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THE DESIGN OF EXERGAMING SYSTEMS FOR AUTONOMOUS REHABILITATION

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Dedicata a Fedilla, in vista di un luminoso futuro insieme.

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Abstract

WHILE the incidence of stroke rises worldwide, so do the costs of the subsequent intensive rehabilitation, setting off alarm bells that call for solutions to lower figures while preserving therapy efficacy. At-home autonomous rehabilitation appears as a promising solution, reducing costs for health providers and patients alike. The trend of *exergaming*, i.e. exercising through video games, may represent the key to its success. However, rehabilitation at home demands careful consideration, as all the requirements of a correct rehabilitation therapy must be addressed even in the absence of a therapist.

The aim of this research is to study the feasibility of at-home autonomous rehabilitation through exergaming. To do so, we explore the state-of-the-art of the exergaming field and devise guidelines to design effective and motivating exergames. We then design and develop a complete *game engine* that integrates exergames and high-usability interfaces with autonomous supervision enabled by computational intelligence, which includes on-line monitoring, on-line adaptation, clear feedback, and long-term motivational mechanisms, also supporting asynchronous configuration and assessment by a remote therapist. We follow our guidelines to develop a set of nine games for posture and balance rehabilitation of post-stroke elderly patients. We conclude with results from several studies performed using our games, including a three-month pilot test with the complete system, proving the benefits of our solution.

Riassunto

MENTRE nel mondo intero l'incidenza dell'ictus cerebrale cresce, i costi relativi al sempre più pressante bisogno di riabilitazione intensiva aumentano a loro volta, facendo suonare un campanello d'allarme alla ricerca di soluzioni per diminuire i costi mantenendo nel frattempo l'efficacia della terapia. La riabilitazione autonoma a domicilio appare una soluzione promettente per ridurre questi costi. Il fenomeno degli *exergames*, i.e. esercizi attraverso videogiochi, rappresenta possibilmente la chiave per il suo successo. Tuttavia, questa autonomia esige un cauto approccio, in quanto i requisiti per una corretta riabilitazione devono essere soddisfatti anche in assenza del terapista.

Lo scopo di questa ricerca è lo studio della fattibilità della riabilitazione autonoma a domicilio attraverso exergames. Per far ciò, esploriamo lo stato dell'arte riguardante gli exergames e così ideiamo linee guida atte allo sviluppo di exergames efficaci e motivanti. Progettiamo e sviluppiamo un completo *game engine* che integra exergames ed interfacce ad alta usabilità con la supervisione autonoma del paziente, comprendente monitoraggio e adattamento in tempo reale, feedback chiaro ed immediato e tecniche per la motivazione a lungo termine, tutto ciò reso possibile dall'uso di intelligenza artificiale, supportando anche la configurazione e validazione effettuate da un terapista in remoto. Seguendo le nostre linee guida, creiamo nove giochi per la riabilitazione della postura e dell'equilibrio di pazienti anziani post-ictus. Concludiamo con risultati riguardanti diversi studi condotti usando i nostri giochi, tra i quali uno studio pilota di tre mesi, i quali dimostrano i benefici della nostra soluzione.

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CHAPTER 1

Introduction

1.1 Stroke and Rehabilitation

Industrialized countries are currently experiencing a large increase in the number of people aged 65 or older: in Europe, for example, its share in the total population is projected to increase from 17.1% to 30.0% and the total number of elderly people is projected to rise from 84.6 million in 2008 to 151.5 million in 2060. Similarly, the number of people aged 80 years or over is projected to almost triple from 21.8 million in 2008 to 61.4 million in 2060 [65].

With the population getting older, the number of people affected by age-related diseases or disturbances is bound to increase. Among disturbances related to aging, stroke (or cerebrovascular accident, CVA) is perhaps the one that demands most attention, as it is the second single most common cause of death in Europe, accounting for almost 1.1 million (12%) deaths each year. The incidence of stroke increases rapidly with age, and around 75% of strokes occur in people aged over 65 years [150]. The term stroke refers to the loss of brain function due to a disturbance in the blood supply to the brain, either due to ischemia[1] or hemorrhage[2] [184]. About one in five stroke cases are fatal [195].

Stroke is also a leading cause of adult disability [138] and causes a greater range of disabilities than any other condition [3]. In the case of survival, about half of stroke survivors must depend on others to carry out the activities of daily living, and more than one third are depressed [202]. 58% of stroke survivors experience significant motor and cognitive disabilities, which can make living independently and returning to the work force difficult and in many cases impossible [151]. Cognitively, stroke survivors lose both memory and speech, losses that can substantially affect a stroke survivor's interaction with the world. They can also experience concentration deficiency and anxiety disorders. Some stroke patients experience hemispatial neglect, a neuropsychological condition in which a deficit in awareness of one side of space is observed. Motor problems, such as balance loss and paralysis or weakness of one side of the body, are also common. The loss of control over one leg can make walking difficult or impossible. The inability to use one arm can limit stroke patients' ability to perform activities of daily living such as bathing, dressing, and feeding themselves [202]. The burden of stroke also affects caregivers, who often have to limit their professional and leisure activities.

Stroke survivors can however recover from their impaired condition. Recovery after a stroke relies on neuronal plasticity that allows other areas of the brain to take over functions of the affected area by creating novel connections or using redundant pathways [169]. Stroke rehabilitation represents the mean through which recover is possible. Patients undergo treatment to help them return to a normal life by regaining and relearning skills of everyday living. If a complete recovery is not possible, stroke rehabilitation can help the survivor in understanding and adapting to difficulties, preventing secondary complications and educating family members to play a supporting role. To facilitate recovery, rehabilitation programs need to be started inside a hospital in the first few days after the stroke event; this is referred to as *inpatient therapy*.

Successful neurorehabilitation relies on intensive training and exercising, and repetitive practice of functional movement helps people to recover [50]. Improvement is proportional to the effort put by the patient into the training, and this effort is best evoked in traditional rehabilitation by the therapist [206].

[1] Ischemia is caused by a lack of blood flow, usually related to the blockage of a blood vessel.

[2] Brain hemorrhage is the bleeding of blood vessels inside or surrounding the brain.

1.1.1 Posture & Balance Rehabilitation

General agreement exists regarding an association between the ability for independent mobility and experiencing a high quality of life. Hence, one of the major goals of post-stroke rehabilitation is to improve patients' gait characteristics and to train the person to the highest possible level of walking ability [14]. However, even though there is a consensus among caregivers that post-stroke therapy should help paralyzed individuals to relearn walking, many different rehabilitation strategies have been used in practice. The most promising approach to improve gait ability during the rehabilitation process is still a substantial uncertainty and, therefore, a relevant research question. Since recently acquired knowledge indicates that muscle strength, balance, and walking endurance play a key role in terms of walking performance, treatment programs should aim to improve these aspects. Thus, through the application of a gait training program that incorporates lower extremity strength, balance, and endurance exercises, optimal walking recovery may be realized. Moreover, in recent years, another factor emerged as important regarding effective gait training methods: several authors state that task-related activities lead to greater improvements in post-stroke walking competency compared to nonspecific practices. In particular, growing evidence suggests that intervention protocols including walking tasks optimize the recovery of walking skills to a greater extent than training programs based on non-walking oriented activities [145].

1.1.2 The Costs of Stroke

Successful rehabilitation requires trained professionals, adequate equipment, and dozens of training sessions. Given the increasing figures of stroke, a large burden is posed on the national health service providers, that are becoming overly saturated. According to recent statistics, stroke costs the European Union over 38 billion euros a year [138]. In an effort to reduce costs, health service providers are forced to shorten the duration of in-hospital rehabilitation services. Since patients require intensive daily rehabilitation sessions, they must thus turn to specialized private centers, an option that cannot be sustained by many patients. In addition, patients that live in remote areas cannot afford the daily commute to the rehabilitation centers. Another solution lies in at-home private visits by rehabilitation specialists. However, due to the intensive nature of rehabilitation, the costs of private visits are still unsustainable by most patients. This situation has an enormous socioeconomic impact also on the patient's families that often feel left alone by the health service providers [113]. Due to these problems, patients that should continue the therapy outside the hospital actually drop out of rehabilitation altogether.

A follow-up rehabilitation period is usually prescribed when the patient is discharged after the initial intensive in-hospital period. After discharge, stroke patients need to perform physical and cognitive exercises regularly to further improve function, reduce dependence on nursing services, and stabilize their psycho-physical condition. Due to lack of motivation to train, usually related to pain and to limited hope for recovery, many patients stop exercising, sometimes even losing the benefits of previous rehabilitation.

The current situation calls for novel solutions to post-stroke rehabilitation involving a reduction of costs for health service providers and for patients alike. Autonomous rehabilitation at-home seems a promising solution, but, to enable personal rehabilitation, the problem of lowering costs for the patients while maintaining high motivation as well as the efficacy of the therapy should be addressed. In this context, the trend of serious games can be of great help.

1.2 From Video Games to Rehabilitation

The last decade witnessed the rise of video games as an important cultural phenomenon, paired with an explosive expansion of the video gaming market. With the advent of the Nintendo Wii[3] console in 2006, a so-called *gaming revolution* took place [54]. Before the Wii, video games were mostly seen as a pastime for teenagers due to their complex gameplay mechanics paired with hard-to-master controllers. Not able to fight against the huge market power of its competitors, i.e. Sony and Microsoft, in the first years of the millennium Nintendo took a risky move: instead of struggling to keep up with the two colossuses' performance and graphics arms race, it created a new console (appropriately codenamed *Revolution*) that tried a different path: the console and its games were designed to be highly accessible by all members of the family, easy to play, and sporting controllers that leveraged active and natural motion [33]. Perhaps the most revolutionary aspect of the new console was its focus on active movements, tracking the player's body movements through its gaming controller: people could use their whole body to play, and not just sit and press buttons. The risk paid off, and the Wii opened to a large, yet untapped, market: families bought the console and played its games, finally legitimizing video games as a social activity. Since then, the video game market has kept increasing beyond expectations. The proliferation of mobile devices, powerful enough

[3] http://wii.com/

to rival modern handheld game consoles, has contributed to this surge, and nowadays gaming represent a consistent part of the lifestyle of many people, to the point that 59% of Americans today play video games [6]. It is interesting to note that older people have begun to approach video games as well [86].

Due to the widened cultural acceptance of video games, the latest years also saw a large increase in research concerning games. This pushed researchers from very diverse fields towards video games, and a question, lingering until then, arose before the spotlight: can we use games for something more than entertainment? As an answer, the concept of *serious games* was born. According to a common definition, serious games can be defined as

> *"A mental contest, played with a computer in accordance with specific rules that uses entertainment to further government or corporate training, education, health, public policy, and strategic communication objectives."* [215]

Games, as a medium, were proven to have great educational power [199]. This is due to the intrinsic interactive nature of play, which lets the player navigate through trial and error in a *pretend* reality, without fear of consequences, thus learning through their actions and the feedback they receive. Children develop social and cognitive skills through play, proving the benefits of games as an educational tool, and video games also stimulate learning due to their motivational nature. The persuasive power of games is not a new discovery, and games have been used for the *edutainment*[4] of children for years. The higher cultural acceptance that video games went through in the second half of the decade helped in making the educational games field, struggling to make itself get taken seriously, grow and expand. In fact, we can nowadays find many commercial games that have other educational purposes, such as games for training military personnel [44], or workers [163]. Serious games however did not limit themselves to edutainment, and expanded to other areas such as marketing with *advergames*, data collection with *games with a purpose* (*GWAP*) [201], and health games.

1.2.1 From Games for Health to Rehabilitation Exergames

A taxonomy of serious games was proposed by Sawyer and Smith in [175], where *games for health* represent one of the most prolific areas, and a quick literature search reveals that they are second only to edutainment.[5] Among

[4]Edutainment describes a form of entertainment that also educates.

[5]While performing our review, we found more than 2,000 papers related to games for health [157].

the applications of games for health we note: games that promote healthy behavior, such as games that educate to fight obesity [176], promote healthy eating habits [159], or promote exercising [18]; games for medical training, such as games designed for training surgery skills in a simulated environment or that teach medical protocols with interactive simulations [45, 72]; games for assessment of health conditions [21]; and last, but not least, the very games for rehabilitation that this thesis addresses. The different games for health are also classified into Sawyer and Smith's taxonomy. The trend of games for health has been growing dramatically in the last decade: they were shown to improve cognitive and perceptual capacities [74] as well as spatial skills and reaction times [73] and to provide a great motivational push.

As highlighted by Gekker [62], therapeutic and personal serious games represent the most popular category in the field of games for health. Games to improve fitness and games for rehabilitation represent common examples of this category, which is created around the concept of *active gaming*: video games can be played while performing full-body movements and thus promote physical exercise. The gaming revolution gave a strong push to fitness and rehabilitation games through the rise of active gaming. In addition to making games more accessible to non-gaming audiences, the Wii also gave birth to the active gaming concept[6]. With the advent of the Microsoft Kinect[7] in 2010, a gaming device capable of tracking the player's full body movements and translate them into game actions through natural full-body interaction, active gaming was further reinforced.

Games that promote physical exercising through the use of active gaming, including fitness games, games for sports training, and games for rehabilitation, require movements that are very similar, if not exact, to traditional exercises. These applications can thus be considered both games and exercises and it is hard to make a clear distinction between these two aspects: the term *exergame* was coined to encompass their dual nature and to better pinpoint their role. An exergame is thus usually defined as a game that promotes physical exercising, be it for healthy living, for training or rehabilitation [18].

It is not surprising that active games have been taken into consideration for serious exergaming, and especially for physical rehabilitation in hospitals. In fact, video games may represent a way to reduce the costs of rehabilitation and a possible way to enable autonomous rehabilitation.

[6] Although a few previous attempts were made, though successful only in the arcade market [18].
[7] http://www.microsoft.com/en-us/kinectforwindows/

1.3 Commercial Entertainment Games used for Rehabilitation

The effectiveness of using games for rehabilitation was recently validated as an actual therapy, especially due to the phenomenon of *Wii-habilitation*, i.e. the use of off-the-shelf games for the Wii to promote active rehabilitation in therapy centers [174]. To date, games such as Wii Sports (which includes several sports-like mini-games to be played with a Wiimote) and Wii Fit (which includes games for balance and posture exercising using a Wii Balance Board, a pressure board designed for playing these games) were successfully used to rehabilitate patients [48,162]. These good results gave momentum to the use of other exergames for rehabilitation. For example, Kloos et al. [106] used *Dance Dance Revolution*[8] and its dancing pad to treat patients with Huntington's disease, and Sandlund et al. [173] used the Sony EyeToy[9] for PlayStation 2 to rehabilitate children with cerebral palsy.

However, video games explicitly designed for entertainment introduce some problems when used for rehabilitation. The goal of physical rehabilitation is to regain lost functions through the repetitive execution of correct movements, while the goal of commercial games is entertainment. This was also pointed out in the recent review of exergames for the rehabilitation of Parkinson's disease by Barry et al. [10]. Games are meant to be fun, intuitive, somewhat challenging, and thus do not concern themselves with how the patients play, as long as they play. This can be detrimental to rehabilitation, as the very thing that makes games so appealing for rehabilitation (the increased motivation) can also function as a distraction for patients, compelling them into performing uncontrolled motion. In fact, Prosperini et al. [162] reported the occurrence of knee or back pain in patients treated with Wii Sports games played autonomously with a balance board, and there is a known problem with injuries caused by Wii use [188]. In addition, entertainment games are designed with a clear target population in mind, which does not include players with large motion or cognitive impairments such as the very people that are in need of rehabilitation. Most commercial games are designed to be engaging for non-impaired people and prove to be too hard to use for patients, possibly undermining the motivational benefits. Commercial entertainment games also pose the problem of configuration and personalization. Especially in post-stroke rehabilitation, where the condition of patients can vary greatly from case to case, a fixed challenge level is bound to be ineffective for most. Most games do

[8] http://www.ddrgame.com/

[9] http://us.playstation.com/ps2/accessories/eyetoy-usb-camera-ps2.html

not actually go farther than allowing a simple difficulty selection between a few fixed choices, while rehabilitation requires a more precise control on both range of motions and frequency of movements. In addition to the aforementioned issues, commercial games have no capability for motion recording and thus cannot provide motion data for reviewing and assessment, although the technology to do so is present. At last, commercial entertainment games are closed-source products that cannot be configured or modified; integrating additional software to solve the issues we mentioned becomes thus practically impossible.

When using commercial games, the aforementioned issues can be mitigated by the presence of a therapist, who can make sure that the movements of the patient are correct at all times, thus maximizing the benefits of entertainment games used for rehabilitation. However, the rising costs of rehabilitation therapies call for autonomous systems, and the use of commercial games without any therapist supervision is problematic [162]. For these reasons, there is a need for ad hoc exergames for rehabilitation to be developed. While we lose the convenience of buying a gaming console at the closest store to rehabilitate, this opens the doors to a large opportunity for fixing the issues we mentioned, and represents indeed an interesting research topic.

1.4 From Virtual Rehabilitation to Rehabilitation Games

Exergames for rehabilitation are the foster children of two separate trends that have known great success in the last decades: one is the serious games trend (of which we have discussed previously), the other is the Virtual Reality Rehabilitation (VRR) movement which involves the use of virtual reality environments as opposed to real environments for rehabilitation. Traditional therapeutic exercises are reproduced through the virtual environment using specialized input devices, enabling the use of technological solutions that can help in making the therapy more effective: tracking of motion data, automatic feedback, and movement constraints through robotic devices.

