have little time to dedicate to the platform, and who prefer to use it exclusively for rehabilitation purpose, 2) Farm Game is designed for long-term use, 7 weeks is probably too short a period, and exer-games alone may be enough to motivate the patient to play. Also, the problem previously reported about the difficult interaction with the PS should not be underestimated. The Farm Game is based exclusively on interaction; it could be assumed that in the face of these problems some patients avoided playing it.

8.1.5 Hospital Station: usability

We gathered some feedback from the hospital staff who used HS, in particular on scheduling and patient assessment. The Patient Management module, also due to its simplicity, was not taken into consideration.

Scheduling

No particular criticalities concerning the scheduling module have been reported. The parameterization of exercises and games has been sufficient to customize every critical aspect of the game. After an initial phase of parameter definition, the therapists did not consider it necessary to make any further changes in the definition of the exercises or their structure. The module is easy to use, although a couple of minor issues have been reported in the interface and in the definition of some parameters, which could be confusing at first use. Therapists often changed the difficulty of the exercises, approximately every two weeks, mainly to meet the demands of patients who, after becoming familiar with the platform, felt that the games were too simple (and sometimes too difficult, after the changes made by the clinical staff). This confirms the need for the automatic adaptation mechanism, which, unfortunately, could not be tested in the pilot.

Patient assessment

Therapists found the detailed view of a single exercise particularly useful. Although the time required to analyze each individual exercise performed can be very long, the quality of this level of detail is required for an accurate understanding of any problems or needs of the patient. Some critical points about the global view, which is sometimes considered not always representative of the critical aspects, not allowing the understanding of the global trend at the moment. This is probably also due to an insufficient pilot length: three sessions per week for seven weeks do not seem to be sufficient to deduce a trend due to too many variations in performance in the short term. Only with the last patient, who played every day, considerably more than required, it is possible to see a trend over time, showing that the global results become useful only in the long run when the exercises played are numerous.

8.2 MoveCare project - Pilot

Exer-games have also been integrated into the MoveCare project, which aimed to provide a system that allows the monitoring of the physical and cognitive conditions of the elderly. The project, among other secondary components, includes a Giraff[2], an autonomous robot operable remotely by the caregiver, and a platform containing a set of activities to be carried

[2]Giraff, `http://www.giraff.org` (visited on 11/30/2020)

Table 8.4: *Summary results of the exer-games questionnaires. Each question included an answer from 1 to 5. N is the number of users who answered the question.*

Question	Mean ± SD	N
1. I enjoyed playing the balance exer-games	4.52 ± 0.6	21
2. I found the balance exer-games easy to play	4.14 ± 0.85	21
3. I found the balance exer-games unnecessarily complex	1.95 ± 1.28	21
4. I felt I needed the support of a technical person to be able to play the balance exer-games	2.05 ± 1.28	21
5. I felt comfortable when using the balance board	4.5 ± 0.76	20
6. It was clear how to use the balance board to play the balance exer-games	4.38 ± 0.86	21
7. I would imagine that most people of my age would learn how to play the balance exer-games very quickly.	4 ± 0.84	21
8. If I have the possibility, I would frequently play the balance exer-games in the future	4.24 ± 1.04	21

out individually or with other elderly. Multiplayer activities include traditional games such as card games, pictionary, or puzzles. Single games, instead, include the PS with a limited set of exer-games. The exer-games that have been included are *Fruit Catcher*, *Bubbles*, *Horse Runner*, and *Hay Collect*. The reason for this limited set is due to the absence of an RGB-D camera; only a Balance Board has been made available for each user. This implies the absence of the posture monitoring system. The Farm Game and Hannah's office have been disabled, also given the unfamiliarity with technology by the elderly would have been an excessive complication and, in any case not, strictly related to the objective of the project.

HS has not been used. At the start of the PS, the elderly could choose the difficulty of the games, selecting a difficulty level among the five that were available; each difficulty level was associated with a different schedule. For this reason, the DDA system has also been disabled. It could have been dangerous to change the difficulty in real-time and without the support of HS and Hannah. Two pilots have been performed on healthy elderly, without pathologies that compromise their physical abilities. However, due to old age (average age around 76 years), although healthy, their motor skills are still limited. Both pilot projects lasted 3 months.

The pilots were carried out both in Italy and in Spain.

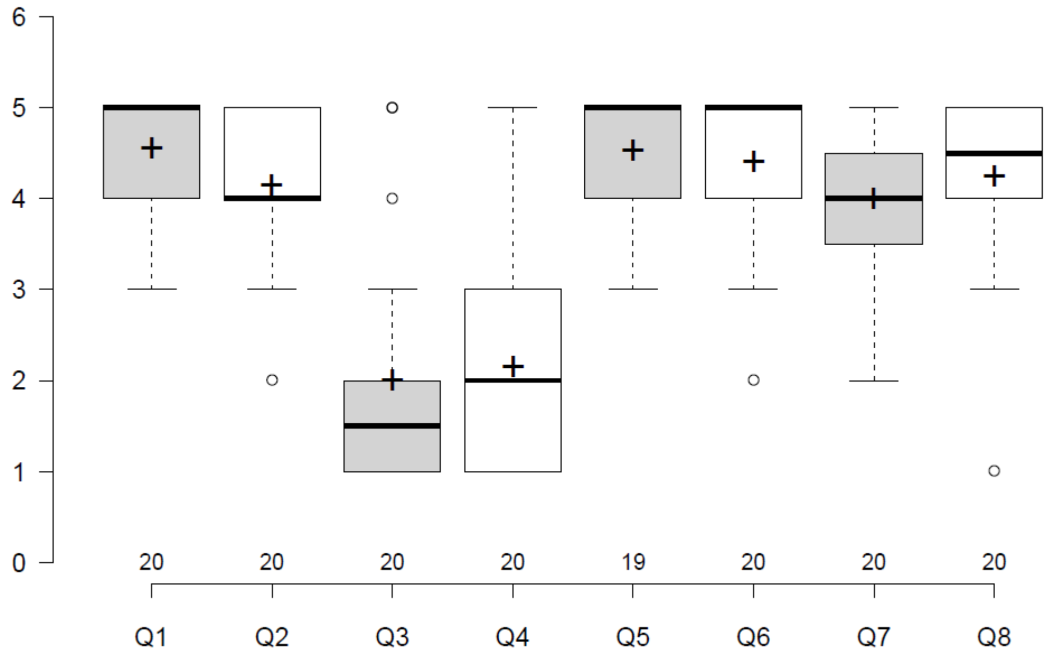

Figure 8.2: *MoveCare questionnaires box plot.*

A total of 24 elderly (14 from Spain and 10 from Italy) voluntarily joined the project, participating more or less actively in all activities, exer-games included. Five elders participated in both the first and the second pilot. One of the elders from Spain dropped the pilot because did not feel confident with the system.

Each elder was asked to complete a questionnaire, which includes eight questions related to exer-games in a 1 to 5 Likert scale. The results are summarized and available in Table 8.4.

To the first question, 95% of users answered positively (at least 4), showing appreciation for the exer-games. The ease of understanding was also good (4.14). Despite some of our concerns about the use of the Balance Board (with the possibility of falling while going up, down, or moving it), it seems that the elderly have felt safe in its use (4.5), its ease of use is also good (4.38). A large percentage of users also reported they were available to play exer-games in the future.

The elderly were also asked what they appreciated most, what they appreciated least, and what they would change. A small part of the subjects confirmed their objective difficulty in using the exer-games, as was foreseeable. It was already clear that exer-games might not be suitable for such elderly people, and with obvious problems of movement re-

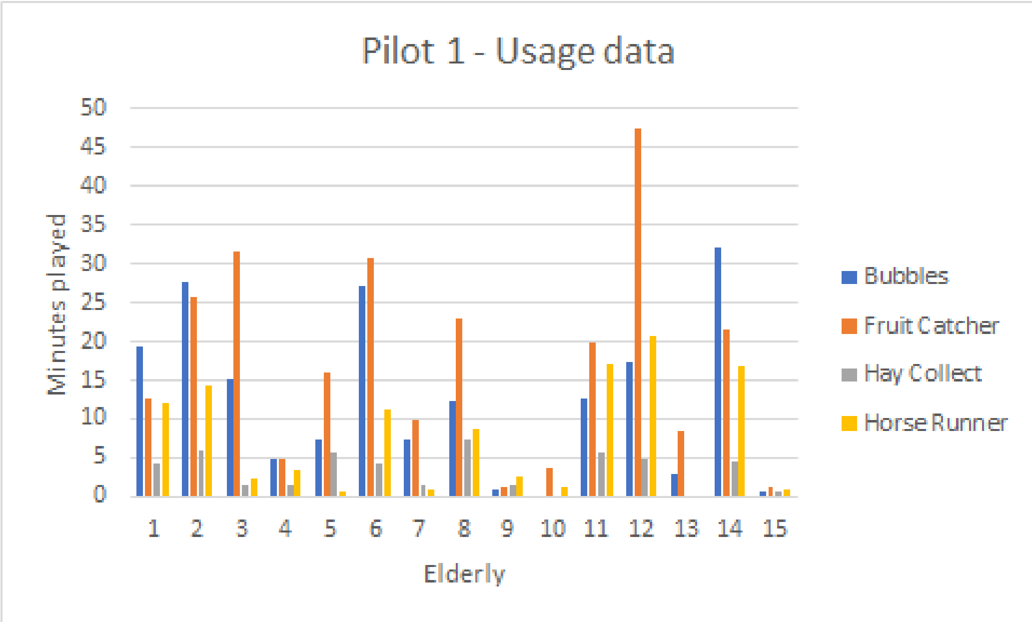

Figure 8.3: *MoveCare pilot 1 usage data.*

lated to age. If we exclude these subjects, the *Fruit Catcher* and *Bubble games* were the most appreciated, discordant opinions on *Horse Runner* instead (someone liked it very much, others struggled). A large part of the elderly, on the other hand, named *Hay Collect* among the things they liked least. Again, we were not surprised: this game had already been discarded in the HoRe project precisely because of its difficulty and the risk of falling. The elderly have confirmed this problem. Some of them complained about the excessive difficulty of the exercises, although there was the possibility to choose between five different levels, probably this was not enough. This is a critical issue and confirms the need for HS and a custom schedule set by a therapist or caregiver.