VRR dates back to the end of the 20th century with psychotherapy applications [68], and it expanded from there to other rehabilitation fields, including physical and cognitive rehabilitation. It is nowadays regarded as a valid alternative to typical rehabilitation: there are plenty of research projects pairing VR with robotic rehabilitation [1,121,160,167], and it also saw commercial success with applications such as the Hocoma Armeo and Lokomat [213] being employed in several advanced medical centers. Recent studies even demonstrated the higher effectiveness of VRR compared to traditional training for motor task learning and execution due to its systematic nature [72].

While initial VRR systems just replaced traditional exercising with virtual exercising, basically representing the same exact exercise in a virtual form, recent systems employ simple games to accompany the exercises, having recognized the motivational benefits of play. However, such games are little more than virtual exercises and do not follow good game design rules; their motivational effect is thus limited. In this context, rehabilitation exergaming appears as an evolution of VRR, pairing all its benefits with the higher motivational content of well-designed video games.

1.5 Bringing Rehabilitation Home

Exergaming seems to be a promising solution to lower rehabilitation costs, but patient autonomy needs to be addressed. The research question that we address in this work is thus *how can we bring effective and autonomous rehabilitation to the patient's home*. In particular, our main research question can be separated into several smaller ones for ease of discussion: (i) what is required to perform rehabilitation in an autonomous and safe setting, and (ii) how can technology help in making rehabilitation autonomous? In addition, we choose to focus on exergaming, and we thus add to our questions: (iii) how can exergames be useful for autonomous rehabilitation, (iv) how can we design such exergames, and (v) how can we efficiently develop them?

We believe that to bring effective rehabilitation at home we need to equip patient homes with an ad hoc exergaming station for rehabilitation, alternating asynchronous therapist supervision with automated supervision by the station itself. We thus present here our work, performed under the REWIRE project[10], that aims to bring rehabilitation home for post-stroke elderly patients (65 to 75 years), providing posture and balance rehabilitation as well as cognitive rehabilitation.

Our work regards the design and development of a Patient Station (PS): a station housed in the patient's home. The patient interacts with the PS to perform daily rehabilitation sessions through exergames and is supervised while doing so. The PS supervises the therapy in absence of the therapist, and is thus equipped with on-line monitoring and adaptation functions. The therapist can interact asynchronously with the PS through a remote station, called Hospital Station (HS); as such, the PS also supports configuration and recording functions. The results we obtained were possible also thanks

[10] http://www.rewire-project.eu/

to the joint effort of the multiple partners of the project. We worked in tight collaboration with therapists and clinical partners to produce effective rehabilitation exergames and validate our results, and we worked tightly with the developers of the HS to design robust interfaces. We direct the reader to [22] for additional information on the project.

1.6 Thesis Contributions

Addressing our research questions, this thesis adds the following contributions to the current state-of-the-art:

1. We conduct a systematic review of the literature concerning exergames for rehabilitation and identify current trends.

2. We propose a new definition of *exergame*, based on the separation of its *game* and *exercise* aspects.

3. Starting from the new definition, we propose a set of guidelines for designing effective and compelling exergames for autonomous rehabilitation.

4. Following our guidelines, we propose a pipeline for the conception, design, and development of exergames for rehabilitation starting from a given exercise.

5. We detail the design and development of a complete game engine for rehabilitation, based on an existing game engine, following the requirements of autonomous at-home rehabilitation and supporting asynchronous configuration and assessment. The engine includes multiple abstractions to increase usability, accessibility, and development efficiency.

6. We design and develop specific solutions based on computational intelligence to address on-line monitoring, on-line adaptation, and scenery randomization.

7. We propose a set of techniques to address long-term motivation in rehabilitation exergames, designing an exergame-specific scoring system and providing directions for reward systems.

8. We design and develop nine exergames for posture and balance rehabilitation using our framework, and we show the results of their clinical and usability validation.

1.7 Thesis Organization

This thesis is organized as follows.

In chapter 2, we review the existing background regarding serious games for rehabilitation, analyzing the state-of-the-art and focusing on post-stroke physical rehabilitation exergames. We identify current trends and research directions.

In chapter 3, we discuss the nature of exergames and present our own definitions. We then identify a set of design guidelines that spur from our experience in developing exergames for physical rehabilitation.

In chapter 4, we provide a pipeline for the design and development of exergames, and present the exercises and the games we created to achieve a complete exergaming therapy for posture and balance rehabilitation.

In chapter 5, we introduce the benefits of game engines for rehabilitation and detail our software architecture for a game engine based on our guidelines. We detail the solutions we took to support accessible and effective exergames.

In chapter 6, we focus on the features of our system that make it able to support autonomous rehabilitation through computational intelligence techniques. We thus address on-line monitoring, on-line adaptation, and feedback capabilities.

In chapter 7, we focus on the issue of patient motivation and provide solutions to improve the motivational effects of our exergames and our system.

In chapter 8, we discuss the results of our work, detailing the usability, acceptance, adherence, and clinical validation tests performed on our system.

In chapter 9, we conclude with a discussion on our results and we present both ongoing and future work regarding rehabilitation exergames.

CHAPTER 2

Serious Games for Rehabilitation

In the previous chapter, we explained why we consider commercial entertainment games unsuitable for autonomous rehabilitation. In this chapter, we analyze instead the state-of-the-art of exergames specifically designed for rehabilitation, focusing on the technological advances and the issues researchers spend their efforts on. We aim to better understand what the current open research questions are, as well as the adopted solutions, in order to grasp the breadth of exploration in the field and therefore orient our approach. Due to the diversity found in the literature and to the lack of common classifiers, we perform our survey from a bird's eye view: we classify the many solutions in the field according to several trends we identified. These trends come from a throughout review of the literature concerning rehabilitation exergames, in which we analyzed over 170 exergames. The complete results of the review can be found in [157]. We also define these trends in light of past surveys on the *games for health* field [62, 164, 204]. We thus analyze the current state-of-the-art from the point of view of application area, technology support, interaction devices, and game design.

2.1 Application Area

As a first classification, we are interested in the reason for the development of a rehabilitation exergame. We find examples of exergames for the rehabilitation of many different impairments, which we can subdivide according to three major areas: behavioral rehabilitation, cognitive rehabilitation, and physical rehabilitation.

Behavioral rehabilitation exergames represent a mix between health and edutainment games; we find, as examples, games created to fight eating disorders [120] or to overcome phobias [192].

Cognitive and physical-related exergames are more common, and sometimes overlap, depending on the actual pathology. Exergames addressing cognitive impairments are especially becoming more common in the latest years. We report exergames for the rehabilitation of post-stroke neglect patients [125], Parkinson's disease patients [149], and to train people with intellectual disabilities [128]. Some exergames are specifically targeted to elders, created to delay the effects dementia [37] or, more specifically, the effects of Alzheimer's disease [15].

Physical rehabilitation exergames represent the largest category. Many are created without a specific pathological condition in mind, but focus instead on a physical impairment regardless of the causes. This is the case of falls rehabilitation, usually related to brain injuries or to old age [99, 198], and of exergames related to specific body injuries. Among physical rehabilitation exergames, games for post-stroke or traumatic brain injuries rehabilitation make up for the majority, with [26, 30, 133] being common examples. We also find several exergames for cerebral palsy rehabilitation of children and adolescents [83, 207]. A few exergames instead directly address multiple sclerosis [141] or the development coordination disorder [32]. We also find instances of pain rehabilitation [200] or rehabilitation after fractures or traumatic body injuries [148, 196]. At last, we report examples of exergames developed for the rehabilitation of speech disorders [27] and of vision disorders [193].

Since our focus is on post-stroke physical rehabilitation, and in particular on balance and posture rehabilitation, the next sections of this state-of-the-art survey will focus on physical rehabilitation exergames.

We separate exergames for physical rehabilitation into *wide-focused* and *tight-focused* exergames. Wide-focused exergames regard whole-body motion, while tight-focused exergames focus on one specific body part or even a single specific movement. Among full-body rehabilitation exergames, we find exergames focusing on posture [186] and on balance [36, 90]. Tight-focused exergames can be further differentiated into exergames for the rehabilitation of the upper limbs and of the lower limbs. Among upper limb rehabilitation, we note exergames targeted to shoulder rehabilitation [35], arm rehabilitation [171], wrist rehabilitation [97], and hand/fingers rehabilitation [209]. For lower limb rehabilitation, we report exergames for rehabilitation of the ankle [207], of the knee [56], and of both legs [80]. In addition, a few exergames focus instead on rehabilitation of the neck [179] or the trunk [12].

We find a large diversity in how exergames are employed in the rehabilitation domain. This reinforces the flexibility of exergaming for very different pathologies and reveals an interest in the research field around exploring its beneficial properties.

2.2 Technology Support

Much like virtual reality rehabilitation, rehabilitation through exergames enables access to technological solutions that support the therapist. In traditional therapy, the therapist performs several tasks, such as configuration, personalization, assessment, motivation, and, perhaps most importantly, constant supervision. Such tasks are tackled by exergaming systems from different angles, and it is even hard to find a consensus on what the required tasks are, with systems often exclusively focusing on single tasks and none discussing the need for an integration of all the features required to make autonomous exergaming possible. Due to the lack of this consensus, and since our goal is autonomous rehabilitation, we analyze the literature in light of how some of the rehabilitation burden is lifted from the therapist through technology, effectively *automating* some of the tasks.

A first category of exergames is played always in the presence of a therapist, usually in-hospital. The supervision role is held by the therapist, and the exergames only possess the role of increasing motivation, although they already provide an useful feature under the form of immediate feedback. We may also place in this category all instances of reusing entertainment games for rehabilitation.

A first step forward comes from exergames that help the therapist during her supervision, usually by providing adaptation features or by constraining movement through robotic devices; the therapist however still makes sure that the therapy is correctly followed. Most of these exergames provide additional help to the therapist through configuration or assessment tools. We report several examples, such as [49], [152], and [57]. Tele-rehabilitation exergames represent an additional improvement: the therapist is, in this case, not required to stand beside the patient, although a constant real-time supervision is still required. Examples are the RehabMaster system [180], Hocoma's Lokomat with the Gabarello exergame [71], and the Home Care system [80].

A large step forward is made by exergames that require only *asynchronous* supervision by the therapist. This is a mixed approach, with standalone and partly autonomous exergames being supervised by a therapist either through a remote tool (as in tele-rehabilitation), by periodic meetings with the patients, or, if in-hospital, by supervising the patient only from time to time. This effectively enables some degree of autonomous rehabilitation. We further classify these exergames into open-loop and closed-loop systems: open-loop systems provide configuration capabilities, but no assessment or review capabilities [139]; closed-loop systems provide both configuration and assessment capabilities, and thus provide better support for a complete therapy, so that assessment results can be used to guide further configuration ([95], also our approach).

At last, we find exergames that do not require any active supervision from a therapist, but function instead as standalone applications [8,94,186]. These exergames can be used by the patient autonomously at home. However, albeit representing an interesting first approach to autonomous rehabilitation, in the current literature no standalone exergame addresses the full range of therapist tasks and cannot thus fulfill the requirements of a complete therapy.

From this review, we extrapolate a novel solution: standalone applications, supervised by artificial intelligence, that need no input by therapists to provide a complete therapy. This is currently an utopian view, as it is hard to imagine how a machine could take over the complete role of the therapist, especially considering the missing social link.

In the current state of the art, we note many approaches that place themselves at different degrees on the *supervised-to-autonomous* spectrum. Most approaches fall however on the *supervised* end, either explicitly requiring a therapist or not mentioning any approach to automated or asynchronous supervision. In the context of at-home autonomous rehabilitation, we cannot possibly ask for a therapist to perform constant real-time supervision, even remotely, if we actively aim to reduce costs. Asynchronous supervision supported by automated tools thus seems to be the best course of action and represents the key to future developments.

2.3 Interaction Devices

The range of possible impairments and conditions for which exergames are created implies that the tracking requirements are very diverse as well. As such, the interaction devices employed in exergame design vary greatly. Reviewing the literature, we note many different configurations: from simple mouse and keyboard configurations, to complex full-body robotic systems. Broadly speaking, we can separate interaction devices into several categories.

Among **standard devices**, we list mouse, keyboard, and joypad/joystick configurations, which are common in serious games due to their seamless integration with software and are used especially for educational or skill training games [204]. Physical rehabilitation exergames do not use these configurations as almost no exercise can be performed using such devices, while cognitive rehabilitation exergames can instead be played using them (for instance, [132]). However, due to the low accessibility of these devices compared to more natural interfaces, especially for elder users, a trend can be seen towards using other devices [165].

Robotic devices are largely used in virtual rehabilitation applications, and this trend leaked into rehabilitation exergames as well. The main benefit of robotic devices lies in the fact that the active components help the patient in performing correct movements while avoiding movements that are detrimental to the therapy, allowing for more accurate exercises. However, this benefit is counterbalanced by the heavy costs of such devices, the need for maintenance, the weight and bulk of the devices that make them less prone to be used outside an hospital, and the possible safety issues tied to their active components. A literature analysis reveals the use of exergames alongside robotic devices for rehabilitation of the lower limbs, such as Hocoma's Lokomat with the Gaberello project [71], and for the upper limbs, such as the ARMin robotic arm [142], the Rutgers Arm II [23], or specific devices for wrist rehabilitation [5]. We also find specific devices for the rehabilitation of single, one degree-of-freedom (1-DOF) movements, such as the AnkleBot [134] for the rehabilitation of ankle injuries or the CR2 robot [38] for arm and leg rehabilitation. The single degree of freedom allows the devices to be less expansive and more portable, effectively moving towards at-home use.

As little brothers to robotic devices, **haptic devices** are used to provide some of the benefits of robots while addressing their drawbacks. Among these devices, we list haptic-enabled joysticks [166], 3-DOF haptic cursors [82, 209], steering wheels [91], and haptic gloves such as the RM-II glove [160] or the 5DT glove [83] that allow rehabilitation of wrist and fingers. The main benefit of haptic devices resides in their active nature which allows the game to give force feedback to the player. Having an additional source of feedback, alongside visual and audial feedback, can be very useful for certain applications to better guide the patient. This makes haptic devices also useful for cognitive rehabilitation, as the force feedback can be readily interpreted by the patient [190].

Switching to passive devices, we find that there is a large bulk of work regarding the use of **motion-enabled devices**, i.e. devices that track user motion either through embedded accelerometers and gyroscopes or through pressure sensors. We place off-the-shelf motion controllers in this category, of which the Nintendo Wiimote is the prime example, with many exergames being developed with it as the main device [77, 149, 197], although a shy move towards more powerful devices such as the Razor Hydra controller can be noted [24]; pressure boards, among which the Nintendo Wii Fit Balance Board is the top choice [9, 81]; dance mats, such as the *Dance Dance Revolution* controller [108]; and custom-developed devices, explicitly created to perform one set of exercises, such as the instrumented wobble board of [95], the shoulder wheel of [35], or the stick-and-ball of [102].

A few attempts use the motion-tracking capabilities of the current generation of mobile phones for the purpose of motion rehabilitation, such as DroidGlove, which uses the accelerometer of an Android phone to track simple wrist exercises and give feedback to the patient [46]. The use of mobile devices with embedded sensors can be beneficial, as the phone itself can be used to give the needed feedback, thus canceling the need for an external computer and video output, making the exergames more portable.

A new trend concerning motion-enabled devices can also be extracted from the literature: the use of instrumented everyday objects. Following this trend, researchers are inserting sensors into objects such as stress balls [98], walking canes [53], cups [88], and so on. This enables the patient to perform natural exergaming activities with known objects, benefiting from their tangible nature.

A drawback of all motion-enabled devices lies in their physical nature, which means that (apart from pressure boards) they can be used only for upper-limb rehabilitation as the patient needs to hold them unless they are made into wearable devices. Wearable devices consist of instrumented objects that are tied or strapped to the patient's body, allowing the device to track the motion of different body parts. For example, Alankus et al. [4] strap Wiimotes to the patient's arm and forearm, and several system employ wearable accelerometers [41, 137].

An interaction technology that has been steadily gaining more interest in the latest years is **camera tracking**, i.e. the use of cameras to track the motion of the patient. Inside this category, we place examples of full-body and high-accuracy motion capture technologies [179], as well as low-cost and single-focus webcam motion tracking [187]. Alongside the advancement of the computer vision field that now allows effective real-time color tracking by using a cheap integrated webcam, the commercialization of the Microsoft Kinect, which functions as a low-cost color-tracking as well as depth-tracking camera, has given a great push to this phenomenon. The literature presents a large number of projects that leverage the Kinect for rehabilitation: it is currently being investigated to rehabilitate posture [183,186] and the upper arms [152, 171, 194]. The main benefit of camera tracking lies in the possibility for body-free interaction, effectively making the interface completely transparent: a webcam can track the motion of the patient's hand or finger without the patient having to wear anything. However, there are some issues: camera tracking, especially color tracking, suffers from the light conditions of the training area as well as from occlusions, effectively reducing the robustness of the approach [205]. In practice, many applications use wearable objects (such as color-coded gloves) or small lightweight objects (such as colored balls) to aid the computer vision algorithms in performing robust tracking.

A last category of interaction devices includes Brain Computer Interfaces (BCI), electroencephalography-enabled devices (EEG), and electromyography-enabled devices (EMG). These devices are useful for acute stroke patients, although their integration with actual exergames is rare [7, 182].

A special mention should be made for output devices as, once again, the literature reveals many different approaches to the matter. Although most exergames are developed with standard visual output through a monitor and standard audial feedback through speakers in mind, several alternative approaches are being explored. We thus note a trend towards the use of highly immersive virtual reality applications due to the enhanced presence effect they can provide [100]. Another trend regards the use of augmented reality techniques, for example by providing augmented mirror modalities using camera tracking devices, thus allowing the patient to see herself inside the game screen [90, 125]. Other authors focus instead on a mixed reality approach, placing virtual objects in a representation of the real world with which the patients can interact, adding tangible objects to the mix [161]. An interesting trend in post-stroke rehabilitation related to visual feedback regards *mirror therapy*, according to which rehabilitation of the impaired limb can be aided by visualizing a movement through the non-impaired limb, triggering the so-called *mirror neurons* that help in cortical reorganization and, ultimately, in regaining the function of the lost limb. In immersive virtual reality applications, the patient can be shown a mirrored version of the impaired limb, thus triggering said mirror neurons [52, 168].

To conclude, just as the range of clinical conditions addressed is large, the range of interaction devices is not less so, once again highlighting both the flexibility of exergames and the breath of the research field.

2.4 Game Design

At last, we survey the current state-of-the-art for what concerns game design aspects, independently of the underlying therapy. This is important as the point of using exergames instead of virtual reality rehabilitation in the first place is to provide a motivational push.

We point out a worrying trend: most reported exergaming applications do not specifically address game design, and often relegate it to simple scoring mechanisms. This is also reflected in the poor aesthetic quality of most proposed research exergames, a symptom of little cooperation with actual game developers.

Nonetheless, we survey the current approaches to exergame design in rehabilitation regarding fantasy, game genre, and multiplayer exergaming.

2.4.1 Fantasy

An interesting differentiation of current exergames can be made regarding their thematic content, i.e. their *fantasy* [126]. Our intent here is to answer the following question: should a rehabilitation exergame focus on depicting *activities of daily living* (ADL), or can it propose an imaginary or abstract task and still be useful for rehabilitation? We base our question on the fact that functional rehabilitation is usually associated with ADL training, and indeed many virtual rehabilitation systems support virtual ADL exercises, such as preparing coffee, walking around, or cooking a meal [111]. This is related to the cortical reorganization that can be triggered in the brain and is most relevant to regain the lost functions in treatment of post-stroke patients. We subdivide exergames into four categories, from more to less realistic: ADL exergames, which represent activities such as cooking, walking, bicycling, or playing sports [37, 166]; realistic exergames, which represent a non-ordinary activity of real life such as driving a plane [79]; imaginary exergames, which represent an activity not feasible in real life, such as flying a spaceship [103] or riding a dragon [12]. We treat separately abstract exergames such as tic-tac-toe [16] or memory [165]. Since these games are abstract, they cannot be considered to depict neither a fantasy nor realistic environment and are thus excluded from this comparison. From our survey, we note that the shares of different fantasies are somewhat equal, again highlighting the diversity of approaches to exergame research.

2.4.2 Game Genre

To match previous reviews, we categorize all exergames based on their *game genre*. However, this categorization can be quite arbitrary, as game genres, evolved from the entertainment industry's press reviews, represent a loose and fuzzy categorization concept. For instance, a shooting game can be considered an action game, but a racing or sports game can be considered action as well, while adventure games can be filled with puzzle-like elements or role-playing elements. Especially nowadays, where genre blending can be found in virtually all games, this categorization loses its significance. Nonetheless, a definite trend can be acknowledged: more active genres (action/sports/racing) represent the vast majority of exergames, followed by coordination games (a genre close to pure exercising) and puzzle games. Note that action and puzzle genres are common in the casual entertainment market, representing a good first approach for people not used to video games, such as elders [92]. Rehabilitation exergames tend to favor simple genres, which is a consequence of the requirement of clear and immediate feedback, often listed as a necessity for making games accessible for impaired people [58].

2.4.3 Multiplayer Exergaming

A timid trend can be extracted from the literature concerning multiplayer exergaming. In his survey, Gekker comments on the lack of a multiplayer focus in serious games for health and on how its presence would benefit them [62]. Although the development of multiplayer games poses some important design and technical challenges, it also brings many benefits for motivation, as demonstrated by the millions of people playing online either through real-time multiplayer games or through asynchronous social games. Confirming Gekker's findings, we report a few first attempts at multiplayer exergaming in the works of [142], [34], and [69], and we thus note that multiplayer games are still under-explored in the rehabilitation domain.

2.5 Conclusion

Our analysis of the literature highlights two important, yet contrasting, facets. On the one hand, we find exergames for very disparate conditions, and subsequently a wide range of interaction devices, technological solutions, and game styles, a diversity that makes it hard to compare the different solutions but shows that exergaming can be a flexible solution. On the other hand, many similar concepts such as configuration, assessment, motivation, or on-line adaptation, are shared and repeated by several different works, although using many different approaches, pointing to the need for a better clarification of the requirements for the design of effective and compelling exergames for rehabilitation.

CHAPTER 3

Developing Guidelines for the Design of Autonomous Exergames for Rehabilitation

In this chapter, we present our guidelines for the design of autonomous exergames for rehabilitation. Our desire to provide such guidelines comes from the analysis of the current literature, where there is a confusion on what constitutes a good exergame for rehabilitation. Due to the short age of the field, the literature is full of exergames developed in very disparate ways, with researchers exploring very different solutions. It is thus very difficult to compare different exergames, as there is no standard nomenclature, nor common methods for the design and development of exergames. This calls for a better understanding of what an exergame actually is.

Previous authors attempted to define guidelines for the design of rehabilitation exergames: Flores et al. [58] define several criteria for elderly exergaming design, while Golomb et al. [70] identify the issues they encountered in an attempt to identify potential pitfalls. Other authors focus on specific guidelines, such as Rego et al. with natural user interfaces [165]. No author, to our knowledge, provides a comprehensive analysis of the requirements for autonomous exergames to be effective, and no general game design guidelines have been defined yet. In this work, we improve on the current state-of-the-art by starting with an analysis of the definition of what an exergame actually is, which will give us the basis for a set of design guidelines. We then present our pipeline for the design and development of rehabilitation exergames.

The guidelines we present here spur from the experience accumulated while developing our exergames in collaboration with experienced clinical partners, from our observations on the traditional rehabilitation sessions we witnessed, and from the analysis of the many exergames described in the literature.

3.1 The Separation of Game and Exercise

We first address a more complete definition of the term *exergame*, a term that has become widespread in research, although its definition is still unclear. We define exergames by addressing their dual nature, as *games* and as *exercises*. Our aim is for the guidelines we present to be more coherent, splitting them into guidelines for creating effective virtual rehabilitation exercises and guidelines for the design of motivational exergames. Through this, we also define an approach for the design and development of new exergames that enables a clear separation of roles between the therapist (which defines the exercise) and the game developer (in charge of creating the game). In fact, while working on this project, prior to making this separation, we experienced a leak of responsibilities, with therapists addressing pure game design elements and thus generating confusion.

Oh and Yang [146] reviewed the use and definition of *exergame* in research, proposing their own definition and specifying also the characteristics of its exercise and game aspects. However, their definition and the previous definitions they list do not consider the strict interaction between the two aspects, nor do they neatly separate them. In addition, we focus here on *rehabilitation* exergames, which require an even more careful design than non-therapeutic exergames.

We start with the definition of *exercise*. The concept of exercising is well known and leaves little doubt to its interpretation. We borrow its definition from a medical dictionary [147]:

> *"Exercise is physical activity that is planned, structured, and repetitive for the purpose of conditioning any part of the body."*

From this definition, it is clear that exergames can indeed be considered exercises, as they share the same purpose.

Finding a suitable definition of *game* is harder, as even if many authors have endeavored to find an all-encompassing definition of what a game is, a consensus has not been reached yet. Dictionaries tend to define a game as a physical or mental contest, played according to specific rules, with the goal of amusing or rewarding the participants [215]. However, different interpretations of the term exist depending on the author's focus, and the fact that the term *game* has many different uses makes a common definition even harder to achieve. Salen and Zimmermann [172] perform a throughout comparison of the definitions in the literature and provide a definition that includes most of the commonly accepted points:

> *"A game is a system in which players engage in an artificial conflict, defined by rules, that results in a quantifiable outcome."*

The two definitions have a point in common: an exercise is *structured*, while a game is *defined by rules*. The two concepts can be assimilated. Especially while treating rehabilitation exergames, the exercise's structure must clearly have priority over the game, as our main goal is to provide valid exercises, and only then to provide entertaining games. By defining how the exercise and the game are linked through this common point, we will come up with a suitable definition of exergame.

Given a game, the person that interacts with it is said to be *playing*. Much like games, *play* has many meanings. We borrow, again from [172], a quite generic definition of play:

> *"Play is free movement within a more rigid structure."*

This definition can be used to better understand the relationship between a game and an exercise. In fact, since an exercise is defined through its structure, we argue that by introducing play into the exercise we manage to assemble a game inside the exercise itself. This last observation provides a natural definition for the term exergame:

> *"An exergame is an exercise with a game built into its structure."*

Through this definition, we reinforce the importance of the exercise over the game. It follows that the game should not interfere with the correct execution of the exercise: this means that the exergame, when stripped of its gaming parts, should still work as a valid exercise. This goes against the common concept of exergames seen mainly as games, and *then* as exercises, and basically pushes the exergame into the realm of virtual reality rehabilitation with gaming elements placed on top.

From the point of view of the game designer, this is an important consideration, as it means that the game mechanics must be constrained by the exercise limits. The freedom of movement needed for the player to enjoy the game, i.e. its *gameplay*, must be designed such that it is contained inside the structure of the exercise, as visually suggested by figure 3.1.

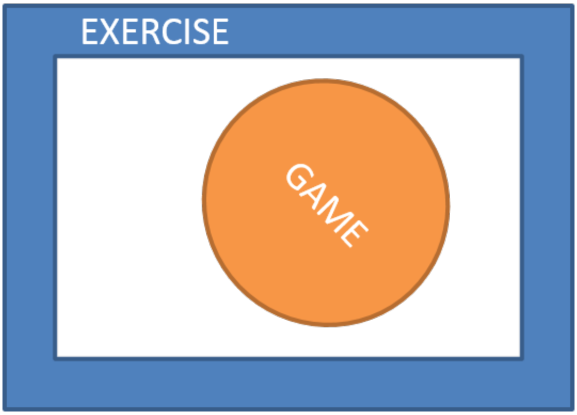

Figure 3.1: *The exercise is here represented by the outer structure, while the game is represented by the inside circle. Intuitively, play can only be performed inside the exercise's structure, functioning as the game's boundaries.*

This constraint is even stricter than may seem at a first glance, because not only does the exercise constitute the structure for play, but it also dictates the allowed physical movements that the patient may perform and their quality and intensity. The game mechanics cannot modify such movements, as they are required by the exercise.

We are then posed with a novel problem: what kind of game can we design to place *inside* the structure of an exercise? We propose here two alternative solutions. As a first solution, the game may be designed as to completely mimic the same movements required by the exercise: the game and the exercise are completely merged, as the actions relevant to the game are represented by the movements required by the exercise. This is the most intuitive and common way to design exergames and typically what is found in the literature. As a second solution, the game can be built upon a different dimension in respect to the exercise. For example, a physical exercise that requires the use of the legs to be performed could allow the player to use her hands to play if the structure of the exercise does not constrain the hands to be still. We are not restricted to the physical domain, however, as a game could be created by asking the patients to observe the scenery while performing a physical exercise in a virtual environment and then asking them to answer questions on the viewed scenery (as done in [64]).

Intuitively, the second approach better maps into our exergame definition and it thus becomes easier to separate the development of game and exercise. However, of the two solutions, we focus on the first one as a direct relationship between the game's goal and the exercise's goal is important to maintain the focus of the patient on the correct movements. This is all the more important since we are treating patients who often possess cognitive impairments or lowered senses and capabilities due to old age. This poses heavy requirements on the game, as the game actions and mechanics are completely subjugated by the mechanics imposed by the exercise, making the game and exercise harder to separate and thus making the job of the therapist and the game developer harder. It is however important to realize that the exercise and the game, even if merged in their mechanics, are still separate entities and should be treated as such. In order to design a compelling game constrained inside an exercise, we can thus work on the gaming elements that are not strictly related to game actions and mechanics. We can also consider introducing some gameplay mechanics that are related to the second solution as an additional layer of orthogonal gameplay, unrelated to the exercises *per se*, that can add a different playful dimension.

Having better defined exergames and the two parts they are composed of, we now detail our guidelines for the design of exergames, focusing on two important questions, respectively pertinent to the exercise and the game aspects: how should the exergame be created to provide effective, autonomous rehabilitation? And how should the exergame be created to maximize motivation?

3.2 Guidelines for Effective Rehabilitation

We present guidelines to create effective exergames, focusing on the requirements of the exercises and completely ignoring the gaming aspects. In fact, we could argue that the guidelines we present here are for the design of autonomous virtual rehabilitation exercises.

These guidelines follow a key concept: we mimic the role of the therapist. When talking about autonomous, at-home personal rehabilitation, we must cope with the fact that the therapist is absent, or present only sporadically or asynchronously. For this reason, for autonomous rehabilitation to be possible and effective, there are some features that all exergames should support that are traditionally provided by the constant supervision of a therapist. As we noted in the previous chapter, automation of rehabilitation tasks can be performed at several degrees, and the features we list here follow this idea so that, while some of them may be completely automated, others may be supported through therapist-controlled tools.

By reviewing the literature, we found some confusion on the usage of terms such as adaptation, personalization, or configuration. We thus also attempt here to better clarify and standardize the nomenclature around these features. Some of the features we list have relationships with dimensions listed in previous works: Rego et al. [164] mention adaptability, performance feedback, and progress monitoring, while Flores et al. [58] refer to adaptability to motor skill level, appropriate feedback, and therapy-appropriate ranges of motion. Since we focus on elderly patients, we also refer to Ijsselsteijn et al. [86] who list possible sources of problems for the elderly when using games: they possess decreased sensory and motion functions, they need adaptable interfaces to their residual functional capabilities, they are unfamiliar with the technology, and they may lack self-confidence.

To better understand what features are needed, we look at how a typical rehabilitation therapy is performed. We begin from the **therapy**, a set of valid exercises that are performed by the patient to rehabilitate. The first role of the therapist is to select the correct exercises and to **schedule** the therapy. This includes **configuring** each exercise to the patient's skills. However, in order to perform configuration, we need some initial data: the patient's **profile**. The therapist also supervises the patient in real-time, **monitoring** the correct execution of the exercises, giving **feedback** to the patient to guide the rehabilitation, **assessing** the results of each exercise session, **adapting** the exercises to the progression of the patient, and **motivating** her to complete the therapy. To perform supervision, new data needs to be collected from the patient by observing her, extracting **physiological** data and **motion** data. When the therapy is finished, the therapist performs a **review** of the progression of the patient. To these, we add requirements posed by the use of technology: high **usability** and **accessibility**.

In the rest of the section we address these features individually. For each feature, we explain why it is important, what examples can be found in the literature, and what can be done to support it.

3.2.1 Therapy Efficacy

For exergames to become a viable therapeutic alternative, therapy efficacy is the most important feature. For this reason, it is of utmost importance that exergames are developed in collaboration with experienced therapists that can contribute with validated exercises to be translated into exergames. In this context, the passage from exercises to exergames is a delicate aspect: a solid collaboration should be created between the clinical staff and game developers, and their roles should be clearly separated.

As mentioned by Flores et al. [58], for an exergaming therapy to be complete, the motions should be appropriate to the therapy, and the exergames should include the whole range of needed movements. We treat this requirement by pointing to the need for multiple exercises to be incorporated into one or more exergames, in order to cover the whole therapy.

In addition, all exergames should also be validated as therapeutic tools. To date, few systematic clinical studies regarding ad hoc rehabilitation exergames were carried out, and even less for autonomous exergames. For example, Cameirão et al. [29] developed the Rehabilitation Gaming System (RGS), a VR-based neurorehabilitation exergaming system for the upper limb and fingers, and validation was carried out with eight patients during a twelve weeks therapy. At the end of the treatment, the RGS group, compared to a control group, displayed significantly improved performance in arm speed and faster improvement over time. Golomb et al. [70] performed a one-year clinical pilot study with three adolescent cerebral palsy patients, using their glove-enabled upper-limb exergame at home. The use of the system at home enabled autonomous use, but the authors found many issues regarding medical, technological (a real risk with prototype systems), safety, personal, and social problems. Although these preliminary studies show that rehabilitation exergames can be beneficial, they also show that for exergames to be taken seriously from a therapeutic perspective a throughout clinical validation is also needed.

3.2.2 Data Tracking

In order to check whether the patients are performing exercises correctly or not, we need to access data relative to their motion. This is done by using special input devices, of which the literature is full of examples. It is important then to choose a suitable input device at design time, which should support all the motion requirements of the exercise.

At minimum, the exergame's software should record the flow of data coming from the input devices. Additional data could be recorded as well to provide a complete snapshot of the patient's state, such as physiological data tracked by specific sensors, event logs to reconstruct a given rehabilitation session, and summary results useful for assessment.

Given the link between technology and exergames, this feature is quite easy to support, as the same input data used to control the exergame can be recorded for other purposes. The availability of this data is a big benefit compared to traditional rehabilitation, where the only data gathered comes from the therapist's observations or from sporadic standardized tests. This feature is also the starting point for the support of assessment, monitoring, and adaptation, and it should thus be given high priority where automation is planned.

3.2.3 Configuration and Scheduling

We use the term *configuration* to refer to all instances of parameter adaptation performed off-line, i.e. prior to the start of a given exergaming session. We thus refer to the possibility for the therapist (and, in some cases, the patient herself) to modify the parameters of the exercise to customize it for the specific condition of the user. This is also referred to, in the literature, as *personalization*, *customization*, or simply *adaptation*.