The questionnaires show that the platform has been well accepted. Some elderly have also asked to further extend the set of games available to reduce monotony. An understandable request, especially considering that they only had half of the exer-games available. This also highlights a problem that we were already aware of: the possible loss of motivation in the long run.

As for the actual use of exer-games, the summary data are available in Figs. 8.3 (Pilot 1) and 8.4 (Pilot 2). 12 of the 24 elderly have shown that they enjoyed playing exer-games, each of them played more than 60 minutes (a couple of them have exceeded 200 minutes).

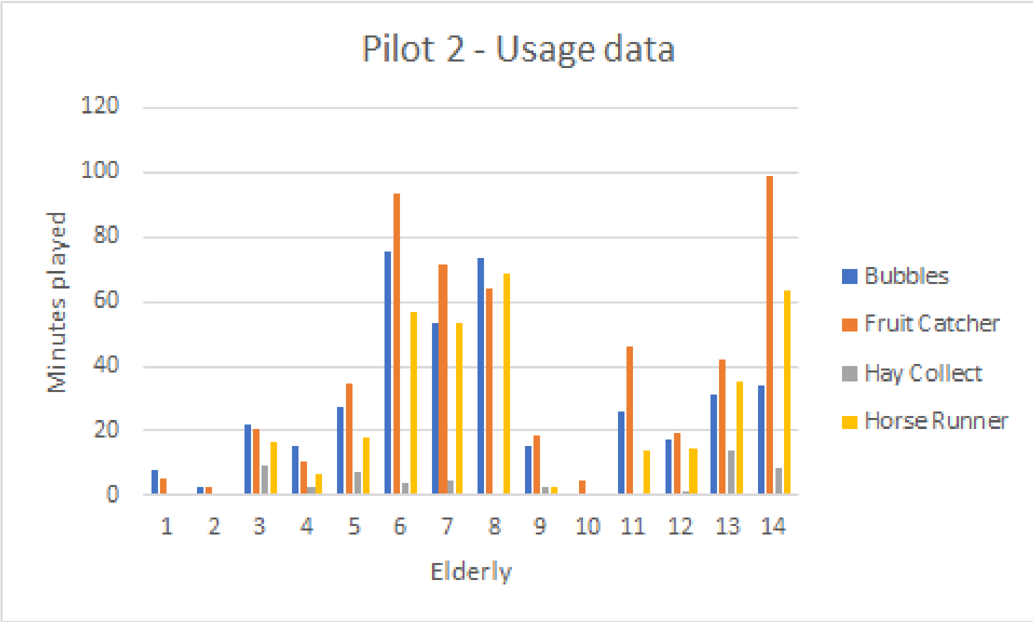

Figure 8.4: *MoveCare pilot 2 usage data.*

On the other hand, confirming the answers to the questionnaires, 5 elderly played less than 10 minutes, showing that the exer-games in their case sometimes for physical problems (too difficult games), other times for other reasons (poor system acceptance) were not actually used. Although the usability data may seem bad compared to the duration of the pilot (3 months), it should also be considered that MoveCare includes a large set of activities, and participants could choose if and when to play independently, without any control or stimulus.

Unfortunately, having used only the Balance Board, we had only the data of the CoP available, and, as we have already anticipated in the previous paragraph, the data make more sense only when the subject plays repeatedly for an extended period. In our case, the most representative data that can be extracted exclusively from the Balance Board are the variations in the range of movement achieved (in the *Weight Shift* exercises), stability (e.g., in the anteroposterior movements in *Weight Shift Lateral*), and the force used to get up (thanks to the speed of weight change in *Sit to Stand*). Obviously, having the elderly played for a limited period, there are no significant variations in the data collected. Further pilots of significantly longer length (e.g., 6 months or more) are necessary to have a reliable trend.

8.3 Home rehabilitation ontology

We wish to close this chapter by including an ontology that describes all the components needed for a home rehabilitation platform based on exer-games. We have long thought about where to illustrate this ontology. We decided to include it here, in the results, because it was defined at the end of the whole design and development process and also after the two pilot tests. We consider it a result of the knowledge and experience gained in this project, and also inherited from the Rewire project.

The ontology is based on two key figures: the therapist and the patient. These two actors are respectively linked to HS and PS. We use the terms HS and PS because the reader should be familiar with them by now; actually, any other platform offering the features described in the ontology can be used.

The first step in the design and development of a home rehabilitation platform is to identify the rehabilitative dimensions (e.g., movement amplitude, accuracy, speed, ...) that need to be trained. They depend on the diseases being treated and should be defined by the therapists. Once these indexes have been settled, it is necessary to define the exercises that will be performed by the patients. Each exercise will improve one or more of the previously defined dimensions. To guarantee safety, exercises need to be carefully selected, and they have to be suitable and customizable for the patient's condition.

For each exercise, as proposed in [113], primary and secondary goals need to be decided, which define what the patients have to do and how. All these steps should be carried out by clinicians, who are the ones who know the domain best.

Once exercises and goals have been defined, they need to be integrated into a set of exer-games. The use of exer-games and other motivational aspects is not mandatory. However, as these aspects are considered fundamental to increase the effectiveness of rehabilitation in the long term, they have been included in the ontology. The exer-games must reflect the exercises proposed by therapists. To do so, always following the guidelines defined in Rewire, exercises, monitor, and game parameters are used. A set of exercises, including all their parameters, is then grouped within a *schedule*, defined by the therapist through the

HS. Schedules will be download by the PS when the patient starts a new rehabilitation session.

Referring to the central part, on the right, of the ontology, since rehabilitation could be boring in the long run, additional features can be added to the PS to try to improve the patient's motivation. In our case, we developed Hannah, the Empathic Virtual Therapist, the DDA system, and the Farm Game. Many different solutions can be found in this area. It is essential that these activities do not distract the patient from the main objective: rehabilitation. Furthermore, they must not change the dynamics of the exercises or their difficulty (or if they do, they must remain within the limits dictated by the therapist, as in the case of our DDA system).

The final part of the ontology (at the bottom) defines the patient's evaluation. HS analyzed the executed exercises using a set of "Output parameters", closely related to the set of "Evaluation indexes" defined by therapists, which are based on the same rehabilitation dimensions used to define the primary goals for an exercise, closing the loop between the definition of an exercise and its evaluation. To facilitate the work of the therapist, we suggest showing the results on two levels of granularity, a very detailed view, where, in case of need, it is possible to review every aspect in detail, and a global view, where it is possible to see the performance trend over a long period.

This ontology represents our first attempt to develop a comprehensive description of the elements necessary for at-home rehabilitation systems, and it logically summarizes all the concepts that have been described in this thesis. It has been developed based on our experience, especially from its use by patients with multiple sclerosis and the elderly, but it should be applicable also to other categories.

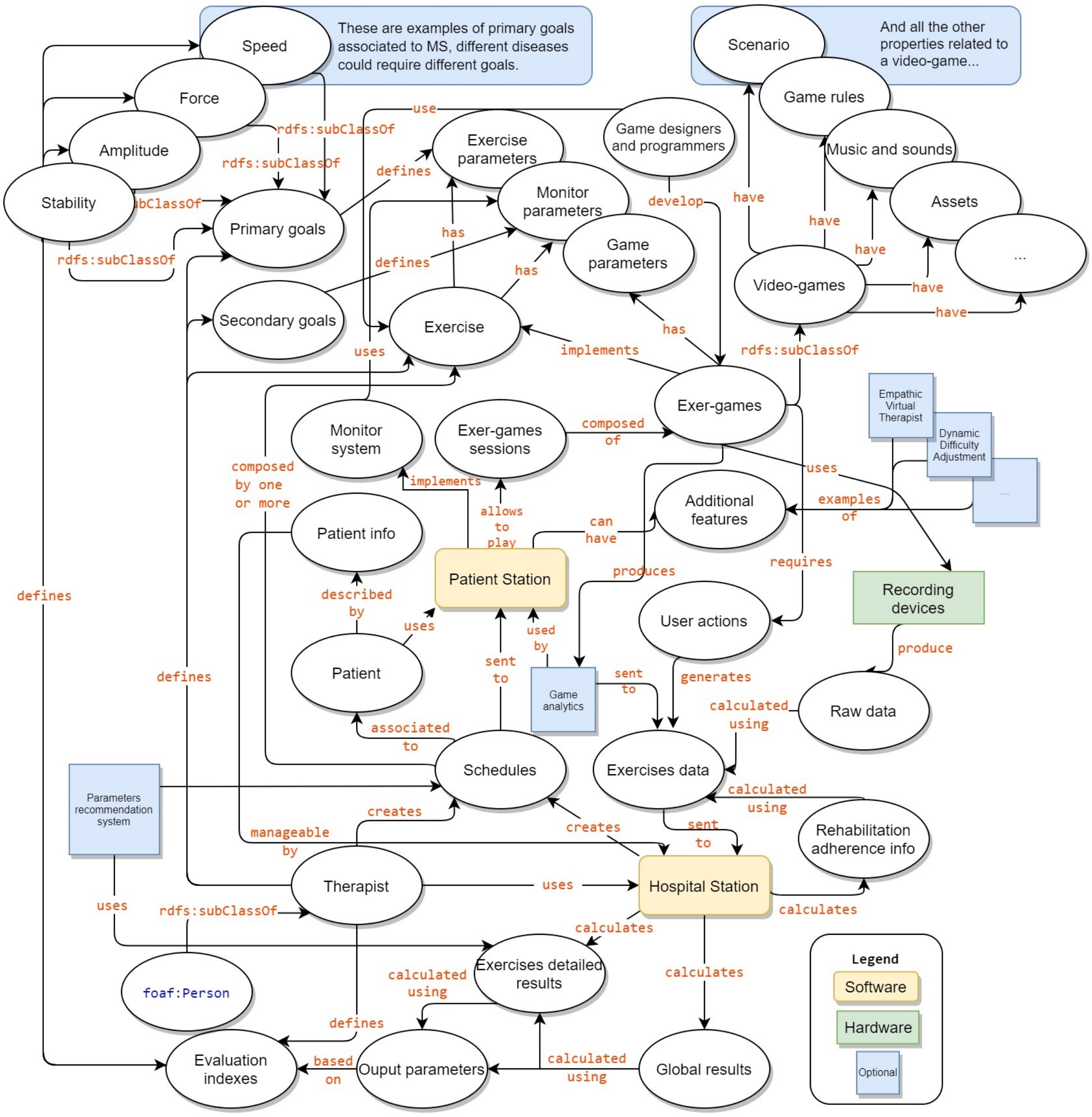

Figure 8.5: *Ontology describing the main elements of an exer-game based home rehabilitation platform.*