Due to the many different conditions of impaired patients, a single, fixed configuration cannot possibly work every time: configuration capabilities thus allow the therapist to increase the size of the target population for a single exergame. In addition, configuration capabilities help in the day-to-day rehabilitation, so that the exercise can be configured to follow the daily condition of the patients and their progression. In fact, Burke et al. [25] list an adaptable difficulty level as an essential factor in designing exergames for rehabilitation.

A solution common to many exergames (for example, [108] or [139]) is a difficulty selection mechanism: the exergame presents multiple pre-defined configurations, ranked according to an arbitrary difficulty setting, that can be switched at will. Another approach allows a complete tuning of the exergame parameters, so that a therapist can tailor the exergame to the patient's specific condition (for example, [83]).

In practice, the flexibility offered by a comprehensive tuning system is outweighed by the convenience of a difficulty selection mechanism. This was also confirmed by our results. We thus believe that a mix between the two methods should be performed, allowing the therapist to use a difficulty mechanism for usability concerns and to switch to a complete tuning if needed. Note also that, for configuration to represent an useful tool for the therapist, exergames should be designed with them in mind, exposing as parameters only values that are relevant to them and thus intuitive.

In the case of systems possessing more than one exergame, another desirable configuration feature is represented by *scheduling*. The therapist should be able to create a complete therapy and the system should then provide the correct exergames at the correct time to the patient.

The feature of *patient profiling*, i.e. allowing the exergame to save different configuration values for different patients, is also tied to configuration. The inclusion of this feature can be of great help to therapists when treating multiple patients at once.

Configuration can be automated, given that data on the patient can be accessed prior to the execution of an exergame. In fact, the results of each exergame could be fed back to the configuration module, thus enabling each session to influence the next one. However, manual configuration is the best way to link them enough control over the system while not requiring constant supervision, and automation is best left to other features.

Another automatic mean for configuring exergame parameters lies in *calibration*: their values are assigned during an initial phase, asking the patient to perform movements and tracking data from which the values can be extracted. Calibration can be seen as the middle ground between manual configuration and automatic adaptation, and can thus represent a good way to make exergames more autonomous.

3.2.4 On-line Adaptation

We refer to the dynamic equivalent of configuration as *on-line adaptation*. On-line adaptation allows the exergame to readjust itself to match the patient's condition transparently during its execution. This feature can be seen as a refinement of the initial configuration as more data about an exergaming session is collected in real-time. In fact, in a traditional rehabilitation session, the therapist typically modifies the exercises according to the current condition of the patient, for example by making exercises easier on the go if the patient is tired.

Much like configuration, on-line adaptation solves the problem of customizing the exergame to the patient's condition and thus maximize the efficacy of the therapy for different patients. In addition, successful online adaptation also affects motivation, and in fact finds its parallel in game design studies under the name of Dynamic Difficulty Adaptation, later addressed among motivation guidelines.

Due to the constant supervision required for on-line adaptation, this feature is a good candidate for automation. Automatic on-line adaptation can leverage the data tracked from the patient: it can use the exercise's performance data (i.e. checking whether the patient is performing it correctly or not) or take advantage of tracked motion and physiological data. Full automation is possible, but the therapist can still be inserted into the loop by letting her choose the adaptation's limits, speed, and behavior.

Several criteria have been proposed in the literature to adapt exergames according to the patient's performance automatically. We find the first mention of dynamic adaptation in the work of Jack et al. on virtual reality rehabilitation [87], which aimed at spatially distributing targets at each trial according to the performance of the patient. Different authors proposed their own adaptation heuristics, based on more complex models of the patient's performance [30, 39, 122, 154] or even to her emotional state [40]. A few authors proposed more advanced methods, with systems based on fuzzy logic [96], Bayesian networks [170], Markov decision processes [189], or motivational models [81].

3.2.5 On-Line Monitoring

Supervising the patient's movements in order to guarantee a correct and safe execution of the rehabilitation exercise is one of the most important tasks of the therapist. During typical rehabilitation sessions, the therapist keeps checking that the movements required by the exercises are correct and advises the patient in case they are not. Due to pain in the impaired limbs (and, in post-stroke rehabilitation, due to the unilateral nature of most physical impairments), the patient is tempted to use compensatory motions to achieve exercise goals. For instance, a patient required to move an impaired leg forward to train her balance may unnaturally bend the hips to compensate for the pain, thus possibly triggering detrimental movements. The therapist's monitoring eye has to be guaranteed, at least to a certain degree, by the exergaming system. We refer to this kind of supervision as *on-line monitoring*.

Exergaming introduces an additional variable into the equation: while playing exergames for rehabilitation, the focus of the patient is drawn into the gameplay activity and her attention to the correctness of the exercise can be lowered, possibly resulting in an increased number of erroneous movements or compensatory actions. In particular, compensatory motion, while not an issue with active devices which automatically provide a form of on-line monitoring through haptic feedback and mechanical constraints, can become a problem with body-free rehabilitation exergames such as camera-based exergames.

Due to the requirement of constant supervision, automatic monitoring can be a great addition to any exergame, and the data tracked from the patient's motion can be used for the purpose. Monitoring should also be paired with adequate feedback, so that the patient can correct her actions. This can be performed in different ways, from simple visual cues to actual verbal warnings.

We find the presence of on-line monitoring in several exergames, be it monitoring the exercise's required motion [186,209], compensatory motion [4, 17], the physiological state of patients [38, 80], or even their emotional state [82].

3.2.6 Clear and Immediate Feedback

To guarantee effective rehabilitation, the patient needs to be given clear and immediate feedback on her exercising state, so that she can understand when the exercise is performed correctly and when she is doing something wrong. This is performed in traditional rehabilitation through verbal feedback, although haptic feedback is also often used, so that the therapist directly corrects the movements and posture of the patient. Exergames should provide the same clear feedback to the patient, especially when passive devices are used (and thus no haptic feedback is possible). Exergames also provide visual feedback which can be easily interpreted while being non-intrusive. Human interface design guidelines should be followed to create useful feedback, with an eye on the needs of particular populations of patients which may require special attention, as is the case with elderly patients [86]. Note that all exergames require clear feedback to even function in the first place, and some sort of feedback is thus present in all the exergames we analyzed.

3.2.7 Performance Assessment

In addition to feedback directed to the patient, a desirable feature is the possibility for the therapist to receive data based on the therapy progression, usually in the form of graphs, to be consulted for further analysis. We refer to this as *assessment*. In the literature, this is also referred to as *evaluation*, *validation*, or *review*.

This feature is enabled by first supporting data tracking. The recorded data should be used to provide some feedback to therapists, so that they can then direct the therapy progression. If possible, the exergame should provide more advanced performance assessment capabilities, such as clear interfaces that show aggregated motion data or the automatic computation of assessment scores. Although current commonly used assessment scores are not geared towards exergames (such as the fugl-meyer score [67]), more easily integrable scores, possibly automated, could become standards in the near feature, and we can find first attempts in this direction in [21].

In the literature, several exergames propose some sort of assessment support and present the therapist with motion graphs (examples are [154] and [96]). As with configuration, we suggest to opt for a mix of two modalities: providing summary values, useful to provide a quick view of the patient state, alongside in-detail graphs. The results of assessment could also be used to guide configuration automatically, basically closing the rehabilitation loop.

3.2.8 Motivation

In traditional rehabilitation environments, therapists also act as motivational guides to the patients: they link with them emotionally, pushing them to perform their exercises and reminding them of the final goal [123]. Rehabilitation exergames should provide this kind of motivation as well, but the emotional and social capabilities of the therapist are hard to emulate. Luckily for us, the gaming nature of exergames is the main reason for using exergames in the first place, and thus a motivational push can still be provided, although in a radically different way than in traditional therapy. However, this does not mean that attempts to provide some social ties between the patient and the exergaming system should be avoided, and the human-computer interaction field is indeed swarming with activity to promote this kind of interaction.

3.2.9 Integration of Features

By integrating some of the features we listed, additional interactions can be created to provide a more complete rehabilitation therapy. Depending on what features are integrated in the exergame and how, we can obtain very different degrees of automation. To truly support autonomous exergames, we should strive for integrated systems that support all the aforementioned features. In the literature, we note that there is a definite trend towards creating more integrated solutions, and thus towards more autonomous rehabilitation [157].

3.2.10 Accessibility and Usability

We list accessibility and high usability among our guidelines for effective rehabilitation exergames as, although they are not specifically related to the therapist's role, it is nonetheless necessary to address them when using any technology.

Accessibility is of utmost importance in rehabilitation exergames as their target population possesses impairments which may render standard input devices (i.e. mouse and keyboard) unusable and interfaces hard to understand. In addition, the target population may be represented by elders, as is the case with most post-stroke rehabilitation exergames or exergames to maintain cognitive skills. Elders are typically less proficient with technology, they are often completely devoid of any experience with video gaming and often also possess additional physical and cognitive impairments related to old age. The need for better digital interfaces for elderly users has in fact been previously reported [86, 212].

Accessibility can be improved through different factors. First of all, improving the usability of exergames has a beneficial effect on accessibility. For rehabilitation exergames, this mainly concerns clear and immediate feedback on the actions of the patient, as well as clear graphical user interfaces that can be safely navigated by impaired people. These clear user interfaces should not be limited to the exergame in itself, but also extend to additional interfaces, such as exergame selection menus or recap sections.

In the field of human-machine interface design, in order to improve usability, a concept that has been gaining a lot of interest lately is that of *Natural User Interfaces* (NUIs). NUIs are commonly defined as those user interfaces that are effectively invisible, and remain invisible as the user continuously learns increasingly complex interactions [165]. Among NUIs, we mention as examples speech control, body and hand gestures, or eye tracking. NUIs can be used to provide a natural mapping between the patient's actions and the control of the exergame, thus making it easier to play exergames also for people with cognitive impairments. This also follows the trend of the video game industry to devise more natural devices to overcome the complexity of standard gaming input controllers.

The literature shows that a wide range of input devices are being explored for rehabilitation exergames due to their various tracking requirements. Among these devices, some better support NUIs, such as free-body camera-tracking devices or wearable systems, and exergame designers should thus focus on these devices.

We also remark that by focusing on providing configuration and/or online adaptation, accessibility can be further increased, as the exergame can be configured for the specific patient's condition.

As an added benefit, high accessibility also leads to higher technology acceptance, leading patients to trust the system and possibly leading to higher motivation in concluding the therapy.

3.3 Guidelines for Motivational Exergames

The issue of patient motivation is a major topic in rehabilitation, as it is of great importance for patient compliance. We could argue that the introduction of exergaming into the therapy would be enough as a motivational push, but this view may be too simplistic. Rehabilitation exercises can be quite stressful: they require slow, repetitive, and often painful movements, performed at high intensity and for long time periods. Depression is also a serious issue with patients, who may not see any improvement in their condition and lose hope in the treatment [202]. On the other hand, a great motivational push in traditional rehabilitation comes from the social presence of the therapist, who instead cannot be present in an autonomous rehabilitation setting. In short words, the power of simple games alone may not be enough to keep patient motivation high for the duration of the whole therapy.

Creating fun and engaging games is a difficult task. Game design calls for a delicate balance, and no surefire method exists to create good games. The field of game design is also quite young, and theorists are still working to define what elements make a good game [172]. Especially in the case of games created by non-professionals developers, as is the case for most rehabilitation games in the research field, the passage from exercise to exergame is not bound to automatically increase motivation. Nonetheless, only a few authors in the exergaming field acknowledge the need for better game design, with most focusing instead on the technology that enables exergaming in the first place. Flores et al. [58] call for a more throughout understanding of the interaction between game design and exergames, and also propose some game design guidelines regarding elderly rehabilitation, while Gotz et al. [71] agree that game design principles in virtual reality rehabilitation are usually neglected.

The high intensity of exergaming also poses a large threat to the game's fun factor: an exergame may be fun the first few times it is played, as many simple casual games are, but it may become boring after a while, especially in the case of shallow and repetitive designs. To all of this, we add that the therapy is a mandatory activity, usually associated with *work* instead of *play*. Most game design theorists agree that the definition of game requires voluntary play [28] and we must thus acknowledge the risk of a lower motivational effect of exergames compared to traditional games. Of course, this depends also on the inclinations of the patient. If the patient sees exergaming as a valid alternative to typical rehabilitation, he will surely see how the gaming aspect can only be a benefit. If, however, the patient sees exergaming as an attempt to undermine serious rehabilitation, the patient may not accept it. Patient acceptance is thus very important, and the game should be designed to maximize this potential. As we can see, there are a lot of obstacles and risks concerned in the creation of exergames for rehabilitation, and this makes a good game design phase all the more important.

All is not lost, however, as good game design, as well as a few other tricks related to improving motivation, can make up for the shortcomings we just listed.

3.3.1 Motivation and Fun

To design *motivating* exergames, we need to first understand what motivation and fun actually are. Our final goal is to create highly motivating exergames and, to do so, we need to understand what it means to motivate, and what we can do to create an engaging activity. Player motivation in games, and motivation on a broader scale, is a major topic of research both in academy and in the industry. The underlying processes that motivate people to do what they do are hard to grasp and even harder to describe, but their understanding can be of great help: the knowledge can be used to design exergames and motivational content in general. To obtain such knowledge, we look into theories of motivation that link game design studies with psychology.

We first introduce the psychological theory proposed by Maslow: the hierarchy of needs [129]. According to this theory, a person's needs are structured in a hierarchy, and only when the lower needs are satisfied will a person focus on higher needs. The need for *safety of health*, which is fulfilled by rehabilitation, belongs to a lower tier than *belonging, esteem, and self-actualization needs*, among which play can be distributed. Maslow's theory explains why the motivational content of exergames risks to be overshadowed by the needs of rehabilitation, reinforcing the fact that the game aspect needs to be quite strong to make an impression.

Intrinsic and Extrinsic Motivation

Following psychology studies, an useful distinction can be made between intrinsic and extrinsic motivation. Intrinsic motivation refers to motivation that comes from internal desires: for instance, the willingness to better one's condition through rehabilitation. In games, we find several examples of intrinsic motivational elements, such as fun, challenge, or immersion. Games represent, after all, the prime example of autotelic activity[1] as no extrinsic reward is gained by playing (apart from the eventual social effect), and motivation comes from the thrill of the challenge, or from the so-called *fun factor*. Intrinsic motivation is a very powerful force, as highlighted by

[1] Autotelic: having a purpose in and not apart from itself.

psychology scholars [155]. It is however hard to design into an activity, hence why extrinsic options are sometimes preferred.

Extrinsic motivation is instead triggered by external rewards: it motivates people to perform tasks they would not normally perform if not for the reward itself. The prime example of extrinsic motivation, especially in our society, is money. Extrinsic motivation is designed around an activity and does not belong to the activity itself, which makes it easier to include. Popular examples of extrinsic motivation related to games come from *gamification*, that is the use of game mechanics or game elements for engagement in non-gaming fields. The term is usually associated with extrinsic solutions such as achievements, rewards, or social status, which renders gamification similar to customer loyalty programs.

Intrinsic motivation is usually preferred to extrinsic motivation and there are large debates on the latter's actual benefits in the first place. An important effect that must be considered is the *overjustification effect*, according to which providing extrinsic motivation for a task may permanently lower the effect of any existing intrinsic motivation, and there is quantitative evidence that supports this [31]. Similarly, Pink argues that monetary rewards in the workplace will decrease performance and that intrinsic drive is what really motivates a person [155].

Strictly speaking about games, we can debate the beneficial effects of *achievements* (virtual badges that can be earned by completing meta-game goals). Jakobsson [89] analyzed what effect achievements in the on-line gaming service *Xbox Live*[2] have on players. A love-hate relationship is found, with signals of addictive behavior. The bad motivational factor given by achievements, which seem to provide an illusion of motivation at the expanse of the strength of the actual game, is also confirmed in [19] and [78]. Note also that most current gamification methods suffer from the same issues (refer to [101] or [47]). In addition, extrinsic elements risk ruining a game's *magic circle* [84], as research on casual mobile game design shows: Lin and Sun [117] describe the effect of purchases in free-to-play games, analyzing the effect that external cash has on the magic circle of the game and on its perceived fairness, finding that monetary concerns ruin the fairness of a game, a conclusion also anticipated in 2004 by Bartle [11].

However, extrinsic motivational elements may be beneficial if introduced with care. Verbal praise, even from a machine, was proven to have a good effect [20] and virtual reward systems are also often used in games with great effectiveness to keep people playing [136], although care must be taken to avoid the pitfalls we mentioned. It is also known that reward

[2]http://www.xbox.com/en-GB/LIVE

systems provide social meaning outside the games [172], thus further increasing their motivational effect.

Short-term and Long-term Motivation

We also differentiate motivation between short-term and long-term motivation. Short-term motivation considers a single gaming instance and is thus concerned with making the game enjoyable from the first play-through. Long-term motivation is instead related to maintaining the interest of the player for multiple sessions.

Albeit long-term motivation is of great importance for rehabilitation, to our knowledge no current work has explicitly addressed the issue of exergaming solutions that maintain the motivation of patients for the entire period of a long therapy. We remark that a game that is fun the first few times may lose its appeal after a while, so the issue of long-term motivation should be addressed. Due to the short history of the field and to the small number and scope of exploitation studies conducted thus far, we suppose that issues regarding long-term motivation have not yet been encountered by most researchers, although a first warning comes from the experience of Golomb et al. [70].

Theories of Fun

Games possess a powerful intrinsic motivational element in the concept of *fun*. Game design theorists try to understand why games motivate us, and often do so by trying to explain this elusive quality. Fun, while well known (anyone can recall experiencing fun with ease), is really hard to define. This becomes all the more difficult when we realize that the very concept of games and play are yet to be fully understood [191]; many scholars tackled the task of defining these terms, with the works of [84], [28], and [172] being the most important. Due to the widespread fame of the most successful games and to the growing gaming industry, with games that net millions of dollars to their investors and developers, the understanding of the motivational aspects that keep a player glued to a particular game is a priority for many.

Can we define fun? Or can we at least identify the elements that can make a game fun? While preferring the notion of *pleasure* instead of fun[3], Salen and Zimmermann devote a complete chapter to why and how playing games produces said pleasure [172], from which we gather that fun cannot be reduced to a single element. In fact, LeBlanc [116] lists a set of different

[3]The distinction is here purposely disregarded for ease of discussion.

kinds of fun a player may experience: *sensation*, *fantasy*, *narrative*, *challenge*, *fellowship*, *discovery*, *expression*, and *submission*. Malone [126] points to three primary aspects present in games that make them an enjoyable activity: *fantasy*, *challenge*, and *curiosity*. Hallford & Hallford [75] analyze and categorize four types of intrinsic rewards in games depending on their effect on the gameplay experience: *glory*, *sustenance*, *access*, and *facility*. Lazzaro [115] classifies the different types of fun by performing tests with gamers and non-gamers alike: she identifies *hard fun*, *easy fun*, *altered states*, and the *people factor*. Similarly, Bartle [11] separates players into *killers*, *achievers*, *explorers*, and *socializers*. Yee [212] analyzes the likelihood of quitting a game against different game factors by using data mining techniques and identifies the main motivators that drive players to play online games in *achievement*, *social play*, and *immersion*. Another great contribution comes from Schell [177], which presents dozens of *lenses*, i.e. ways to look at the design of a game, once again reinforcing the fact that fun, and game design, are extremely multi-faceted. Intrinsic motivation seems to be the main source of engagement for casual audiences as well, as highlighted by Begy and Consalvo [13] who explored the role of reward systems in casual games through their analysis of the social network game *Faunasphere*. Through a survey, they identified completing goals as the main drive for player attachment to the game.

Other authors focus instead on one of these many facets and point to it as the main source of fun. Koster [107] defines fun as the process of learning and mastering the game, arguing that when a player stops learning (for example by completely mastering the scope of the game), she stops having fun: fun is thus in the challenge and the discovery made possible by player agency. Juul [93] analyzes the meaning of challenge in video games, shedding some light on why the risk of failure is necessary in games as an intrinsic motivation aspect. The author argues that winning all the time makes for a dull game. However, care must be taken not to punish players unnecessarily, instead making them responsible for their actions. Still related to challenge, from psychologist Csikszentmihalyi [43] comes the motivational theory of flow: a state of concentration and complete absorption in which skills and challenge are matched and the person feels a sense of happiness. This easily relates to games and their difficulty levels. A specific symptom of the flow state is the transformation of time, where it seems to fly by while having fun, an effect for which good games are quite famous [42].

This overview teaches us that the motivational content of exergames may not come from a single source, and that careful design of multiple elements is needed. Also, it teaches us that not all players look for the same thing in games, and fun thus comes from different elements for different people. While not usually considered in the exergaming literature, this multifaceted nature of fun explains why good game design is hard to achieve.

Game Design for Elders

In the case of exergames targeted to the older population, additional game design considerations must be made for this novel class of gamers. A few authors have addressed the lack of research on game design targeted to elders. For example, Ijsselsteijn et al. [86] found that despite common misconceptions elders seem to enjoy video gaming, and they are not against the use of new technology. Flores et al. [58] define a set of criteria for elderly entertainment based on a review of the literature and especially on the findings of the *Eldergames* project [60]; some of their criteria are defined for elders in particular: games designed for elders require adaptability to motor skill level, appropriate cognitive challenges, a simple objective and simple interface, some elements of social activity (as also highlighted in [212]), an appropriateness of genre (and of content, we may add) and a sensitivity to decreased sensory acuity and slower responses.

Introducing the Guidelines

From the previous discussion we gather that fun is not a simple concept, and that there is no single ingredient that is commonly accepted to be the secret for a fun game. Instead, we find a collection of different elements, which all contribute to create an entertaining game for the largest number of people, and thus increase motivation. Following this, and keeping in mind our hints on the power of intrinsic motivation, on the issue of long-term motivation, and on elderly design requirements, we now present a set of guidelines that can be referred to when developing the gaming aspects of exergames for rehabilitation. We aim to discuss all the elements that can contribute to create an engaging, entertaining, and fun game, focusing on the limits imposed by the therapeutic nature of the underlying exercise. As such, therapists should not be concerned with the following guidelines, which are instead directed to game developers.

These guidelines should work as a starting point for designing an exergame, but this does not mean that the exergame designer needs to introduce all of them into the same exergame at once, although some of them are strictly required to create a compelling game in the first place. Instead, they should be seen as methods to increase the motivational factor of a particular exergame.

3.3.2 Basic Guidelines

We first address elements that are required to obtain a playable game in the first place, as the remaining elements would not be able to have any motivational effect without this basis.

Meaningful Play

As agreed upon by most authors, *meaningful play* is the most important element for good game design: it requires that game actions are somewhat significant inside the fantasy of the game and an action performed into the game should thus have logical consequences [172]. To provide meaningful play, we need to create a suitable goal, compatible with the fantasy of the game as well as with the underlying exercise. This is related to the concept of *artificial conflict*, intrinsic to the definition of game.

In rehabilitation exergames, since the movements of the exercises are directly translated into game actions, these same actions need to make sense towards the goal of the game, lest the patient does not feel her action meaningful in the context of the game and thus ceases to be motivated.

As an example, we take our *Fruit Catcher* game (section 4.2.2). In the fantasy of the game, the patient needs to collect all the apples into a large basket. In a farming context, collecting apples from a tree is meaningful, and thus the fantasy works. In addition, with apples falling to the left and to the right, the patient has a meaningful reason for performing the underlying exercise: i.e. not letting the apples fall to the ground.

Clear and Immediate Feedback

Clear and immediate feedback to the player's actions is related to the concept of *quantifiable outcome*, part of the definition of game. If the player's actions trigger unclear feedback, it is hard to discern what consequences actions have, or whether they had any consequence at all. If the feedback is not immediate, it may be hard to discern which action triggered which feedback, or to correct wrong behavior in time. The lack of clear and immediate feedback makes the game feel arbitrary and random, and does not help in achieving meaningful play. For elderly gamers, this is made all the more important by the fact that they may possess limited sensory capabilities, making the specifications for clear feedback even stricter.

Feedback guidelines are common also in rehabilitation requirements, and this is one of the reasons it is hard to neatly separate games and exercises: is the feedback part of the game, or part of the exercise? If we follow the separation we made thus far, we can argue that the feedback required by the exercise is related to the exercise goal, and thus to the correctness of movements. On the other hand, feedback related to the game should make it clear that we are advancing towards the game's goal. The two types of feedback can be merged into one single element, as is often the case, and this is a consequence of enforcing meaningful and direct relationships between the exercise's goal and the game's goal.

Simple and Direct Interactions

Following the need for clear feedback, exergames should provide simple and direct interactions: the mapping between the exercise's required movement and the game actions must be as direct, and as natural, as possible. A direct interaction is needed for the patient to understand intuitively what she needs to do, and this is necessary to achieve meaningful play. This requirement becomes even more important if the target population of the exergames is not used to complex games, or if it may possess cognitive impairments, as is the case with elderly patients.

To obtain natural interaction, we refer to the concept of *affordance*: the games should be designed so that the virtual fantasy *affords* the actions required by the exercise [140]. For example, if patients need to move their left leg to the left, we should present them with a task that, in the virtual world, affords exactly that action: this could mean that they need to kick a virtual ball, clearly visible to the left, to complete the task.

To make the game more compelling, we could be tempted to add layers of indirect interaction, but this would be detrimental. For example, we refer to our *Hay Collector* game (see section 4.2.5). Initially, this game used a steering mechanism with accelerations, reminiscent of realistic driving. However, this control scheme was very hard to use and unintuitive for patients and also required excessive tuning. We at last removed acceleration and recreated the game using simpler interaction: moving left starts moving the tractor to the left, and moving right moves it to the right. This allowed the game to be more playable and, ultimately, more compelling, while still maintaining the same fantasy. To approach this guideline, a correct separation of the game and exercise elements of the exergame can be useful, as the relationship between the game's actions and the exercise's movements are clearer.

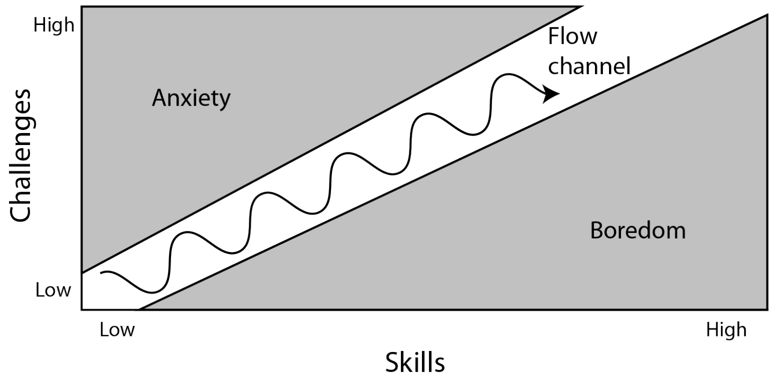

Figure 3.2: *The flow channel. Reprinted with permission from [177].*

3.3.3 Fun-driven Guidelines

Given that the basics are taken care of, we now present guidelines related to increasing the intrinsic motivational benefit of the exergames.

Challenge

A good way to provide fun in a game is to add some degree of *challenge*. As we saw earlier, many authors agree that this is one of the key components that make a game fun, and, for some, no game can be possible without a certain amount of challenge [107, 126]. In the literature, the concept is also represented as *hard fun*, *mastery*, and sometimes *learning* or *achievement*. The basis of challenge comes from the notion of uncertain outcome: if the outcome of a game is certain from the start, for example by making sure that the player always wins no matter what she does, no challenge is present and the game fails to be compelling. A requirement for challenge to be present is thus a *clear goal* to achieve. A challenging game does not need to be *hard*, it merely needs to match the player's skills. This can be achieved even with simple and intuitive games.

When treating challenge, *flow theory* [43] is commonly referred to. The theory establishes a relationship between a task's challenge level and the performer's skill: when the skills of the performer are matched by the level of challenge posed by the task, the performer enters a state of complete focus and immersion in which she loses track of time and enters a state of heightened motivation. The relationship between challenge and skill is reported in figure 3.2, where a beneficial trajectory is suggested that alternates moments of difficulty and moments of tranquility [177]. If we restrict change to only one dimension, there are two ways to reach the flow state from any starting position: either (1) the player changes her performance, given a fixed difficulty level, or (2) the game changes its difficulty level, given that player skills do not change. Any other combination can also be achieved, with the game and the player changing their challenge and skills at unison.

Entertainment games usually proceed by confronting the player with obstacles of increasing difficulty that must be surpassed by learning the game rules and developing increased skills (case 1). This gives the players a sense of mastery as they proceed in the game, needed for the challenge to be meaningful. Many games employ the concept of *levels* which increase in difficulty as players advance, so that they need to improve their skills to complete one level after another. Other games resort to a simple and intuitive control scheme, which can be learned with ease, but they progressively increase the difficulty and ask the player to keep up with the pace. An example is the classic *Tetris*, which becomes more difficult as the game advances until the player is overwhelmed.

Some games use a totally different approach: instead of giving the player an increasing challenge, the game adapts itself to the user, effectively changing its difficulty to match the player's fixed skills (case 2). This is a well-known technique in the game industry, and appears under the name Dynamic Difficulty Adaptation, or DDA. DDA requires that the game learns a model of the player's performance and acts accordingly by adapting the parameters that govern the game's difficulty in real-time. It is introduced into a video game in order to support a larger population of players, where fixed difficulty settings are not enough. In the game studies literature, adaptation is considered one of the most powerful means to increase the engagement of the player when the target population of players is too wide to allow everyone to play using the same settings [119, 210]. Many adaptation techniques have been explored in the game community, such as parameter modification through hill climbing, reinforcement learning, or artificial neural networks [119, 135]. However, DDA should be performed with care, as it should be transparent to the players, lest they realize that the game is reacting to all their actions and the challenge is, in fact, fabricated. The famous *Oblivion*[4] is a good example of this so-called *rubber band* adaptation.

In the context of rehabilitation exergames, the introduction of challenge is even more problematic as the skills of the target population can vary greatly due to impairments and skill improvement is quite slow: we cannot rely on patients to increase their skills to match the difficulty of the game. For this reason, a fixed difficulty level or just a few choices of difficulties

[4] The Elder Scrolls 4: Oblivion - Bethesda - 2006

would not suffice for most patients. The use of DDA methods can thus be of great help, so that the correct amount of challenge is given to the patients after having modeled their skills. This allows patients to enter a state of flow, so that they can be completely focused on the game while everything else vanishes, hiding the rehabilitation burden as well as the difficulties arising from their impairments. Studies show that physical pain is also reduced when a flow state is reached [105], another useful benefit for rehabilitation.

It follows that there is a link between flow theory and the features needed for correct rehabilitation. In fact, as flow theory is not limited to games, we can argue that a state of flow could be entered even by just exercising, if the exercise's challenge level is matched by the patient's motor skills. This gives challenge, similarly to feedback, a dual nature: it can be seen from a therapeutic point of view, and thus must be tuned to allow the patients to perform useful exercises to train their skills without stressing their body and mind, or it can be seen from a gaming point of view as a motivator. This dual nature has also been noted by previous authors [185]. This pushes our discussion back to the set of features for rehabilitation that allow the game's (and exercise's) challenge level to be modified: configuration, as the exercise can be personalized to be perfectly aligned to the patient's skills beforehand, and on-line adaptation, which can be used to refine the challenge on-line and thus perform the equivalent of DDA for exergames.

In the rehabilitation domain, the difficulty of an exercise is associated to its therapeutic goal, and this is tied to the skills required by the exercise's domain. Critical parameters that are tied to these aspects must thus be identified for each exergame and be subject to adaptation, if we want to make sure both that the exercises have a therapeutic effect and that a flow state can be reached.

Fantasy

Fantasy is the name given to the imaginary virtual context of the game. This does not mean that the game needs to be placed into an unrealistic environment: even playing basketball or driving a car can be considered a fantasy. Fantasy is listed by Malone as one of the main elements that make games fun [126], suggesting that it is even more important than feedback in determining the appeal of a game. This is also reinforced by the experiments of Yannakakis [211], who found that fantasy, in respect to challenge or curiosity, better correlates with engagement regardless of player type, at least for children. A good fantasy helps in creating *immersion*, i.e. the sense of presence that the player feels when interacting with the game world, also further helping the player to enter a flow state. A fantasy is presented to the player through two means: *aesthetics*, the presentation of the graphical and auditory elements that make up the game world, and *narrative*, the story told by (or inside) the game.

Fantasy can be a great tool for exergame design as it works as a coat over the exercise, diverting the patient's focus from reality and pushing it towards the game's world. It is a versatile tool, as it does not depend on the patient's condition and, as such, an exercise can be paired with many different fantasies. Focusing on the need for natural interactions we mentioned earlier, the fantasy can also work as a metaphor for the underlying exercise, increasing the intuitiveness of the interaction. The chosen fantasy should also be appropriate to the target population, which is especially important when creating a fantasy for elderly people as we must use a fantasy they can relate to.

The concept of fantasy is in contrast with traditional rehabilitation environments and virtual reality rehabilitation, where training related to activities of daily living (ADL) is preferred in order to promote the restoration of the skills related to these activities which are relevant to the patient's life. If we apply our *exercise-game* separation, we note that the underlying exercise is unchanged by the game and it can thus mimic ADL training, proving that a fantasy can be safely applied, as many current exergames do.

Curiosity

With *curiosity*, we refer to the pleasure of discovery related to playing a game. In the literature, this is related to the concept of *exploration*, *learning*, and *easy fun*, and the game's *uncertain outcome* requirement also has a part. A certain degree of curiosity is needed to keep the player engaged, as it gives her a reason to continue playing a game. A player that is not curious loses interest in a game, as she feels the game has already given her everything it can offer. Curiosity is also the most important ingredient for long-term motivation in games, as it is required to maintain interest when the novelty of the game mechanics wear off. Curiosity is usually triggered by presenting the patient with new game content, with the promise of new content, or with a large possibility space.

Exergames, limited by the exercise actions, cannot easily present new game content as they cannot introduce additional game mechanics, nor can they provide a large possibility space. A way to fuel curiosity comes thus from introducing variations into the fantasy environment, and from introducing small variations into the gameplay where possible. Fantasy variations can take the form of graphical changes in subsequent instances of the same game, such as changing the shape and texture of game elements. The effect on curiosity is even stronger if special variations appear only from time to time. Due to the limits of the exercise, gameplay variations are harder to implement, but this can be solved by integrating several different exercises into the same game, effectively presenting the patient with different *game modalities*. In fact, the presence of multiple games and exercises is of great help to maintain curiosity.

Creating new content to maintain novelty requires a lot of development resources and can thus be inefficient. A way to provide new content for exergames efficiently comes from the use of Procedural Content Generation (PCG) techniques, as also suggested by [51]. PCG techniques allow the developers to introduce controlled randomized elements into the game, drastically enlarging the possibility space of the game. Compared to traditional authored game design, PCG techniques are prone to errors especially due to their pseudo-random nature, but when used with care they can save a lot of development resources.