CHAPTER 9

Conclusion

In this work, we have developed a new advanced platform for exer-game based autonomous home rehabilitation, including all the necessary tools, both for patient and therapist, to carry out an effective, safe, and fun rehabilitation. The need for this type of platform arises from the fact that in recent years the costs incurred by national health systems have increased continuously, also due to the progressive aging of the population. The resulting cut in expenditure has led to a reduction in some essential services, including physical rehabilitation, reducing the duration (and consequently the effectiveness) of the health services offered to patients.

In this context, home rehabilitation can be of fundamental benefit, allowing patients to continue their therapy at home, saving money, and avoiding frequent hospital visits. Also, in this particular historical period, many patients have been unable to receive any form of hospital treatment or care for prolonged periods of time due to mobility restrictions imposed to stem the COVID-19 pandemic, with possible negative health consequences, emphasizing, even more, the need for this type of technology.

Our platform has been developed to guarantee a high level of flexibility, which allows it to be used with different pathologies and different types of patients. Therapists can schedule personalized exercises and monitor patients' progress and the quality of the executed exercises; while patients can perform rehabilitative exercises tailored to their level in a safe and stimulating environment.

The preliminary results obtained in the two pilots performed demonstrate a good degree of acceptance and usability of the system, good feedback has been received. Unfortunately, it has not yet been possible to verify and validate all the solutions proposed here, so more tests will be necessary.

9.1 About results

Let us now see some final considerations on what emerged from the two pilots carried out in the HoRe and MoveCare projects.

9.1.1 Hore project

The collaboration with therapists has been fruitful, both in the modeling of the exercises and in the analysis and visualization of the patient evaluation. The exer-games have been highly appreciated, showing a greater interest than traditional exercises. From the point of view of short-term motivation and the acceptance and usability of the exer-games, therefore, our goals have been achieved. No falls or other adverse events were reported using the platform. A negative aspect has been the Farm Game, which did not find the hoped-for success, perhaps also due to the too limited duration of the tests. Other experiments have to be conducted to understand how long exer-games alone can motivate patients and how necessary the introduction of more structured solutions such as the Farm Game is.

From the therapists' point of view, the results have also been partially achieved. As far as exercise scheduling and patient safety are concerned, we can be satisfied. Thanks to the numerous parameters exposed by the exer-games, it was possible to schedule their personalized exercises according to their needs to guarantee the effectiveness and safety of the rehabilitation. As for the analysis of the results, while the detailed analysis of a single exercise was used, the overall analysis was probably a little less indicative of the patient's status. Also in this case, our hypothesis is that the number of exercises played and the duration of the pilot project are not sufficient to identify a trend in the patient's performance. For this reason, the global graphs show a trend that is difficult to interpret, consisting of numerous variations. Only in the last patient, who played a higher number of exercises, was it possible to identify some trends.

It is, therefore, necessary to perform other tests, with a greater number of patients, even of different age groups, to see how the exer-games act on their motivation, and if it is possible to identify some trends, which could lead to more targeted therapies.

9.1.2 MoveCare project

Although the target group of our platform is not the healthy elderly, we can still draw some interesting conclusions from the MoveCare project pilot. First of all, exer-games for the elderly are a current topic, and of primary importance to allow the elderly to maintain a good motor capacity over the years. The simplicity of games has allowed them to be used without problems even by older people with little or no familiarity with technology. Moreover, despite the presence of only four exer-games and the use of the Balance Board alone, their use was still good, and seniors generally did not get bored, although someone has highlighted the need to increase the number of games. This shows that with people so unfamiliar with technology, even mini-games with few, clear and simple mechanics can be used to entertain them effectively. The Balance Board, as expected, has proved uncomfortable for the elderly with greater mobility problems; for the more compromised people, it is necessary to find an alternative to its use.

Unfortunately, it was not possible to verify the effectiveness of the exer-games. They were not developed with the aim of being used by the elderly, and, even in this case, we do not have enough data to be able to determine an evaluation of their performance. The absence of an RGB-D camera also greatly limits the possible metrics that we can extract; we believe that the Balance Board alone does not produce enough data for a complete evaluation. In any case, even the use of exer-games alone to maintain a good physical condition and slow down the physical decline of the elderly is an important feature worth exploring.

9.2 Discussion

Before closing with future work, we want to have a brief discussion on the work done, also illustrating the main current limitations.

Patient Station The use of exer-games by patients has been more than satisfactory. Very good also the usability and ease of use of PS and exer-games even by people not accustomed to technology. The small number of patients, however, allows few conclusions on the effective effectiveness of the platform from both a rehabilitative and motivational point of view. Also due to the pandemic and mobility restrictions, it was not possible to properly test the solutions we proposed for long-term motivation. The Farm Game has hardly ever been used, and even the automatic difficulty has only been tested on a small number of healthy subjects and not on real patients. Further tests of longer duration are necessary to investigate how much and how the solutions proposed by us can motivate the patient, because although the exer-games have been well accepted and appreciated by patients, it is not possible to deduce patients' behavior and motivation in the long term, when, once the initial novelty is over, boredom may occur. Unfortunately, therefore, our goal of providing a platform capable of motivating in the long term has not yet been achieved, as the solutions we have proposed so far have not yet been used and tested properly.

Hospital Station The basic functionalities of the HS have been successfully tested; they represent a good starting point towards the development of more advanced features. The flexibility with which the HS has been developed allows us to use it quickly and easily in other areas; qualities that will certainly be useful in future projects and collaborations. The biggest challenge is clearly the evaluation of the patient. From this point of view, a lot can still be done to make the platform more usable and effective. The metrics that are currently calculated and shown to therapists still need to be compared with clinically validated tools to verify that the results shown are consistent. Here, too, further work and testing are needed to verify the patient's long-term assessment, as the tests performed so far do not seem long enough to notice significant changes in the patient's condition.

Mirarts Mirarts represents a first attempt to apply the new mixed reality technologies to rehabilitation. We believe that these new devices can help therapists to have additional objective information in real-time. Although still at an early stage, from the first feedback, it would appear to be an interesting research direction, either applied to traditional rehabilitation, or through the exer-game approach or integrated with other PS-like software. Unfortunately, it has not yet been possible to do any test with Mirarts, a gap that we want to fill as soon as possible. Tests on patients will be needed to validate the usefulness of the information provided by devices such as Hololens. However, to date, current mixed reality devices can still be considered at a prototype state, mainly due to the narrow field of view. In the coming years, hopefully, they are expected to become increasingly reliable and affordable, and their application could transform several fields.

As the reader will have understood, one of the major limitations of this work has been the impossibility to test many of the solutions proposed here. This has unfortunately been caused for several reasons, including the COVID-19 pandemic, which, to date, has blocked every possible form of collaboration in the medical field. However, we hope that what we have illustrated here will help and inspire other researchers in this area; in the meantime, we will continue to work to validate the effectiveness of our solutions.

For researchers who want to approach the field of serious games for rehabilitation, we recommend always work with hospital staff, who is the only one who can guarantee the effectiveness and safety of the exercises. We also reiterate, once again, the importance of a studied and careful game design that can motivate and entertain patients. This aspect, often neglected, is fundamental for the effectiveness of the rehabilitation program.

9.3 Future work

Considering the heterogeneity of the platform and its many potential features, there are several directions and possibilities for future work.

About long-term motivation, we want to extend and apply our work described in [153] to the exer-games, giving the patient the possibility to perform the exercises within a procedurally generated story. For greater player immersion, the story would also affect the appearance of the exer-games (e.g., environment, characters, ...). In this way, the exer-games would become an integral part of the narrative. They could represent, for example, a challenge that the player has to perform, or a movement from one location to another (*Horse Runner* would be a perfect example in this case).

Hannah, the EVT, will also be improved as part of the new H2020 *Essence* Project[1]. She will be able to automatically analyze the patient's emotions through facial analysis (and possibly also by the tone of voice) and react according to the patient's emotional state. In this way, the emotional component in the DDA system should find more importance compared to now, where it is the minority part.

From the rehabilitation point of view, instead, another long-term goal could be to verify the effectiveness of the PS (e.g., through an RCT). The number of subjects involved so far is too small, in this regard, in the coming months, as a continuation of the HoRe project, another pilot with patients suffering from multiple sclerosis could be carried out. In these new tests, we also aim to integrate Mirarts so that it can be tested and eventually improved.

Two new trials are also likely to be planned in which HS will be used to display results related to hand rehabilitation performed through exer-games and for the study of freezing events in Parkinson's patients. Always referring to HS, another interesting direction would be the development of a recommendation system to suggest to the therapist the best values of the exercise parameters to maximize the effectiveness of rehabilitation.

As can be seen, there are numerous possible directions; the field of home rehabilitation is relatively new, and there is still a lot of work to be done before a comprehensive and clinically validated platform can be developed.