Sensation

Sensation, i.e. the aesthetically pleasing elements of games, is a critical part of what makes a game engaging. Although it could be regarded and nothing more than *eye candy*, and a game with ugly graphics and no sound can still be fun, the presence of good graphics and sound makes a game better and subsequently more engaging in the eyes of the player, to the point that some games even live on their aesthetic appearance alone.

An exergame, to have a good motivational effect, cannot fall short in comparison with current entertainment games. This is even more important for children and teenagers, who will surely compare the exergame to their favorite games, but we should strive to achieve good quality for other populations as well. However, this is ignored in most of the exergames found in the literature, possibly due to the absence of game design experience, and we find only a handful of games which propose a well-refined style (a good example is [71]). This does not mean that the exergames must be of a quality rivaling top entrainment games, as that would require millions of dollars in investments. Simple styles can instead be chosen, such as the 3D cartoon-style graphics we use, which can help achieving a quality that is good without a large expenditure of resources.

Still related to sensation, we also mention here the concept of *juicy feedback* which refers to all the small details that make interaction with the game engaging: buttons should react with visual and sound effects, and victories should be rewarded with plenty of visual and verbal praise [177].

The attention to these details makes the game enjoyable at all times, even while only navigating the interface, thus increasing its motivational effect. In addition, juicy feedback can be used to reinforce the fantasy of the game.

Social Play

Social play regards all instances of interaction with other people through the game. Also mentioned in the literature as the *people factor* or *fellowship*, it is listed by many authors as a great source of motivation, and one of the main source for long-term motivation. Through competitive play, it also works to further promote challenge. Flores et al. identify social play as a requirement for good elderly game design [58], and Yee even found that the attitude towards social play increases with age [212].

Exergames could greatly benefit from social play, especially in an autonomous setting where the daily link to the therapist is missing and thus its motivational effect is lowered. However, traditional rehabilitation is usually performed through single-user exercises tuned for the specific patient's condition and guided by a therapist; multi-user exercises are uncommon and, subsequently, most exergames tend to be designed for single players.

How can we insert social play into exergames? One way is to add multiplayer capabilities to already existing exergames by allowing them to be played concurrently by multiple people at once, be it locally or online. This has the benefit of not requiring any modification of the underlying exercise, using the exergame result as a performance indicator to determine the outcome of the multiplayer game. The game could be designed as competitive or cooperative, although the differences of rehabilitation patients pose issues regarding fair play, which rules out most competitive play. A better argument can be made for cooperative play, with patients playing the same exergame together towards the same goal. However, multiplayer games introduce technological issues: we need to cope with multiple devices and limited screen space in local play, while online play introduces synchronization issues. As an alternative, we may introduce cooperative gameplay mechanics unrelated to the exercise, making room for a second non-impaired player. This can be used as a way to promote caregivers, relatives, or even the therapists to play alongside the patient without requiring additional specific hardware, helping with the game while the patient performs the exercise. As a last resource, we may introduce asynchronous social gaming mechanics, something that, to our knowledge, has not been done in this research field yet. The benefit of these mechanics comes from the fact that they may be linked to the results of the exergame and not to the actual in-game actions, and from their asynchronous nature and independence from physical movements that allow more freedom of design and reduce technological issues. Social game mechanics, due to their focus on socialization and personalization instead of competitiveness, are also well known for their long-term motivational benefits.

3.3.4 Extrinsic Motivation Guidelines

Thus far, we focused on the intrinsic elements that can make an exergame engaging. We present here instead extrinsic elements that can help in achieving good motivation. As we discussed previously, special care must be taken when treating extrinsic motivational elements. However, if done with care, some elements can be beneficial, and we mentioned in particular verbal praise and virtual rewards.

Verbal praise is especially useful for exergames, as it has a direct link with traditional rehabilitation. The patient should be thus rewarded with praise whenever possible, through text or, preferably, through actual speech.

Virtual rewards can instead be given at the end of an exergaming session based on the patient performance, and are thus easy to integrate due to their independence from the actual exergame actions. We also remark that, for a virtual reward system to be effective, it should have no feedback loop on the exergames themselves, or specific strategies may arise, voiding their beneficial effect. The benefit of virtual rewards lies in the possibility of integration with other game elements, such as social game mechanics, which can increase the long-term motivational effect of the exergames. In fact, virtual rewards can be used as social motivators, making sure to provide personalization options and some way for patients to share their rewards with other people.

3.3.5 Scoring

We treat separately *scoring mechanisms*, as they represent a gaming paradigm that relates to several features we listed thus far and is simple to integrate. Scoring mechanisms assign virtual points to game actions, and these points are then shown to the players as they play. Scoring is a direct indicator of player skill (and is thus related to challenge), while providing immediate and easy to discern feedback about the game's progression; as such, it is a good idea to add scoring to any exergame. Hallford & Hallford place score in the *glory* reward class [75].

Scoring also improves long-term motivation, as it can be used as an indicator of performance in subsequent exergame sessions, prompting the patient to improve her score. It also ties well with social play, as it can be shown to other patients to promote competition. At last, scoring can be linked to virtual rewards, functioning as a sort of virtual currency, effectively attaching further meaning to each single exergame.

However, a score system should be inserted into the exergame with care, as it must correctly reflect the patient's performance. If we introduce a scoring system that doesn't take into account all the different modifiers of difficulty, patients may feel cheated as the scores may feel biased and unfair, thus becoming a burden instead of a motivator.

3.3.6 Collection of Exergames

Up to now, we treated exergames as if they were single entities, as is mostly done in the literature, but in view of a complete exergaming therapy we consider the fact that exergames do not exist in a vacuum. It is in fact preferable to create a set of multiple, connected exergames, with each being created for a specific exercise in the therapy. This view shares some similarities with a well known gaming paradigm, collections of mini-games, which are usually tied to a casual user base (players that want simple, easily accessible games). These collections present simple, fast, and funny mini-games, often with little or no connection between one mini-game and the next. Exergames, as we saw, should be simple and focused, and can thus be seen as mini-games, while a set of exergames can be seen as an *exergame collection*.

This view brings several additional benefits related to the concept of *gestalt*, which can be summarized with the Aristotelian quote *"the whole is greater than the sum of its parts"*. Having multiple exergames to choose from has a good effect on *curiosity*, since the patient can experience more varied play. A good selection of mini-games can also favorably affect *challenge*, as the selection mechanism can take into account the difficulty of the exergames and propose to the patient those matching her skill level. *Fantasy* benefits greatly from having multiple exergames, as a shared fantasy (also termed *shared theme*) can be built over the single exergames, helping in linking them in a narrative context. Other elements, such as *sensation* and clarity of feedback, can indirectly benefit from this higher view, as the exergames can share parts of the whole system, such as the navigation interface, feedback elements, graphics and sounds, as well as scoring mechanisms. This effectively reduces the cost of development while increasing the consistency of the exergames and thus their usability.

CHAPTER 4

The Design of Exergames for Post-Stroke Posture and Balance Rehabilitation

Having defined what an exergame is, and what features its two aspects should possess, we propose here how the design of valid exergames for rehabilitation can be translated into a suitable design pipeline.

The pipeline we designed has a few distinct phases:

- Starting from a therapy goal, a set of exercises is chosen, making sure that the exercises cover all the needs of the therapy.
- Each exercise is properly defined, structured in terms of required movements, constraints, difficulty levels, adaptation, and required output data.
- A set of *virtual exercise environments* is then created into a virtual world, with each supporting multiple virtual exercises. This phase makes the result a virtual reality rehabilitation application.
- Virtual exercise environments are then transformed into exergaming environments by adding gaming elements.

In the rest of this chapter, we get into the details of the pipeline, focusing on the design of balance and posture exergames, of which we provide examples throughout the discussion.

4.1 Designing Exercises for Posture and Balance Rehabilitation

In this section, we start from the design of exercises and arrive at their transformation into exergames.

4.1.1 The Rehabilitation Therapy

To provide a complete rehabilitation therapy, a set of exercises that encompasses all the requirements for the treated condition is needed. We first need to specify the domain of the exercise, which is necessary to highlight what are the skills required to perform it and, subsequently, to describe its nature and purpose. In the domain of balance and posture rehabilitation, these skills are *physical accuracy* and *reaction time*.

A physical rehabilitation session is composed of a mix of exercises that often involve both coordination and strength [112]. Recent findings indicate that balance and muscle strength are important determinants of walking performance [52] and as a consequence treatment programs should comprehend exercises aimed to improve these components. Such exercises are geared towards improving motor learning [109]. We based our work on two fundamental motor learning principles, known to positively affect rehabilitation: task variability, which indicates that varied practice is superior to repetitive single tasks when it comes to motor learning [178], and progression, which implies that motor learning benefits from a continuous adaptation of task difficulty to increasing skill level [55]. From the two motor learning principles it follows that rehabilitation programs should contain a constellation of exercises, the difficulty of which is progressively adapted to the skill level of an individual patients.

These principles are captured by Gentile's motor skills taxonomy [63, 124]. A notable feature of the taxonomy is the two-dimensional approach: the dimensions systematically define physical actions through (1) the environmental context and (2) the function of the action. Environmental context refers to the environmental conditions to which the patient has to react in order to successfully perform a motor task. This dimension is characterized by (1a) regulatory conditions and (1b) inter-trial variability. The regulatory conditions define the relevant environmental features that constrain movement execution and may be stationary (stationary regulatory conditions) or moving (in-motion regulatory conditions). The taxonomy also differentiates between regulatory conditions that change between trials (inter-trial variability) and those that do not (no inter-trial variability). The second dimension, action function, is also characterized by two indicators: (2a) body orientation and (2b) object manipulation. Body orientation indicates whether an action requires the performer to move from one location to another (body transport) or not (body stability). Object manipulation indicates whether an object has to be controlled during the exercise (object manipulation) or not (no object manipulation). Through the interaction of the resulting four environmental context characteristics and four action function characteristics, sixteen different skill categories can be defined that provide a comprehensive template to classify motor skills. Each category is associated with unique features and poses qualitatively different demands on the performer. The sixteen skill categories included in Gentile's taxonomy are positioned in such a way that simple conditions are followed by more complex conditions, with the simplest skill category at the top left position. The task difficulty increases throughout the categories and the most challenging is placed at the bottom right of the table. Accordingly, Gentile's taxonomy allows a systematic progression in difficulty of physical actions (see figure 4.1).

This taxonomy is the basis on which we and our clinical partners designed a set of exercises, defining them in terms of goals and required movements, and we used these definitions as a basis to create virtual exercises and, subsequently, exergames.

4.1.2 Exercises for Posture and Balance Rehabilitation

As we explained in the introductory chapter, posture and balance rehabilitation requires task-related exercises based on balance, strength, and endurance. Following these premises, we illustrate here the exercises for balance and posture rehabilitation, mapped on Gentile's taxonomy, we developed our exergames around.

The first phase of a rehabilitation program should focus on basic skills. For balancing, this means maintaining the body's center of pressure (COP) centered between the two feet while standing quietly. We devised an exercise that requires the patient to just stand still for its duration and we named it *Stand Still*. Patients often find achieving even this simple goal problematic, as they tend to rely more on the unimpaired leg. Subsequently, patients are guided to shift their weight repetitively from the left to the right leg to

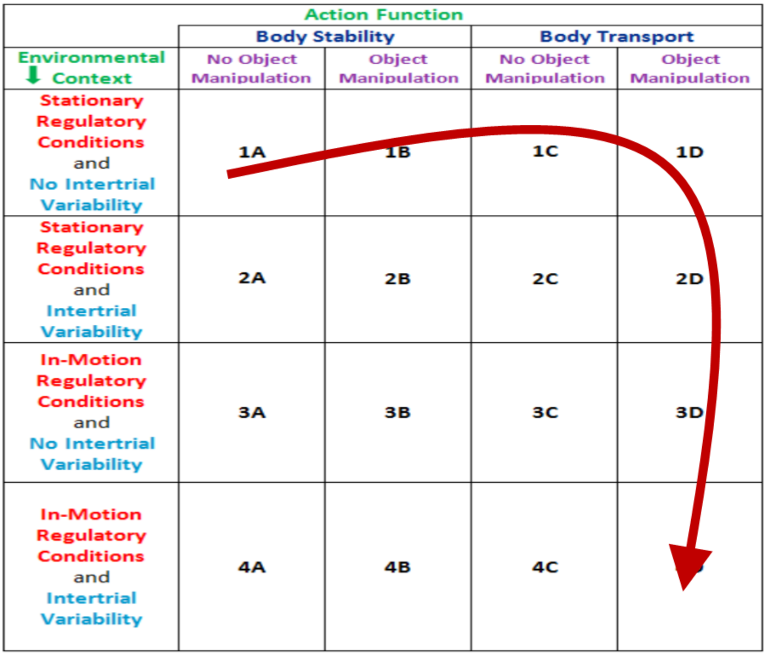

Figure 4.1: *Modified from Gentile's taxonomy of motor skills [124]. A possible rehabilitation progression is represented by the arrow.*

relearn the control of balance while moving. We refer to this as the *Weight Shift* exercise. Such exercises are preparatory to regain stable walking and, to correctly execute these exercises, patients are also required to maintain a straight posture. These two exercises, in their bare forms, belong to category 1A in the taxonomy. We also expanded the two exercises to account for the variations of the taxonomy. We added in-motion regulatory conditions by asking the patient to perform movements in a specific time frame, opening these exercises to class 3A. We refer to these timed exercises as *imposed-pace* exercises, in contrast with *self-paced* exercises. By adding randomization to the required movements, we then expanded them to class 2A and 4A. At last, by adding object manipulation, we expand to classes 1B, 2B, 3B, and 4B.

For the later stages of stroke rehabilitation, to meet patients' needs in the final stage of recovery, the program should include advanced stepping tasks. Specifically, we defined an exercise in which the patient is required to perform steps in eight directions, simply named *Steps*. We also define an exercise that requires the patient to lift her legs at a certain height, alternating one after the other, named *Lift Legs*. With these exercises, we expand to the C and D columns of the taxonomy, thus completing the progression.

The exercises we described have the goal to increase balance (apart from *Lift Legs*, which has a strength component). We also address strength increase through a specific exercise which requires the patient to do sit-to-stand and stand-to-sit actions, named *Sit-to-Stand*. For this exercise, a chair is required. Endurance is instead addressed by all exercises through repetitive use.

As per the requirements of therapists and also highlighted by our design guidelines, each exercise should also support multiple levels of difficulty. The difficulty level of the exercise is based on Fitts' law, according to which speed and accuracy are crucial aspects when addressing motor skills and both components determine task difficulty [214].

4.1.3 Structure and Parameterization of Exercises

To create virtual renditions of the exercises, a more detailed description must be provided. A complete description needs to list what atomic actions are required to perform the exercise, the relationship between the different actions, and their constraints. The simple descriptions we provided earlier need to be completed by specifying how long the exercise should last, how far the patient can and should move, and how fast and with what accuracy. We call the descriptive values of the exercise *input parameters*, and we call the description of the sequence of different actions needed to complete the exercise *action sequence*. The action sequence describes a model for a set of similar exercises that share all actions, although the actual values of the parameters that define such actions can change, thus specifying an *exercise instance*. To complete the exercise's definition, we also define additional *secondary constraints* that must be fulfilled to consider the exercise's execution correct. These constraints are not inserted into the following discussion as they are left out of the exergame design *per se*, but are instead later treated by our monitoring system. We refer to each of the exercise's actions in an action sequence as *trials*; each trial requires a specific movement to be completed and can either end with a success or a failure. The player will perform many similar trials during the course of the exercise, and we refer to a set of trials as a *repetition*.

For implementation purposes, we separate the exercises into sub-exercises, which share a common goal and common parameters, but have different action sequences. For example, the *Weight Shift* exercise is subdivided into *Frontal Weight Shift*, which requires movements only on the frontal plane; *Lateral Weight Shift*, which requires movements only on the sagittal plane;

360 Weight Shift, which requires movements in all eight directions in a clockwise motion; and so on. We also define a different sub-exercise for each taxonomy class the exercise can be assigned to.

We analyzed the exercises in order to find the best set of parameters that can be used to describe them, trying to find a lowest common denominator in order to standardize their definition. For each posture and balance rehabilitation sub-exercise, we thus identified the following parameters. The **area of movement** parameter (A_m) determines the limits of the movement required for the patient. The meaning of this value depends on the actual exercise, but it is always related to the action the patient needs to perform: in the case of body stability exercises, this is related to the Level of Stability (LOS) of the patient, while in the case of body movement exercises, this is related to the maximum step length of the patient (for *Steps* exercises) or to her strength (for *Sit-to-Stand* and *Lift Legs* exercises). The **spatial accuracy** parameter (x_A) determines the accuracy needed to complete a trial, and again its meaning depends on the exercise's nature. The **total duration** parameter (T_{tot}) determines how long the exercise should last. The **inter-trial period** parameter (T_I) defines the time period between one trial and the next. The **trial duration** parameter (T_t) defines the time period between the start of the trial and its end, and is related to reaction time. By defining exercises in terms of parameters, we lend the exercises to easy configuration, as the configuration capabilities need just to mimic this parameterization, also making it easier for the therapist to configure since exercises share common definitions.

To better visualize the effect of the parameters and of the action sequence we defined, we provide visual interpretations of how they affect the exercises. Let us consider a simple exercise whose action sequence requires movement on a single dimension. Let's assume we are concerned with the patient's COP movement on the y-axis. We can plot the patient's possible trajectory on a graph (figure 4.2). The total duration of the exercise T_{tot} determines the domain of the graph.

The trial duration T_t can instead be visualized as follows: the event of the trial start is outlined by a small circle at its starting y coordinate, while the moment the trial ends is highlighted by a small cross. In the case of imposed-pace exercises, the patient should complete the trial between those two events (figure 4.3). If the patient does not complete the trial in time, the trial is considered a failure. We refer to this as the *miss condition*.

In the case of a self-paced exercise, the patient can instead complete the trial whenever she prefers. There is thus no time limit, and the trial's duration is infinite (figure 4.4).

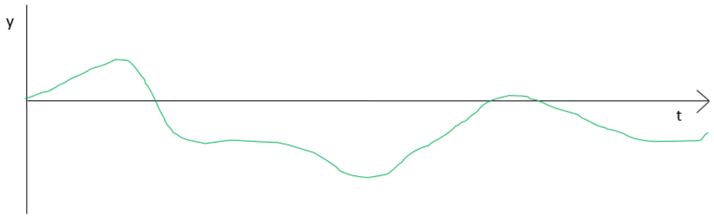

Figure 4.2: *The possible trajectory of a patient in a sample exercise.*

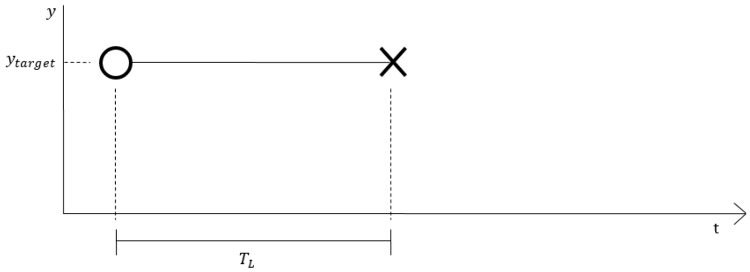

Figure 4.3: *In an imposed-pace exercise, the trial needs to be completed before its duration elapses.*

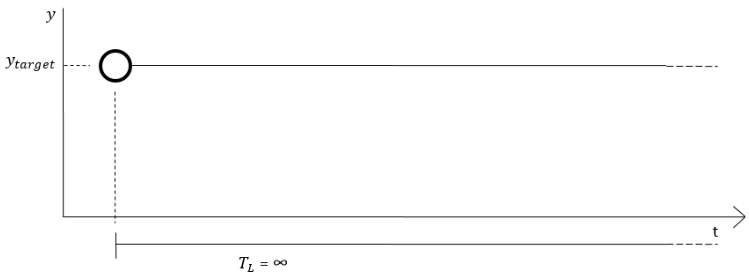

Figure 4.4: *In a self-paced exercise, the patient chooses when to complete the trial.*

The patient completes the trial with a success if she reaches the target position during its duration (figure 4.5).

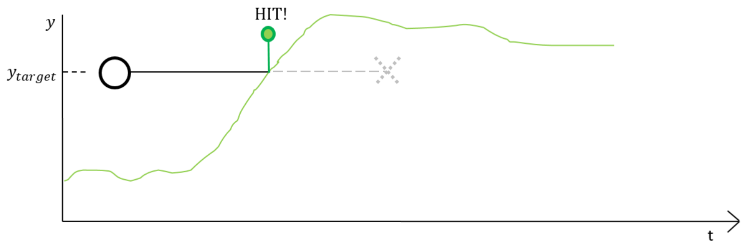

Figure 4.5: *A trial is completed if the patient reaches the trial's target position.*

An exercise session is however composed of multiple trials, with different coordinates chosen according to the action sequence of the exercise. If the exercise has an imposed pace, then the period between one trial and the next is the exercise's inter-trial time period T_I, independent of what the patient does (figure 4.6).

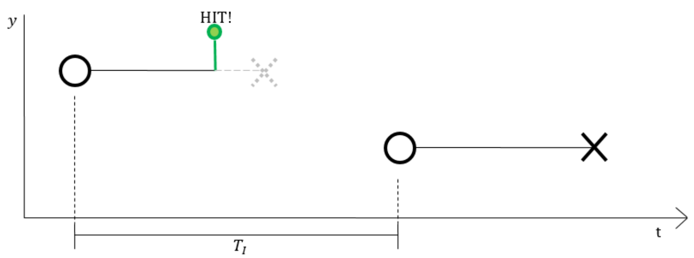

Figure 4.6: *The meaning of the inter-trial period parameter for imposed-pace exercises.*

If the exercise is instead self-paced, that period determines the time that elapses between the end of one trial and the appearance of the next one (figure 4.7).

At last, the accuracy parameter defines a range of values centered at the trial's target coordinate at which the target is considered hit (figure 4.8).

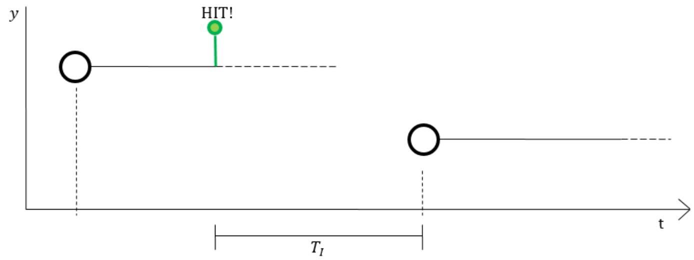

Figure 4.7: *The meaning of the inter-trial period parameter for self-paced exercises.*

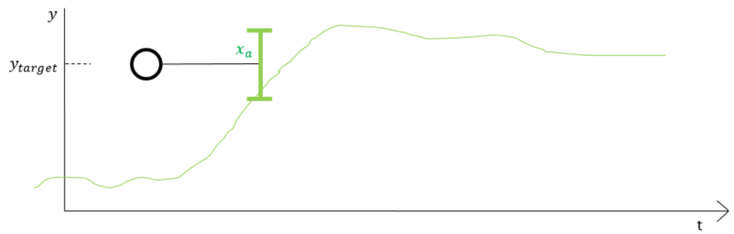

Figure 4.8: *The accuracy parameter increases the hit zone for a trial.*

4.1.4 From Exercises to Virtual Exercise Environments

Exercises need to be then transformed into their virtual counterparts, and the common structure we detailed makes this task easier. We call the result of the transformation process *Virtual Exercise Environment* (VEE). A VEE represents a particular implementation of an exercise, or of multiple exercises, created using the tools of the virtual environment (see figure 4.9). A VEE provides a virtual environment for the patient to perform the needed exercises and obtain clear feedback on the performance. The exercises can thus be analyzed without the distractions of the gaming aspects, making each VEE, according to our definitions, a virtual reality rehabilitation application.

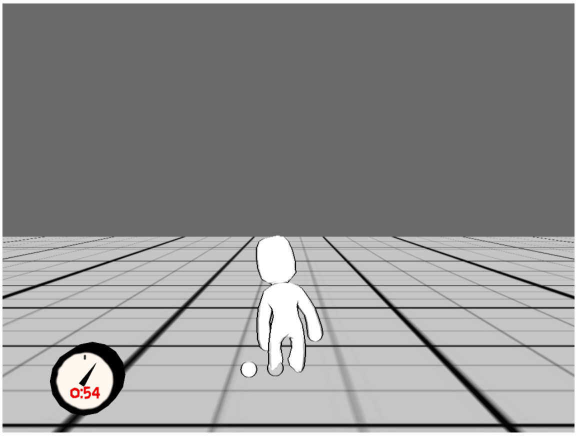

Figure 4.9: *The Lateral Movement VEE. A target can be seen to the left of the player's avatar.*

In practice, each VEE requires one specific implementation to be created. To obtain it, the exercise's logic, simple graphical elements, one or more input devices, a rendering engine, and an output device are required. During this transformation we also define a suitable set of input devices that can fulfill the needed tracking requirements. Each VEE should also already support all the features that are required to provide effective rehabilitation. Thanks to the structural definition of each exercise we can easily implement multiple exercises inside a single VEE, using conditional logic to support the different exercises or sub-exercises. Additional details on the implementation of VEEs can be found in section 5.5.

We must note that VEEs, due to their virtual nature, impose some constraints on what games can be assigned to them. As an example, each VEE is related to a specific virtual point of view, from which the patient sees the virtual scene. A VEE with a third person point of view, seen from behind, can only support exercises that require a lateral or up-down movement, but no front or back movements (as is the case with our *Lateral Movement VEE* of figure 4.9). However, these same constraints allow us to design interesting games: this is the case of *Fruit Catcher*, whose falling-fruit fantasy is only possible due to the specific point of view of the VEE it is related to. According to this approach, we can also create VEEs that support all the exercises of another VEE but also support additional exercises by just changing the virtual point of view. This is the case with our *Over-the-shoulder Movement VEE*, which places the player's point of view above the avatar's shoulders. On the other hand, the *Over-the-shoulder Movement VEE* poses as a constraint that no graphical element should be placed above the avatar in order to not hide its movements, and we thus could not link it to *Fruit Catcher*. At last, we remark that multiple games can be created for a single VEE, effectively allowing many games to be used for the same exercise.

4.1.5 Posture and Balance VEEs

For posture and balance rehabilitation, we defined the following VEEs. In order to track all the movements needed by the exercises, we chose as input devices the Nintendo Wii Balance Board and the Microsoft Kinect for all involved VEEs. The balance board is used to track the patient's center of pressure, and its accuracy is useful for weight shifting exercises. We instead use the Kinect sensor to track full-body motion of the patient, enabling us to track patient posture and the movement of the legs, needed to detect steps and sit-to-stand motion.

Stand Still VEE

This VEE is concerned with the simplest class of exercises for posture and balance: those we termed *Stand Still* exercises. This VEE does not actually require active movement from the patient, as the exercises it supports only ask the patient to stand still. We track the patient's full body movements and define a generic threshold of movement for all body parts, checking that the patient does not exceed it. We also track the patient's COP and define limits for it as well. In practice, we define a trial for this VEE as a period of time for which this threshold must not be surpassed. Each trial is passed if the movement of the patient does not surpass the given threshold for the required amount of time. The point of view selected for this VEE is in third person with a humanoid avatar seen from behind, so that the patient can check her posture through an avatar that mimics her movements and correct if needed.

Lateral Movement VEE

This VEE supports *Weight Shift* exercises (by monitoring that the patient does not move her feet but just shifts her weight, using her COP to touch the targets) and *Step* exercises (by monitoring that the targets are reached using the patient's feet). The selected point of view is again a third person view seen from behind through a 3D humanoid avatar. This limits the exercises that can be supported to sagittal exercises, but allows clear feedback on posture. We define a trial through targets that appear to the left or to the right of the patient's avatar. These targets need to be reached for a trial to be considered a success.

Over-the-shoulder Movement VEE

This VEE supports *Weight Shift* and *Steps* exercises as well, but we use an over-the-shoulder point of view so that the humanoid avatar can still be seen, while also enabling the support for front-back exercises. Note that the above view, however, makes it harder to read the posture of the humanoid avatar; a tradeoff is thus made between clarity of feedback on posture and of front-back distances. Targets appear around the patient's avatar according to the exercise's action sequence.

Above Movement VEE

This VEE supports again *Weight Shift* and *Steps* exercises. The point of view is from above, but the avatar is an inanimate object instead of a humanoid avatar. This enables us to achieve a view from above, allowing maximum clarity of actual distances. However, we cannot show feedback on the patient's posture, if not with additional feedback elements. In this VEE, targets appear around the patient's avatar according to the exercise's sequence.

Sit-to-Stand VEE

We created this VEE to support *Sit-to-Stand* exercises. As such, the point of view is a third person from behind, useful to correctly understand the upwards movement. This VEE, in addition to the input devices, requires a chair. This requirement is reminded to the patient in a specific setup scene. Targets appear at the height of the patient's head, so that the patient must be standing to hit them. These are alternated with lower targets, asking the patient to sit.

Lift Legs VEE

We at last created a VEE to specifically support *Lift Legs* exercises. Once again, the point of view is in third person from behind. In this VEE, targets appear above the avatar's foot, so that the patient needs to rise her foot to touch them. An additional target appears on the ground when the foot is in the air, prompting the patient to complete the step.

4.1.6 From Virtual Exercise Environments to Exergames

The last step is to dress each VEE with gaming characteristics, and thus create complete exergames. By adding visual feedback and scores related to the VEE, we provide an artificial conflict as well as a quantifiable outcome, performing an initial transformation of the VEE into a game environment. By also introducing graphics and sounds, we provide a fantasy, further reinforcing the playful nature of the environment. In practice, when a single exercise is selected to be performed inside a VEE, and the game coat is placed over the VEE, we finally obtain an exergame.

We remark that, following this pipeline, the same game is not tied to a single exercise, nor is an exercise tied to a single game. For example, the *Fruit Catcher* game can be played with the *Lateral Weight Shift* exercise, or with the *Lateral Steps* exercise. On the other hand, the *Lateral Weight Shift* exercise can be performed either alongside the *Fruit Catcher* game, or alongside the *Fire Fighter* game. This many-to-many relationship allows more games to be played for a single exercise, and thus increases motivation. It also allows multiple exercises to be performed while playing a single game, with a subsequent reduction of required development resources. Note that only by neatly separating the game from the exercise we were able to provide this many-to-many relationship, further reinforcing the need for this separation.

4.2 Designing Games for Posture and Balance Rehabilitation

In this section, we detail the nine games we designed and developed for posture and balance rehabilitation. Before getting into the details of the specific games, we explain in general terms design methods and choices common to all of them.

We designed all games using an iterative prototyping technique [177]. According to this method, based on the requirements of the VEEs, we created initial prototypes of the games that would represent an unrefined version of the final ones, but with mechanics and feedback fully implemented.

These prototypes were shown to post-stroke patients in multiple occasions, allowing them to try the exergames (see chapter 8). The prototypes were also tested with non-impaired people (adults, elders, and children alike) at several events and exhibitions, such as at *PlayModena* in Modena, Italy, at *MeetMe Tonight: Notte dei ricercatori* in Milan, Italy, and at *ICT 2013* in Vilnius, Lithuania. We collected feedback during these sessions, which was then used to improve the games by making the goal of the game more obvious if unclear, by improving the graphics where needed, or by changing additional parameters to improve usability, such as camera viewpoints or virtual object sizes. The steady use of feedback allowed us to leverage the MDA approach to game design [85], making sure that feedback regarding the *aesthetics*[1] of the game would reflect in a correspondent change in mechanics.

All the games we designed follow the guidelines we previously addressed to increase their motivational effect under the constraints of exergaming and with an eye on the elderly population. In general terms, we address the game design guidelines as follows. We create all games keeping *meaningful play* in mind, and we thus design clear, immediate, and simple interactions. A good degree of *challenge* is achieved through automatic on-line parameter adaptation, for which we refer the reader to section 6.3. *Curiosity* is instead triggered through the selection of exergames and the variations of the underneath exercises, through randomized surprises (which have no in-game effect), and with graphical variations introduced through PCG (see section 7.1).

As our *shared fantasy*, we chose the theme of *farm life*: all games involve activities such as picking fruits from trees, driving a tractor, or scaring crows in a field. We feel that the farm life theme can resonate with the target patient population, i.e. people in the range of 65 to 75 years, due to their possible experience with a rural environment during youth. In addition, farm life is known to be peaceful and relaxing, while at the same time it requires hard work. We believe this can suggest a sense of duty to the rehabilitating patient, increasing adherence. Farm life follows the slow times of yearly crops and of the seasons and is thus a good candidate as a theme for our games that need to be played for several months, hinting at the long-term nature of rehabilitation. At last, farm life deals with the growth of plants and animals, with life and growth being the reward of hard work. We feel this can be a good metaphor for rehabilitation and training, where the patient is required to exercise intensively to recover her lost functions. To provide this fantasy, we focus on aesthetics instead of narrative,

[1]The meaning of *aesthetics* here is considered in light of [85].

as the single-focus of the exergames makes it hard to add narrative content, while aesthetics can be more easily incorporated. From the responses on the usability and acceptance tests we conducted, we realized that the farm theme was indeed a good choice.

Regarding *sensation*, we designed the game's graphical style to be easily interpretable and thus highly accessible even for elderly people. To do so, we use bright, saturated colors and simple textures with little detail in order to not distract the patients from their tasks. The graphical style thus follows a cartoon appearance, reminiscent of the games published by Nintendo and known to be popular with people of all ages. The use of this graphical style also made it easier to obtain a good quality and thus increase the appeal of the games. This style was well-received by all kinds of players, from children to elderly patients.

Features that do not depend on the actual games, such as a scoring mechanism and extrinsic rewards, are at last included into the higher-level system (see chapter 7).

4.2.1 Scare Crow

We created the *Scare Crow* game (figure 4.10) to provide a suitable fantasy for *Stand Still* exercises, and it is thus built over the *Stand Still VEE*. In *Scare Crow*, the patient sees herself under the guise of a scarecrow placed in the middle of a crop field.

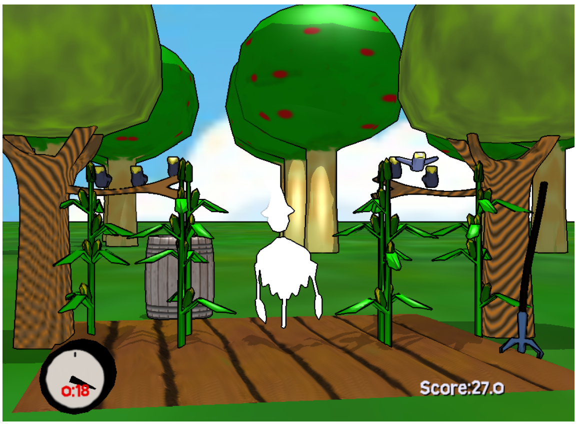

Figure 4.10: *The Scare Crow game, played here using the Stand Still exercise.*

The player controls the scarecrow as an avatar using a third person viewpoint. After a while, a few birds start flying from the sky towards the trees placed around the field. One after the other, all the birds fly towards the scarecrow, resting on its arms and shoulders. If the player moves while a bird is flying to her avatar, the bird is scared and flies away and the player loses points. If the player stands perfectly still, the bird feels safe and lands on the player, netting her some points. To add a surprise element, once in a while a larger and differently colored bird appears, although this has no effect on the gameplay.