[1]Essence Project, `https://www.essence2020.eu` (visited on 11/30/2020)

Bibliography

[1] Vasilis Kontis, James E. Bennett, Colin D. Mathers, Guangquan Li, Kyle Foreman, and Majid Ezzati. Future life expectancy in 35 industrialised countries: projections with a Bayesian model ensemble. In *The Lancet*, 389(10076):1323–1335, 2017.

[2] Pedro Conceição. Human development report 2019. In *Beyond income, beyond averages, beyond today: Inequalities in human development in the 21st century. New York, UNDP*, 2019.

[3] United Nations. *World Population Prospects 2019: Volume II: Demographic Profiles*. Department of Economic and Social Affairs, Population Division, 2019.

[4] Eurostat. *People in the EU: Who are we and how do we live?* Publications Office of the European Union, 2015.

[5] Eurostat. *People in the EU: Population projections*, 2018.

[6] Anders Gustavsson, Mikael Svensson, Frank Jacobi, Christer Allgulander, Jordi Alonso, Ettore Beghi, Richard Dodel, Mattias Ekman, Carlo Faravelli, Laura Fratiglioni, et al. Cost of disorders of the brain in Europe 2010. In *European neuropsychopharmacology*, 21(10):718–779, 2011.

[7] Sanjay Saini, Dayang Rohaya Awang Rambli, Suziah Sulaiman, Mohamed Nordin Zakaria, and Siti Rohkmah Mohd Shukri. A low-cost game framework for a home-based stroke rehabilitation system. In *Proceedings of the International Conference on Computer & Information Science (ICCIS)*. IEEE, pages: 55–60, 2012.

[8] Emelia J. Benjamin, Michael J. Blaha, Stephanie E. Chiuve, Mary Cushman, Sandeep R. Das, Rajat Deo, James Floyd, Myriam Fornage, Cathleen Gillespie, Carmen R. Isasi, et al. Heart disease and stroke statistics-2017 update: a report from the American Heart Association. In *Circulation*, 135(10):e146–e603, 2017.

[9] Vincent Y. Ma, Leighton Chan, and Kadir J. Carruthers. Incidence, prevalence, costs, and impact on disability of common conditions requiring rehabilitation in the United States: stroke, spinal cord injury, traumatic brain injury, multiple sclerosis, osteoarthritis, rheumatoid arthritis, limb loss, and back pain. In *Archives of physical medicine and rehabilitation*, 95(5):986–995, 2014.

[10] Thomas Truelsen, Bartlomiej Piechowski-Jóźwiak, Ruth Bonita, Colin Mathers, Julien Bogousslavsky, and Gudrun Boysen. Stroke incidence and prevalence in Europe: a review of available data. In *European journal of neurology*, 13(6):581–598, 2006.

[11] Victoria L. Phillips, Susan Vesmarovich, Roxanne Hauber, Edith Wiggers, and Amanda Egner. Telehealth: reaching out to newly injured spinal cord patients. In *Public health reports*, 2016.

[12] Imre Cikajlo, Marko Rudolf, Nika Goljar, Helena Burger, and Zlatko Matjačić. Telerehabilitation using virtual reality task can improve balance in patients with stroke. In *Disability and rehabilitation*, 34(1):13–18, 2012.

[13] Carl V. Granger, Samuel J. Markello, James E. Graham, Anne Deutsch, and Kenneth J. Ottenbacher. The uniform data system for medical rehabilitation: report of patients with stroke discharged from comprehensive medical programs in 2000-2007. In *American Journal of Physical Medicine & Rehabilitation*, 88(12):961–972, 2009.

[14] Gale Whiteneck, Julie Gassaway, Marcel Dijkers, Deborah Backus, Susan Charlifue, David Chen, Flora Hammond, Ching-Hui Hsieh, and Randall J Smout. Inpatient treatment time across disciplines in spinal cord injury rehabilitation. In *The journal of spinal cord medicine*, 34(2):133–148, 2011.

[15] Marie-Eve Lamontagne, Cynthia Gagnon, Anne-Sophie Allaire, and Luc Noreau. Effect of rehabilitation length of stay on outcomes in individuals with traumatic brain injury or spinal cord injury: a systematic review protocol. In *Systematic reviews*, 2(1):59, 2013.

[16] Serafin Beer, Fary Khan, and Jürg Kesselring. Rehabilitation interventions in multiple sclerosis: an overview. In *Journal of neurology*, 259(9):1994–2008, 2012.

[17] Fary Khan, Bhasker Amatya, Jurg Kesselring, and Mary Galea. Telerehabilitation for persons with multiple sclerosis. In *Cochrane Database of Systematic Reviews*, (4), 2015.

[18] Fred S. Sarfo, Uladzislau Ulasavets, Ohene K. Opare-Sem, and Bruce Ovbiagele. Tele-rehabilitation after stroke: an updated systematic review of the literature. In *Journal of Stroke and Cerebrovascular Diseases*, 27(9):2306–2318, 2018.

[19] Douglas A Perednia and Ace Allen. Telemedicine technology and clinical applications. In *Jama*, 273(6):483–488, 1995.

[20] Kate E. Laver, Daniel Schoene, Maria Crotty, Stacey George, Natasha A. Lannin, and Catherine Sherrington. Telerehabilitation services for stroke. In *Cochrane Database of Systematic Reviews*, 12, 2013.

[21] Ross A. Clark, Yong-Hao Pua, Karine Fortin, Callan Ritchie, Kate E. Webster, Linda Denehy, and Adam L. Bryant. Validity of the Microsoft Kinect for assessment of postural control. In *Gait & posture*, 36(3):372–377, 2012.

[22] Tilak Dutta. Evaluation of the Kinect™ sensor for 3-D kinematic measurement in the workplace. In *Applied ergonomics*, 43(4):645–649, 2012.

[23] Jing Chen, Wei Jin, Xiao-Xiao Zhang, Wei Xu, Xiao-Nan Liu, and Chuan-Cheng Ren. Telerehabilitation approaches for stroke patients: systematic review and meta-analysis of randomized controlled trials. In *Journal of Stroke and Cerebrovascular Diseases*, 24(12):2660–2668, 2015.

[24] Pakaratee Chaiyawat and Kongkiat Kulkantrakorn. Effectiveness of home rehabilitation program for ischemic stroke upon disability and quality of life: a randomized controlled trial. In *Clinical neurology and neurosurgery*, 114(7):866–870, 2012.

[25] Massimiliano Pau, Giancarlo Coghe, Federica Corona, Bruno Leban, Maria Giovanna Marrosu, and Eleonora Cocco. Effectiveness and limitations of unsupervised home-based balance rehabilitation with Nintendo Wii in people with multiple sclerosis. In *BioMed research international*, 2015.

[26] James W. Burke, Michael McNeill, Darryl K. Charles, Philip J. Morrow, Jacqueline Crosbie, and Suzanne M. McDonough. Optimising engagement for stroke rehabilitation using serious games. In *The Visual Computer*, 25:1085–1099, 2009.

[27] Denise G. Tate. The state of rehabilitation research: art or science? In *Archives of Physical Medicine and Rehabilitation*, 87(2):160–166, 2006.

[28] Sandra VanderKaay, Sandra E. Moll, Rebecca E. Gewurtz, Pranay Jindal, Adalberto Loyola-Sanchez, Tara L. Packham, and Chun Y. Lim. Qualitative research in rehabilitation science: opportunities, challenges, and future directions. In *Disability and rehabilitation*, 40(6):705–713, 2018.

[29] Pamela A. Ochieng. An analysis of the strengths and limitation of qualitative and quantitative research paradigms. In *Problems of Education in the 21st Century*, 13:13–18, 2009.

[30] Jeff Hearn, John Lawler, and George Dowswell. Qualitative evaluations, combined methods and key challenges: general lessons from the qualitative evaluation of community intervention in stroke rehabilitation. In *Evaluation*, 9(1):30–54, 2003.

[31] Cecilie Fjeldstad, Gabriel Pardo, Christine Frederiksen, Debra Bemben, and Michael Bemben. Assessment of postural balance in multiple sclerosis. In *International Journal of MS Care*, 11(1):1–5, 2009.

[32] Damien Djaouti, Julian Alvarez, and Jean-Pierre Jessel. Classifying serious games: the G/P/S model. In *Handbook of research on improving learning and motivation through educational games: Multidisciplinary approaches*. IGI Global, 118–136, 2011.

[33] Ben Sawyer and David Rejeski. *Serious games: Improving public policy through game-based learning and simulation*. 2002.

[34] Per Backlund and Maurice Hendrix. Educational games-are they worth the effort? A literature survey of the effectiveness of serious games. In *Proceedings of the International Conference on Games and Virtual Worlds for Serious Applications (VS-GAMES)*. IEEE, pages: 1–8, 2013.

[35] Voravika Wattanasoontorn, Imma Boada, Rubén García, and Mateu Sbert. Serious games for health. In *Entertainment Computing*, 4(4):231–247, 2013.

[36] Chang-Wook Lim and Hyung-Won Jung. A study on the military Serious Game. In *Advanced Science and Technology Letters*, 39:73–77, 2013.

[37] Feifei Xu, Dimitrios Buhalis, and Jessika Weber. Serious games and the gamification of tourism. In *Tourism Management*, 60:244–256, 2017.

[38] Yoonsin Oh and Stephen Yang. Defining exergames & exergaming. In *Proceedings of Meaningful Play*:1–17, 2010.

[39] Hayeon Song, Jihyun Kim, Kelly E. Tenzek, and Kwan Min Lee. The effects of competition and competitiveness upon intrinsic motivation in exergames. In *Computers in Human Behavior*, 29(4):1702–1708, 2013.

[40] Albert “Skip” Rizzo and Gerard Jounghyun Kim. A SWOT analysis of the field of virtual reality rehabilitation and therapy. In *Presence: Teleoperators & Virtual Environments*, 14(2):119–146, 2005.

[41] Nunzio Alberto Borghese, Michele Pirovano, Renato Mainetti, and Pier Luca Lanzi. An integrated low-cost system for at-home rehabilitation. In *Proceedings of the International Conference on Virtual Systems and Multimedia (VSMM)*. IEEE, pages: 553–556, 2012.

[42] Jose-Antonio Lozano-Quilis, Hermenegildo Gil-Gómez, Jose-Antonio Gil-Gómez, Sergio Albiol-Pérez, Guillermo Palacios-Navarro, Habib M. Fardoun, and Abdulfattah S. Mashat. Virtual rehabilitation for multiple sclerosis using a kinect-based system: randomized controlled trial. In *JMIR serious games*, 2(2):e12, 2014.

[43] Mateus Trombetta, Patrícia Paula Bazzanello Henrique, Manoela Rogofski Brum, Eliane Lucia Colussi, Ana Carolina Bertoletti De Marchi, and Rafael Rieder. Motion Rehab AVE 3D: A VR-based exergame for post-stroke rehabilitation. In *Computer methods and programs in biomedicine*, 151:15–20, 2017.

[44] Mohamad Hoda, Haiwei Dong, Dewan Ahmed, and Abdulmotaleb El Saddik. Cloud-based rehabilitation exergames system. In *Proceedings of the International Conference on Multimedia and Expo Workshops (ICMEW)*. IEEE, pages: 1–6, 2014.

[45] Stephen Margolis and Valmae Ypinazar. Tele-pharmacy in remote medical practice: the Royal Flying Doctor Service Medical Chest Program. In *Rural and remote health*, 8(2):937, 2008.

[46] Rashid Bashshur, Gary Shannon, Elizabeth Krupinski, and Jim Grigsby. The taxonomy of telemedicine. In *Telemedicine and e-Health*, 17(6):484–494, 2011.

[47] David Webster and Ozkan Celik. Systematic review of Kinect applications in elderly care and stroke rehabilitation. In *Journal of neuroengineering and rehabilitation*, 11(1):108, 2014.

[48] Bhasker Amatya, Mary Pauline Galea, Jurg Kesselring, and Fary Khan. Effectiveness of telerehabilitation interventions in persons with multiple sclerosis: A systematic review. In *Multiple sclerosis and related disorders*, 4(4):358–369, 2015.

[49] Michael McCue, Andrea Fairman, and Michael Pramuka. Enhancing quality of life through telerehabilitation. In *Physical Medicine and Rehabilitation Clinics*, 21(1):195–205, 2010.

[50] Blaine Reeder, Jane Chung, and Jennifer Stevens-Lapsley. Current telerehabilitation research with older adults at home: an integrative review. In *Journal of gerontological nursing*, 42(10):15–20, 2016.

[51] Xian-Liang Liu, Jing-Yu Tan, Tao Wang, Qi Zhang, Min Zhang, Li-Qun Yao, and Jin-Xiu Chen. Effectiveness of home-based pulmonary rehabilitation for patients with chronic obstructive pulmonary disease: a meta-analysis of randomized controlled trials. In *Rehabilitation Nursing*, 39(1):36–59, 2014.

[52] Fernanda Dultra Dias, Luciana Maria Malosá Sampaio, Graziela Alves da Silva, Évelim LF Dantas Gomes, Eloisa Sanches Pereira do Nascimento, Vera Lucia Santos Alves, Roberto Stirbulov, and Dirceu Costa. Home-based pulmonary rehabilitation in patients with chronic obstructive pulmonary disease: a randomized clinical trial. In *International journal of chronic obstructive pulmonary disease*, 8:537, 2013.

[53] Ines Frederix, Luc Vanhees, Paul Dendale, and Kaatje Goetschalckx. A review of telerehabilitation for cardiac patients. In *Journal of telemedicine and telecare*, 21(1):45–53, 2015.

[54] Ewa Piotrowicz, Rafał Baranowski, Maria Bilinska, Monika Stepnowska, Malgorzata Piotrowska, Anna Wójcik, Jerzy Korewicki, Lidia Chojnowska, Lukasz A Malek, Mariusz Klopotowski, Walerian Piotrowski, and Ryszard Piotrowicz. A new model of home-based telemonitored cardiac rehabilitation in patients with heart failure: effectiveness, quality of life, and adherence. In *European journal of heart failure*, 12(2):164–171, 2010.

[55] Gillian Barry, Brook Galna, and Lynn Rochester. The role of exergaming in Parkinson's disease rehabilitation: a systematic review of the evidence. In *Journal of neuroengineering and rehabilitation*, 11(1):33, 2014.

[56] Nancy K. Latham, Bette Ann Harris, Jonathan F. Bean, Timothy Heeren, Christine Goodyear, Stacey Zawacki, Diane M. Heislein, Jabed Mustafa, Poonam Pardasaney, Marie Giorgetti, Nicole Holt, Lori Goehring, and Alan M. Jette. Effect of a home-based exercise program on functional recovery following rehabilitation after hip fracture: a randomized clinical trial. In *Jama*, 311(7):700–708, 2014.

[57] Johanna Edgren, Anu Salpakoski, Sanna E. Sihvonen, Erja Portegijs, Mauri Kallinen, Marja Arkela, Pirkko Jäntti, Jukka Vanhatalo, Mika Pekkonen, Taina Rantanen, Ari Heinonen, and Sarianna Sipilä. Effects of a home-based physical rehabilitation program on physical disability after hip fracture: a randomized controlled trial. In *Journal of the American Medical Directors Association*, 16(4):350.e1–7, 2015.

[58] Paula Rego, Pedro Miguel Moreira, and Luis Paulo Reis. Serious games for rehabilitation: A survey and a classification towards a taxonomy. In *Proceedings of the Iberian Conference on Information Systems and Technologies (CISTI)*. IEEE, pages: 1–6, 2010.

[59] Christine Lisetti, Reza Amini, Ugan Yasavur, and Naphtali Rishe. I can help you change! an empathic virtual agent delivers behavior change health interventions. In *ACM Transactions on Management Information Systems (TMIS)*, 4(4):1–28, 2013.

[60] Chuan-Jun Su, Chang-Yu Chiang, and Jing-Yan Huang. Kinect-enabled home-based rehabilitation system using Dynamic Time Warping and fuzzy logic. In *Applied Soft Computing*, 22:652–666, 2014.

[61] Elham Saraee, Saurabh Singh, Kathryn Hendron, Mingxin Zheng, Ajjen Joshi, Terry Ellis, and Margrit Betke. ExerciseCheck: Remote monitoring and evaluation platform for home based physical therapy. In *Proceedings of the International Conference on PErvasive Technologies Related to Assistive Environments (PETRA)*, pages: 87–90, 2017.

[62] Lucy Dodakian, Alison L. McKenzie, Vu Le, Jill See, Kristin Pearson-Fuhrhop, Erin Burke Quinlan, Robert J. Zhou, Renee Augsberger, Xuan A. Tran, Nizan Friedman, David J. Reinkensmeyer, and Steven C. Cramer. A home-based telerehabilitation program for patients with stroke. In *Neurorehabilitation and neural repair*, 31(10-11):923–933, 2017.

[63] Miguel Pedraza-Hueso, Sergio Martín-Calzón, Francisco Javier Díaz-Pernas, and Mario Martínez-Zarzuela. Rehabilitation using kinect-based games and virtual reality. In *Procedia Computer Science*, 75:161–168, 2015.

[64] Emmanuel Tsekleves, Ioannis Theoklitos Paraskevopoulos, Alyson Warland, and Cherry Kilbride. Development and preliminary evaluation of a novel low cost VR-based upper limb stroke rehabilitation platform using Wii technology. In *Disability and Rehabilitation: Assistive Technology*, 11(5):413–422, 2016.

[65] Yves Rybarczyk, Jan Kleine Deters, Clément Cointe, and Danilo Esparza. Smart web-based platform to support physical rehabilitation. In *Sensors*, 18(5):1344, 2018.

[66] Fabián Narváez, Fernando Arbito, Carlos Luna, Christian Merchán, María C. Cuenca, and Gloria M. Díaz. Kushkalla: a web-based platform to improve functional movement rehabilitation. In *Proceedings of the International Conference on Technologies and Innovation*. Springer, pages: 194–208, 2017.

[67] Gabriel Fuertes Muñoz, Ramón A. Mollineda, Jesús Gallardo Casero, and Filiberto Pla. A RGBD-Based interactive system for gaming-driven rehabilitation of upper limbs. In *Sensors*, 19(16):3478, 2019.

[68] Giancarlo Fortino and Raffaele Gravina. A cloud-assisted wearable system for physical rehabilitation. In *Proceedings of the Workshop on ICTs for Improving Patients Rehabilitation Research Techniques*. Springer, pages: 168–182, 2014.

[69] Cristina Costa, David Tacconi, Roberto Tomasi, Flavio Calva, and Valerio Terreri. RIABLO: a game system for supporting orthopedic rehabilitation. In *Proceedings of the Biannual Conference of the Italian Chapter of SIGCHI (CHITALY)*, pages: 1–7, 2013.

[70] Amir Mobini, Saeed Behzadipour, and Mahmoud Saadat Foumani. Accuracy of Kinect's skeleton tracking for upper body rehabilitation applications. In *Disability and Rehabilitation: Assistive Technology*, 9(4):344–352, 2014.

[71] Štěpán Obdržálek, Gregorij Kurillo, Ferda Ofli, Ruzena Bajcsy, Edmund Seto, Holly Jimison, and Michael Pavel. Accuracy and robustness of Kinect pose estimation in the context of coaching of elderly population. In *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, pages: 1188–1193, 2012.

[72] Elżbieta Mirek, Monika Rudzińska, and Andrzej Szczudlik. The assessment of gait disorders in patients with Parkinson's disease using the three-dimensional motion analysis system Vicon. In *Neurologia i neurochirurgia polska*, 41(2):128–133, 2007.

[73] Markus Windolf, Nils Götzen, and Michael Morlock. Systematic accuracy and precision analysis of video motion capturing systems—exemplified on the Vicon-460 system. In *Journal of biomechanics*, 41(12):2776–2780, 2008.

[74] Yaejin Moon, Ryan S. McGinnis, Kirsten Seagers, Robert W. Motl, Nirav Sheth, John A. Wright Jr, Roozbeh Ghaffari, and Jacob J. Sosnoff. Monitoring gait in multiple sclerosis with novel wearable motion sensors. In *PLoS One*, 12(2):e0171346, 2017.

[75] Todd Hester, Richard Hughes, Delsey M. Sherrill, Bethany Knorr, Metin Akay, Joel Stein, and Paolo Bonato. Using wearable sensors to measure motor abilities following stroke. In *Proceedings of the International Workshop on Wearable and Implantable Body Sensor Networks (BSN)*. IEEE, pages: 4–pp, 2006.

[76] Roberto Nerino, Laura Contin, W. J. Gonçalves da Silva Pinto, Giuseppe Massazza, M. Actis, Patrizia Capacchione, Antonio Chimienti, and Giuseppe Pettiti. A BSN based service for post-surgical knee rehabilitation at home. In *Proceedings of the International Conference on Body Area Networks (BODYNETS)*, pages: 401–407, 2013.

[77] Wenbing Zhao, Hai Feng, Roanna Lun, Deborah D. Espy, and M. Ann Reinthal. A Kinect-based rehabilitation exercise monitoring and guidance system. In *Proceedings of the International Conference on Software Engineering and Service Science (ICSESS)*. IEEE, pages: 762–765, 2014.

[78] Irina Mocanu, Cosmin Marian, Lucia Rusu, and Raluca Arba. A Kinect based adaptive exergame. In *Proceedings of the International Conference on Intelligent Computer Communication and Processing (ICCP)*. IEEE, pages: 117–124, 2016.

[79] Jacob Kritikos, Anxhelino Mehmeti, George Nikolaou, and Dimitris Koutsouris. Fully portable low-cost motion capture system with real-time feedback for rehabilitation treatment. In *Proceedings of the International Conference on Virtual Rehabilitation (ICVR)*. IEEE, pages: 1–8, 2019.

[80] Alejandro Baldominos, Yago Saez, and Cristina García del Pozo. An approach to physical rehabilitation using state-of-the-art virtual reality and motion tracking technologies. In *Procedia Computer Science*, 64:10–16, 2015.

[81] Madina Alimanova, Saulet Borambayeva, Dinara Kozhamzharova, Nurgul Kurmangaiyeva, Dinara Ospanova, Gulnar Tyulepberdinova, Gulnur Gaziz, and Aray Kassenkhan. Gamification of hand rehabilitation process using virtual reality tools: Using leap motion for hand rehabilitation. In *Proceedings of the IEEE International Conference on Robotic Computing (IRC)*. IEEE, pages: 336–339, 2017.

[82] Maryam Khademi, Hossein Mousavi Hondori, Alison McKenzie, Lucy Dodakian, Cristina Videira Lopes, and Steven C. Cramer. Free-hand interaction with leap motion controller for stroke rehabilitation. In *CHI'14 Extended Abstracts on Human Factors in Computing Systems*, pages: 1663–1668, 2014.

[83] Fraser Anderson, Michelle Annett, and Walter F Bischof. Lean on Wii: physical rehabilitation with virtual reality Wii peripherals. In *Stud Health Technol Inform*, 154:229–34, 2010.

[84] Michael W. Kennedy, James P. Schmiedeler, Charles R. Crowell, Michael Villano, Aaron D. Striegel, and Johan Kuitse. Enhanced feedback in balance rehabilitation using the Nintendo Wii Balance Board. In *Proceedings of the International Conference on E-Health Networking, Applications and Services (HEALTHCOM)*. IEEE, pages: 162–168, 2011.

[85] Dominic Holmes, Darryl Keith Charles, Philip J. Morrow, Sally I. McClean, and Suzanne M. McDonough. Usability and performance of Leap Motion and Oculus Rift for upper arm virtual reality stroke rehabilitation. In *Proceedings of the International Conference on Disability, Virtual Reality & Associated Technologies (ICDVRAT)*. Central Archive at the University of Reading, 2016.

[86] Donglin Chen, Hao Liu, and Zhigang Ren. Application of wearable device HTC VIVE in upper limb rehabilitation training. In *Proceedings of the IEEE Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC)*. IEEE, pages: 1460–1464, 2018.

[87] Henrique Galvan Debarba, Marcelo Elias de Oliveira, Alexandre Lädermann, Sylvain Chagué, and Caecilia Charbonnier. Augmented Reality Visualization of Joint Movements for Rehabilitation and Sports Medicine. In *Proceedings of the Symposium on Virtual and Augmented Reality (SVR)*. IEEE, pages: 114–121, 2018.

[88] Jeremia Philipp Oskar Held, Kevin Yu, Connor Pyles, Janne Marieke Veerbeek, Felix Bork, Sandro-Michael Heining, Nassir Navab, and Andreas Rüdiger Luft. Augmented Reality–Based Rehabilitation of Gait Impairments: Case Report. In *JMIR mHealth and uHealth*, 8(5):e17804, 2020.

[89] James William Burke, Michael McNeill, Darryl Charles, Philip J. Morrow, Jacqueline Crosbie, and Suzanne McDonough. Serious Games for Upper Limb Rehabilitation Following Stroke. In *Proceedings of the Conference in Games and Virtual Worlds for Serious Applications (VS-Games)*. IEEE, pages: 103–110, 2009.

[90] Robin Hunicke. The case for dynamic difficulty adjustment in games. In *ACM International Conference Proceeding Series (ICPS)*, pages: 429–433, 2005.

[91] Janani Venugopalan, Chih-Wen Cheng, and May D Wang. MotionTalk: personalized home rehabilitation system for assisting patients with impaired mobility. In *Proceedings of the Conference on Bioinformatics, Computational Biology, and Health Informatics (ACM BCB)*, pages: 455–463, 2014.

[92] Katherine O. Berg, Sharon L. Wood-Dauphinee, J. Ivan Williams, and Brian Maki. Measuring balance in the elderly: validation of an instrument. In *Canadian journal of public health= Revue canadienne de sante publique*, 83:S7–11, 1992.

[93] Mary E. Tinetti, T. Franklin Williams, and Raymond Mayewski. Fall risk index for elderly patients based on number of chronic disabilities. In *The American journal of medicine*, 80(3):429–434, 1986.

[94] Christopher M. Bishop. *Pattern recognition and machine learning*. Springer, 2006.

[95] Donald J. Berndt and James Clifford. Using dynamic time warping to find patterns in time series. In *Proceedings of the Workshop on Knowledge Discovery in Databases (KDD)*, pages: 359–370, 1994.

[96] Xiaoqun Yu and Shuping Xiong. A Dynamic Time Warping Based Algorithm to Evaluate Kinect-Enabled Home-Based Physical Rehabilitation Exercises for Older People. In *Sensors*, 19(13):2882, 2019.

[97] Naimul Mefraz Khan, Stephen Lin, Ling Guan, and Baining Guo. A visual evaluation framework for in-home physical rehabilitation. In *Proceedings of the IEEE International Symposium on Multimedia (ISM)*. IEEE, pages: 237–240, 2014.

[98] Janani Venugopalan, Chihwen Cheng, Todd H. Stokes, and May D. Wang. Kinect-based rehabilitation system for patients with traumatic brain injury. In *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, pages: 4625–4628, 2013.

[99] Paolo Tormene, Toni Giorgino, Silvana Quaglini, and Mario Stefanelli. Matching incomplete time series with dynamic time warping: an algorithm and an application to post-stroke rehabilitation. In *Artificial intelligence in medicine*, 45(1):11–34, 2009.

[100] Lucio Ciabattoni, Francesco Ferracuti, Giuseppe Lazzaro, Luca Romeo, and Federica Verdini. Serious gaming approach for physical activity monitoring: A visual feedback based on quantitative evaluation. In *Proceedings of the International Conference on Consumer Electronics-Berlin (ICCE-Berlin)*. IEEE, pages: 209–213, 2016.

[101] Danilo Avola, Luigi Cinque, Gian Luca Foresti, Marco Raoul Marini, and Daniele Pannone. VRheab: a fully immersive motor rehabilitation system based on recurrent neural network. In *Multimedia Tools and Applications*, 77(19):24955–24982, 2018.

[102] Zheng-An Zhu, Yun-Chung Lu, Chih-Hsiang You, and Chen-Kuo Chiang. Deep Learning for Sensor-Based Rehabilitation Exercise Recognition and Evaluation. In *Sensors*, 19(4):887, 2019.

[103] Yalin Liao, Aleksandar Vakanski, and Min Xian. A Deep Learning Framework for Assessing Physical Rehabilitation Exercises. In *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 28(2):468–477, 2020.

[104] Marianna Capecci, Lucio Ciabattoni, Francesco Ferracuti, Andrea Monteriù, Luca Romeo, and Federica Verdini. Collaborative design of a telerehabilitation system enabling virtual second opinion based on fuzzy logic. In *IET Computer Vision*, 12(4):502–512, 2018.

[105] Wenbing Zhao, Roanna Lun, Deborah D. Espy, and M. Ann Reinthal. Real-time motion assessment for rehabilitation exercises: Integration of kinematic modeling with fuzzy inference. In *Journal of Artificial Intelligence and Soft Computing Research*, 4(4):267–285, 2014.

[106] Alana Da Gama, Thiago Chaves, Lucas Figueiredo, and Veronica Teichrieb. Guidance and movement correction based on therapeutics movements for motor rehabilitation support systems. In *Proceedings of the Symposium on Virtual and Augmented Reality (SVR)*. IEEE, pages: 191–200, 2012.

[107] David Antón, Alfredo Goñi, Arantza Illarramendi, Juan José Torres-Unda, and Jesús Seco. KiReS: A Kinect-based telerehabilitation system. In *Proceedings of the International Conference on E-Health Networking, Applications and Services (HEALTHCOM)*. IEEE, pages: 444–448, 2013.

[108] Kevin Desai, Kanchan Bahirat, Sudhir Ramalingam, Balakrishnan Prabhakaran, Thiru Annaswamy, and Una E Makris. Augmented reality-based exergames for rehabilitation. In *Proceedings of the International Conference on Multimedia Systems (MM-Sys)*, pages: 1–10, 2016.

[109] Brook Galna, Dan Jackson, Guy Schofield, Roisin McNaney, Mary Webster, Gillian Barry, Dadirayi Mhiripiri, Madeline Balaam, Patrick Olivier, and Lynn Rochester. Retraining function in people with Parkinson's disease using the Microsoft kinect: game design and pilot testing. In *Journal of neuroengineering and rehabilitation*, 11(1):60, 2014.

[110] Martina Eckert, Ignacio Gomez-Martinho, Cristina Esteban, Yadira Peláez, Mónica Jiménez, Maria-Luisa Martín-Ruiz, Maite Manzano, Alicia Aglio, Victor Osma, Juan Meneses, and Luis Salgado. The Blexer system–Adaptive full play therapeutic exergames with web-based supervision for people with motor dysfunctionalities. In *EAI Endorsed Transactions on Serious Games*, 5(16), 2018.

[111] Gustavo Saposnik, Robert Teasell, Muhammad Mamdani, Judith Hall, William McIlroy, Donna Cheung, Kevin E. Thorpe, Leonardo G. Cohen, and Mark Bayley. Effectiveness of virtual reality using Wii gaming technology in stroke rehabilitation: a pilot randomized clinical trial and proof of principle. In *Stroke*, 41(7):1477–1484, 2010.

[112] Nor Shahizan Redzuan, Julia P. Engkasan, Mazlina Mazlan, and Saini Jeffery Freddy Abdullah. Effectiveness of a video-based therapy program at home after acute stroke: a randomized controlled trial. In *Archives of physical medicine and rehabilitation*, 93(12):2177–2183, 2012.

[113] Michele Pirovano, Elif Surer, Renato Mainetti, Pier Luca Lanzi, and N. Alberto Borghese. Exergaming and rehabilitation: A methodology for the design of effective and safe therapeutic exergames. In *Entertainment Computing*, 14:55–65, 2016.

[114] Seline Wüest, Rolf Van De Langenberg, and Eling D. De Bruin. Design considerations for a theory-driven exergame-based rehabilitation program to improve walking of persons with stroke. In *European Review of Aging and Physical Activity*, 11(2):119–129, 2014.

[115] A. M. Gentile. Skill Acquisition: Action, Movement, and Neuromotor Processes. In *J.H. Carr & R.B. Shepard (Eds.), Movement Science: Foundations for Physical Therapy (2nd ed., pp.111-187). Rockville, MD: Aspen*, 2000.

[116] Michele Pirovano, Renato Mainetti, Gabriel Baud-Bovy, Pier Luca Lanzi, and Nunzio Alberto Borghese. Self-adaptive games for rehabilitation at home. In *Proceedings of the IEEE Conference on Computational Intelligence and Games (CIG)*. IEEE, pages: 179–186, 2012.

[117] N. Alberto Borghese, Renato Mainetti, Michele Pirovano, and Pier Luca Lanzi. An intelligent game engine for the at-home rehabilitation of stroke patients. In *Proceedings of the International Conference on Serious Games and Applications for Health (SeGAH)*. IEEE, pages: 1–8, 2013.

[118] Sebastian Boring, Marko Jurmu, and Andreas Butz. Scroll, tilt or move it: using mobile phones to continuously control pointers on large public displays. In *Proceedings of the Annual Conference of the Australian Computer-Human Interaction Special Interest Group: Design: Open 24/7 (OZCHI)*. ACM, pages: 161–168, 2009.

[119] Mauro Zampolini, Elisabetta Todeschini, Hermie J. Hermens, Stephan Ilsbroukx, Velio Macellari, Riccardo Magni, Marco Rogante, Miriam M. Vollenbroek, and Claudia Giacomozzi. Tele-rehabilitation: present and future. In *Annali dell'Istituto superiore di sanita*, 44(2):125–134, 2008.

[120] Ralph Sichler. Motivation, Overview. In. *Encyclopedia of Critical Psychology*. Ed. by Thomas Teo. New York, NY: Springer New York, pp. 1204–1209, 2014.

[121] Edward L. Deci and Richard M Ryan. The "what" and "why" of goal pursuits: Human needs and the self-determination of behavior. In *Psychological inquiry*, 11(4):227–268, 2000.

[122] Daniel L. King and Paul Delfabbro. Motivational differences in problem video game play. In *Journal of Cybertherapy and Rehabilitation*, 2(2):139–149, 2009.

[123] Edward L. Deci and Richard M. Ryan. *Intrinsic motivation and self-determination in human behavior*. Springer, 1985.

[124] Marc-André K. Lafrenière, Jérémie Verner-Filion, and Robert J. Vallerand. Development and validation of the Gaming Motivation Scale (GAMS). In *Personality and individual differences*, 53(7):827–831, 2012.

[125] Richard M. Ryan and Edward L. Deci. Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. In *American psychologist*, 55(1):68, 2000.

[126] Julian Togelius, Renzo De Nardi, and Simon M. Lucas. Towards automatic personalised content creation for racing games. In *Proceedings of the IEEE Symposium on Computational Intelligence and Games (CIG)*. IEEE, pages: 252–259, 2007.

[127] Noor Shaker, Georgios Yannakakis, and Julian Togelius. Towards automatic personalized content generation for platform games. In *Proceedings of the Artificial Intelligence and Interactive Digital Entertainment Conference (AIIDE)*, pages: 63–68, 2010.

[128] Luigi Cardamone, Daniele Loiacono, and Pier Luca Lanzi. Interactive evolution for the procedural generation of tracks in a high-end racing game. In *Proceedings of the Annual Conference on Genetic and Evolutionary Computation (GECCO)*. ACM, pages: 395–402, 2011.

[129] Hiroyuki Iida, Nobuo Takeshita, and Jin Yoshimura. A metric for entertainment of boardgames: its implication for evolution of chess variants. In. *Entertainment Computing*. Springer, pp. 65–72, 2003.

[130] Nicola Beume, Holger Danielsiek, Christian Eichhorn, Boris Naujoks, Mike Preuss, Klaus Stiller, and Simon Wessing. Measuring flow as concept for detecting game fun in the Pac-Man game. In *Proceedings of the IEEE Congress on Evolutionary Computation (IEEE WCCI)*. IEEE, pages: 3448–3455, 2008.

[131] Lennart Nacke and Craig A. Lindley. Flow and immersion in first-person shooters: measuring the player's gameplay experience. In *Proceedings of the Conference on future play: Research, play, share (FUTUREPLAY)*, pages: 81–88, 2008.

[132] Elisa D. Mekler, Julia Ayumi Bopp, Alexandre N. Tuch, and Klaus Opwis. A systematic review of quantitative studies on the enjoyment of digital entertainment games. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI)*, pages: 927–936, 2014.

[133] Mihaly Czikszentmihalyi. *Flow: The psychology of optimal experience*. New York: Harper & Row, 1990.

[134] Kevin M. Malloy and Leonard S. Milling. The effectiveness of virtual reality distraction for pain reduction: a systematic review. In *Clinical psychology review*, 30(8):1011–1018, 2010.

[135] Mihaly Csikszentmihalyi. *Beyond boredom and anxiety*. Jossey-Bass, 2000.

[136] Manuel Pezzera, Alessandro Tironi, Jacopo Essenziale, Renato Mainetti, and N Alberto Borghese. Approaches for increasing patient's engagement and motivation in exer-games-based autonomous telerehabilitation. In *Proceedings of the IEEE International Conference on Serious Games and Applications for Health (SeGAH)*. IEEE, pages: 1–8, 2019.

[137] Alessandro Tironi, Renato Mainetti, Manuel Pezzera, and N. Alberto Borghese. An Empathic Virtual Caregiver for assistance in exer-game-based rehabilitation therapies. In *Proceedings of the IEEE International Conference on Serious Games and Applications for Health (SeGAH)*. IEEE, pages: 1–6, 2019.

[138] Manuel Pezzera and N Alberto Borghese. Dynamic difficulty adjustment in exer-games for rehabilitation: a mixed approach. In *Proceedings of the IEEE International Conference on Serious Games and Applications for Health (SeGAH)*. IEEE, pages: 1–7, 2020.

[139] Robin Hunicke, Marc LeBlanc, and Robert Zubek. MDA: A formal approach to game design and game research. In *Proceedings of the AAAI Workshop on Challenges in Game AI*, 2004.

[140] George Kelly and Hugh McCabe. Citygen: An interactive system for procedural city generation. In *Proceedings of the International Conference on Game Design and Technology*, pages: 8–16, 2007.

[141] Alexandru Iosup. POGGI: generating puzzle instances for online games on grid infrastructures. In *Concurrency and Computation: Practice and Experience*, 23(2):158–171, 2011.

[142] Mark Hendrikx, Sebastiaan Meijer, Joeri Van Der Velden, and Alexandru Iosup. Procedural content generation for games: A survey. In *ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM)*, 9(1), 2013.

[143] Noor Shaker, Julian Togelius, and Mark J. Nelson. *Procedural content generation in games*. Springer, 2016.

[144] Crammond Geoff. *The Sentinel*. Firebird. 1986.

[145] David Braben and Ian Bell. *Elite*. Acornsoft, Firebird and Imagineer. 1984.

[146] Blizzard North. *Diablo*. Blizzard Entertainment. 1997.

[147] Mojang. *Minecraft*. Mojang and Microsoft Studios. 2011.

[148] Hello Games. *No man's sky*. Hello Games. 2016.

[149] Dajana Dimovska, Patrick Jarnfelt, Sebbe Selvig, and Georgios N. Yannakakis. Towards procedural level generation for rehabilitation. In *Proceedings of the Workshop on Procedural Content Generation in Games (PCG)*. ACM, 2010.

[150] Arsénio Reis, Jorge Lains, Hugo Paredes, Vitor Filipe, Catarina Abrantes, Fernando Ferreira, Romeu Mendes, Paula Amorim, and João Barroso. Developing a system for post-stroke rehabilitation: an exergames approach. In *Proceedings of the International Conference on Universal Access in Human-Computer Interaction (UAHCI)*. Springer, pages: 403–413, 2016.

[151] Ken Perlin. An image synthesizer. In *ACM Siggraph Computer Graphics*, 19(3):287–296, 1985.

[152] Fujio Yamaguchi. *Curves and surfaces in computer aided geometric design*. Springer Science & Business Media, 2012.

[153] Riccardo Cantoni, Jacopo Essenziale, Manuel Pezzera, Renato Mainetti, and N. Alberto Borghese. Procedural constrained story generation based on Propp's and Fabula models. In *Proceedings of the IEEE International Conference on Serious Games and Applications for Health (SeGAH)*. IEEE, pages: 1–8, 2020.

[154] Reza Amini, Christine Lisetti, Ugan Yasavur, and Naphtali Rishe. On-demand virtual health counselor for delivering behavior-change health interventions. In *Proceedings of the International Conference on Healthcare Informatics (HEALTHINF)*. IEEE, pages: 46–55, 2013.

[155] Hendrikus J. A. op den Akker, Randy Klaassen, and Anton Nijholt. Virtual coaches for healthy lifestyle. In *Toward Robotic Socially Believable Behaving Systems-Volume II*. Springer, 121–149, 2016.

[156] Cynthia LeRouge, Kathryn Dickhut, Christine Lisetti, Savitha Sangameswaran, and Toree Malasanos. Engaging adolescents in a computer-based weight management program: avatars and virtual coaches could help. In *Journal of the American Medical Informatics Association*, 23(1):19–28, 2016.

[157] Matthijs Pontier and Ghazanfar F. Siddiqui. A virtual therapist that responds empathically to your answers. In *Proceedings of the International Workshop on Intelligent Virtual Agents (IVA)*. Springer, pages: 417–425, 2008.

[158] Lindsay Alexander Shaw, Romain Tourrel, Burkhard Claus Wunsche, Christof Lutteroth, Stefan Marks, and Jude Buckley. Design of a virtual trainer for exergaming. In *Proceedings of the Australasian Computer Science Week Multiconference (ACSW)*, pages: 1–9, 2016.

[159] Paul Ekman and Wallace V. Friesen. Measuring facial movement. In *Environmental psychology and nonverbal behavior*, 1(1):56–75, 1976.

[160] James A. Russell. Core affect and the psychological construction of emotion. In *Psychological review*, 110(1):145, 2003.

[161] Duc Truong Pham and Marco Castellani. Action aggregation and defuzzification in Mamdani-type fuzzy systems. In *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 216(7):747–759, 2002.

[162] Robin Hunicke and Vernell Chapman. AI for dynamic difficulty adjustment in games. In *Challenges in Game Artificial Intelligence AAAI Workshop*, 2, 2004.

[163] Valve Software. *Half-Life*. 1998.

[164] Valve Software. *Left 4 Dead*. 2008.

[165] Alexander E. Zook and Mark O. Riedl. A Temporal Data-Driven Player Model for Dynamic Difficulty Adjustment. In *Proceedings of the Eighth AAAI Conference on Artificial Intelligence and Interactive Digital Entertainment*. AAAI Press, pages: 93–98, 2012.

[166] Changchun Liu, Pramila Agrawal, Nilanjan Sarkar, and Shuo Chen. Dynamic difficulty adjustment in computer games through real-time anxiety-based affective feedback. In *International Journal of Human-Computer Interaction*, 25(6):506–529, 2009.

[167] Ricardo Lopes and Rafael Bidarra. Adaptivity Challenges in Games and Simulations: A Survey. In *IEEE Transactions on Computational Intelligence and AI in Games*, 3(2):85–99, 2011.

[168] Nadia Hocine, Abdelkader Gouaïch, Stefano A. Cerri, Denis Mottet, Jérome Froger, and Isabelle Laffont. Adaptation in serious games for upper-limb rehabilitation: an approach to improve training outcomes. In *User Modeling and User-Adapted Interaction*, 25(1):65–98, 2015.

[169] Jan Smeddinck, Sandra Siegel, and Marc Herrlich. Adaptive Difficulty in Exergames for Parkinson's Disease Patients. In *Proceedings of Graphics Interface (GI)*, 2013.

[170] Keunyeong Kim, Michael G. Schmierbach, Saraswathi Bellur, Mun-Young Chung, Julia Daisy Fraustino, Frank Dardis, and Lee Ahern. Is it a sense of autonomy, control, or attachment? Exploring the effects of in-game customization on game enjoyment. In *Computers in Human Behavior*, 48:695–705, 2015.

[171] Sebastian Deterding, Rilla Khaled, Lennart E. Nacke, and Dan Dixon. Gamification: Toward a definition. In *Proceedings of the CHI Gamification Workshop (CHI 2011)*, 2011.

[172] Juho Hamari, Jonna Koivisto, and Harri Sarsa. Does gamification work?–a literature review of empirical studies on gamification. In *Proceedings of the Hawaii International Conference on System Sciences (HICSS)*. IEEE, pages: 3025–3034, 2014.

[173] Jason T. Bowey, Max V. Birk, and Regan L. Mandryk. Manipulating leaderboards to induce player experience. In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play (CHI-PLAY)*. ACM, pages: 115–120, 2015.

[174] Rachel Bailey, Kevin Wise, and Paul Bolls. How avatar customizability affects children's arousal and subjective presence during junk food–sponsored online video games. In *CyberPsychology & Behavior*, 12(3):277–283, 2009.

[175] David Pinelle, Nelson Wong, and Tadeusz Stach. Heuristic evaluation for games: usability principles for video game design. In *Proceedings of the Conference on Human Factors in Computing Systems (CHI)*. ACM, pages: 1453–1462, 2008.

[176] Manuel Pezzera, Eleonora Chitti, and N Alberto Borghese. MIRARTS: A mixed reality application to support postural rehabilitation. In *Proceedings of the IEEE International Conference on Serious Games and Applications for Health (SeGAH)*. IEEE, pages: 1–7, 2020.

[177] Luis I. Gomez-Jordana, James Stafford, C. Lieke E. Peper, and Cathy M. Craig. Crossing virtual doors: a new method to study gait impairments and freezing of gait in Parkinson's disease. In *Parkinson's Disease*, 2018.

[178] Gabriel Evans, Jack Miller, Mariangely Iglesias Pena, Anastacia MacAllister, and Eliot Winer. Evaluating the Microsoft HoloLens through an augmented reality assembly application. In *Degraded Environments: Sensing, Processing, and Display*. International Society for Optics and Photonics, 2017.

[179] Matthew G. Hanna, Ishtiaque Ahmed, Jeffrey Nine, Shyam Prajapati, and Liron Pantanowitz. Augmented reality technology using Microsoft HoloLens in anatomic pathology. In *Archives of pathology & laboratory medicine*, 142(5):638–644, 2018.

[180] Ivo Kuhlemann, Markus Kleemann, Philipp Jauer, Achim Schweikard, and Floris Ernst. Towards X-ray free endovascular interventions–using HoloLens for on-line holographic visualisation. In *Healthcare technology letters*, 4(5):184–187, 2017.

[181] Philip Pratt, Matthew Ives, Graham Lawton, Jonathan Simmons, Nasko Radev, Liana Spyropoulou, and Dimitri Amiras. Through the HoloLens™ looking glass: augmented reality for extremity reconstruction surgery using 3D vascular models with perforating vessels. In *European radiology experimental*, 2(1):2, 2018.

[182] Oren M. Tepper, Hayeem L. Rudy, Aaron Lefkowitz, Katie A. Weimer, Shelby M. Marks, Carrie S. Stern, and Evan S. Garfein. Mixed reality with HoloLens: where virtual reality meets augmented reality in the operating room. In *Plastic and reconstructive surgery*, 140(5):1066–1070, 2017.

[183] Lei Shi, Tao Luo, Li Zhang, Zhongcheng Kang, Jie Chen, Feiyue Wu, and Jia Luo. Preliminary use of HoloLens glasses in surgery of liver cancer. In *Zhong nan da xue xue bao. Yi xue ban= Journal of Central South University. Medical sciences*, 43(5):500–504, 2018.

[184] Lorenzo Chiari, R. Van Lummel, Clemens Becker, K. Pfeiffer, Ulrich Lindemman, and W. Zijlstra. Classification of the user's needs, characteristics and scenarios—update. In *Report from the EU Project (6th Framework Program, IST Contract no. 045622) Sensing and Action to support mobility in Ambient Assisted Living*, 2009.

[185] John Brooke. Sus: a "quick and dirty'usability. In *Usability evaluation in industry*, 189, 1996.

[186] Michele Korostil and Anthony Feinstein. Anxiety disorders and their clinical correlates in multiple sclerosis patients. In *Multiple Sclerosis Journal*, 13(1):67–72, 2007.

[187] Richard J. Siegert and Darrell A. Abernethy. Depression in multiple sclerosis: a review. In *Journal of Neurology, Neurosurgery & Psychiatry*, 76(4):469–475, 2005.

[188] Shaun A. Rigby, Cesar Domenech, Everard E. Thornton, S. Tedman, and Carolyn A. Young. Development and validation of a self-efficacy measure for people with multiple sclerosis: the Multiple Sclerosis Self-efficacy Scale. In *Multiple Sclerosis Journal*, 9(1):73–81, 2003.