This game represents a good fantasy for standing still, as the avatar has no feet and is actually an inanimate object, thus suggesting that it should not move. In addition, real birds are easily scared by movement, again reinforcing the fantasy. However, after initial feedback, which pointed out the possible inconsistency of the game's goal (a real scarecrow would try to scare the birds away), we changed the avatar to an animated tree.

4.2.2 Fruit Catcher

Fruit Catcher (figure 4.11) is the first game we designed and it has been a patients' favorite since the first day.

Figure 4.11: *The Fruit Catcher game, played here using the Lateral Weight Shift exercise.*

We initially designed this game to accommodate *Lateral Weight Shift* exercises, and we then expanded it to support *Lateral Steps* exercises. As such, the game was built upon the *Lateral Movement VEE*, the player sees herself from behind under the guise of a 3D humanoid avatar.

In the fantasy of the game, the player takes the role of a farmer that must pick apples from a tree to fill a basket. The apples spawn on the tall tree and the player's avatar cannot reach them with its hands. Instead, the avatar has a small basket on its head, which is used to catch the falling apples before they touch the ground. At each game trial, a small apple appears on the tree, grows, and then falls down. If an apple touches the ground, the trial is considered a failure. If the player manages instead to catch the apple with the basket, by moving either left or right depending on where the apple will fall, the trial is considered a success. To add a surprise element, once in a while a worm falls out of an apple after it is successfully caught, disappearing into the grass.

Following feedback after testing with the initial prototype, this game received only small changes, such as changing the shape of the tree or adding animated objects around the environment to increase visual variety.

4.2.3 Fire Fighter

In the *Fire Fighter* game (figure 4.12), the player sees herself as a 3D humanoid avatar inside a barn, surrounded by hay bales. Due to the high temperature, the hay may catch fire and small flames may appear around the player. The player must reach the fire to extinguish it.

Figure 4.12: *The Fire Fighter game, played here using a 360 Steps exercise.*

We created the game over the *Over-the-Shoulder Movement VEE*. Thanks to its view, the game can support lateral, front-back, and 360 exercises alike. It can work with *Steps* exercises (and the player steps over the flames) or *Weight Shift* exercises.

Following feedback from patients, we progressively tuned the point of view of the virtual camera to make sure the scene was clear enough, and we increased the size of the flames. We also added a small shade under the feet of the avatar, so that it is easier to see where the foot is while playing, which is made more difficult by the non-frontal point of view.

4.2.4 Bubbles Burster

We created the *Bubbles Burster* game (figure 4.13) with neglect rehabilitation in mind, but we also adapted it to posture and balance rehabilitation. The player is here represented by a stick inside a cauldron. The aim of the player is to burst bubbles in the cauldron using the stick. According to the chosen exercise's action sequence, bubbles appear as targets on the surface of the liquid at different positions.

Figure 4.13: *The Bubbles Burster game, played here using a 360 Weight Shift exercise.*

The game was designed for the *Above Movement VEE*. As such, it supports lateral, front-back, and *360 Weight Shift* exercises.

Following feedback, we increased the size of the bubbles and changed the point of view to make the interaction easier.

4.2.5 Hay Collector

In the *Hay Collector* game (figure 4.14), the player sits in a tractor that can be seen in the middle of the screen. The tractor automatically travels forward on a plain field, determining the pace of the game, and the player controls the steering wheel of the tractor, directing it around the field. The goal of the player is to steer the tractor in order to hit the hay bales scattered around the field. Each trial in this game is related to one hay bale: if the hay bale is surpassed without hitting it, the trial is considered a failure, while if the hay bale is hit, the trial is considered a success. Due to the dynamic nature of the game, it was well received by patients.

The game was introduced in our collection to provide a more dynamic environment for *Weight Shift* exercises. The game is thus built over the same VEE supported by *Fruit Catcher*, i.e. the *Lateral Movement VEE*.

Figure 4.14: *The Hay Collector game, played here using the Lateral Weight Shift exercise.*

The initial version used a semi-realistic control scheme: the tractor had inertia, and the steering wheel controlled its lateral acceleration, effectively creating a second-order relationship between the player's input and the position of the tractor. The feedback we received from patients and therapists using this control scheme was not good, as the patients (and the therapists themselves) had some trouble controlling the tractor and directing it where they wanted. The inertia of the system made things even worse, also considering the slight delay introduced by the input devices. For this reason, the game was made simpler: the input of the patient now directly controls the steering angle of the tractor, effectively reducing the interaction to a first-order relationship. This resulted in a more enjoyable game, allowing us to also make the relationship between the game and the underlying exercises more direct.

4.2.6 Horse Runner

The *Horse Runner* game (figure 4.15) places the patient's avatar on the back of a galloping horse in the middle of the woods which follows a pre-determined cleared path among the trees. The path is filled with low branches, which must be avoided lest a failure is registered, and floating honey jars, which must instead be collected to obtain a successful trial. Due to the dynamic nature of the game, Horse Runner was well received by patients.

We created Horse Runner explicitly for the *Sit-to-Stand VEE* and it thus supports sit-to-stand and stand-to-sit exercises. The fantasy of riding a horse allows such exercises to be intuitively performed, since it provides

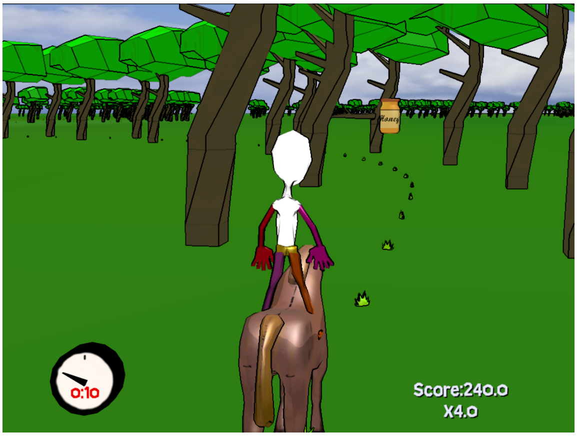

Figure 4.15: *The Horse Runner game, played using the Sit-To-Stand exercise.*

a reason for sitting and affords standing up from the horse as a plausible action.

In the initial versions of this game, the speed of the horse was controlled by the patient's actions. This was however seen as unintuitive by patients and therapists alike, and the option has thus been removed, once again creating a simpler interaction.

4.2.7 Animal Hurdler

We created the *Animal Hurdler* game (figure 4.16) to support stepping exercises. We thus built the game over the *Lift Legs VEE*. In the game, the player sees herself as a humanoid avatar viewed from behind while small creatures (worms and snakes) travel towards the avatar's feet. The player needs to raise her left or right feet to avoid hitting the creature, and when a creature is successfully stepped over (or hit, resulting in a failure), the avatar advances alongside a pre-determined path.

4.2.8 Wheel Pumper

In the *Wheel Pumper* game (figure 4.17), the player sees her humanoid avatar in front of a large tractor. One of the back tires is flat and it is connected to a pump which must be operated with a rising and lowering motion of the player's leg. When the player successfully rises and then lowers a leg, a trial is completed successfully. The game is thus built over the *Lift Legs VEE*.

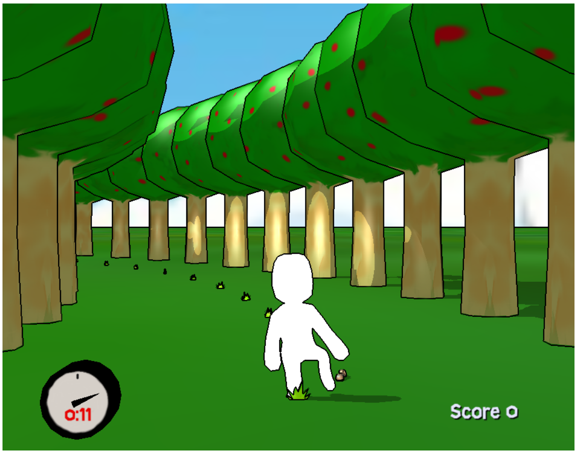

Figure 4.16: *The Animal Hurdler game, played using the Lift Legs exercise.*

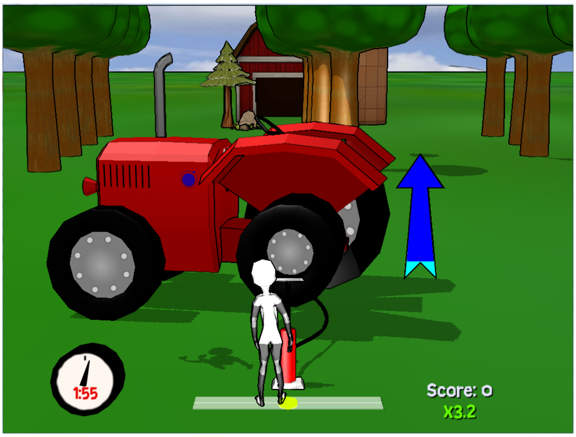

Figure 4.17: *The Wheel Pumper game, played using the Lift Legs exercise*

4.2.9 Balloon Popper

In the *Balloon Popper* game (see figure 4.18), the player controls a cursor in the middle of the screen and tries to pop the balloons that fly around. When a balloon is reached, a trial is considered successfully completed.

We initially designed the game for upper-limb rehabilitation and later adapted it to support the *Above Movement VEE*.

Figure 4.18: *The Balloon Popper game, played with a Weight Shift exercise.*

CHAPTER 5

IGER: a Game Engine for Rehabilitation

In this chapter, we present our work on the design and development of a *game engine for rehabilitation*, a solution we devised to support the development of multiple, coherent exergames, focusing on autonomous home rehabilitation. We used the engine to develop the exergames we presented thus far, following a specific set of requirements: we should create a complete set of exercises for post-stroke rehabilitation of balance and posture, the exergames and the system should be used autonomously by elderly patients in their own home during daily sessions, the therapist should be inserted into the loop through remote and asynchronous supervision, and we should focus on low-cost solutions.

5.1 The Need for a Game Engine

We remind the reader that our goal is to provide a complete rehabilitation therapy, and for this reason we need a complete set of exergames. Instead of creating each exergame from scratch, and thus develop the same solutions for each exergame, a more orderly approach can be taken: the exergames can be developed as a coherent system, designing general solutions to address the shared requirements and getting into the specifics of each exergame where needed.

With this work, we decided to make an additional step forward and design a complete *game engine for rehabilitation* instead of just a closed set of exergames. A game engine is a set of tools, or a framework, that helps in the development of games: it provides the developers with the base components of game creation, such as graphics rendering, collision handling, and multiple deployment platforms support, allowing the developers to focus on the details of the gameplay. New games created with a game engine can make use of the existing features of the engine. The latest years have seen the advances of full-fledged but reasonably priced game engines such as the popular Unity3D[1] game engine, which allowed small teams of game developers to enter the gaming industry, which in turn made engines even more common. Research can benefit from the proliferation of game engines as well, as small teams can now develop complete games while achieving good production values.

The use of a game engine comes however with a couple of drawbacks. On the one hand, the ease of creation of games comes with less flexibility, as they need to abide to the rules of the whole framework. In our case, since we were able to accommodate all of the exercises under a generic structure, this has not been an issue. On the other hand, the development of a game engine instead of a single game catered to the specific exercise takes more resources upfront, although a lot of time is saved in the long run as new games are added.

Simply using a game engine is not enough to make sure that all the exergames that are created with it also provide effective rehabilitation. What we truly need is a game engine *specifically tailored to rehabilitation*. For this reason, alongside the capabilities of a standard game engine, our software architecture accommodates all the features that are needed to support effective rehabilitation. In the context of home rehabilitation, the important figure of the therapist is missing, and we thus deemed the presence of a virtual *backup* of the therapist a necessity, introducing the *Virtual Therapist* (VT) into our architecture. The VT takes the role of the real therapist in her absence, following the patient during the rehabilitation session, providing motivation, instructions, monitoring, and whatever else is needed for a safe and correct at-home therapy, leveraging artificial intelligence techniques to provide all the needed features.

[1] http://unity3d.com/

5.2 IGER: the Intelligent Game Engine for Rehabilitation

Following the need for a game engine to support the requirements of rehabilitation, we designed the *IGER* system: *the Intelligent Game Engine for Rehabilitation*. IGER is built upon the open-source game engine Panda3D[2] and can thus be used to create and run games, but, due to the presence of the VT and by reinforcing our common exercise structure, it also supports effective exergames for rehabilitation.

The architecture of IGER is shown in figure 5.1. The IGER system is composed of two parts: the game engine itself (A) and the VT (B). At a given time, the game engine runs the current exergame (A1) and the engine collects inputs, runs the exergame's logic, renders the virtual environment, and provides game-related feedback. Patient inputs are provided by different tracking devices and are mediated by the IDRA module (A2) that performs an abstraction to support many different devices. The recording module (A3) saves the tracked data into local files. The exergame is shown to the patient through an output system (A4), such as a display and, eventually, through the input devices themselves (as is the case with haptic devices). At the start, the end, or in-between exergames, the patient interacts with the menu system (A5), used to check patient progression and introduce exergames. A score system (A6) is tied to the results of the exergames, and is used to show to the patient her progression in a specific menu scene. The reward system (A7) is tied to the score system and can be accessed through the menu system as well. The procedural content generation module (A8) provides the methods to implement variations inside exergames and in the reward system.

The VT oversees each exergame, providing the functions needed for effective rehabilitation such as on-line monitoring (B1) and on-line adaptation (B2). It also motivates the patient and guides her in the navigation of the menus, communicating through the feedback system (B3), or through the Virtual Therapist Avatar (B4).

As our system is built to support asynchronous supervision, configuration (C1) as well as assessment (C2) are not automated, and are instead connected through the internet to the therapist stationed at the Hospital Station.

IGER is built upon an existing 3D game engine. The 3D domain was chosen because we wanted to create full three-dimensional virtual environments inside which the players can interact in a natural way. We chose to use the Panda3D engine as the basis on which we developed IGER as it is

[2] https://www.panda3d.org/

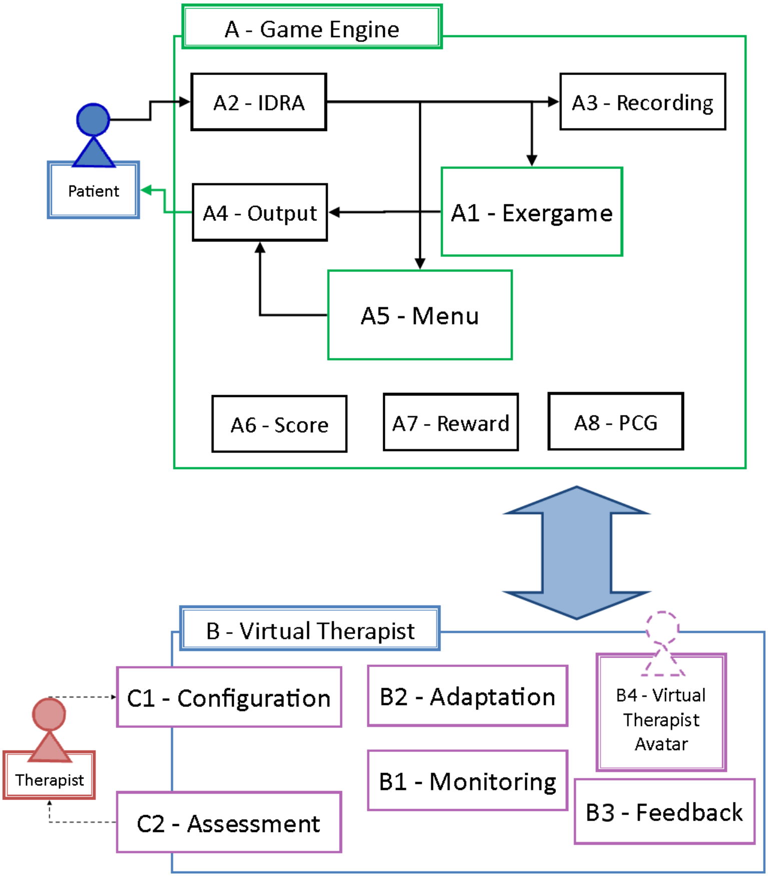

Figure 5.1: *An overview of IGER and its Virtual Therapist.*

open-source and thus completely modifiable, which is useful because the transformation of the engine to a game engine for rehabilitation cannot be limited by the features of the base game engine. Also, Panda3D is free for any use, which allows us to consider publishing our modified game engine for rehabilitation as open and free software. In addition, Panda3D has an active community that is always eager to give help where needed and that is still supporting and updating the software with the newest discoveries in game engine development. We developed all the modules needed by our architecture using the Python programming language and integrated them into the Panda3D engine. Where needed, due to performance reasons or to language requirements, we wrote C# libraries (to use the Kinect SDK) and C++/C libraries (to leverage CUDA capabilities).

In the remainder of this chapter, we describe the components we developed inside IGER to enable the creation of effective and usable exergames for rehabilitation: input abstraction, user interface, exergame abstraction, data tracking, and configuration. The next chapter instead goes into the details of the modules tied to the role of the VT: on-line adaptation, on-line monitoring, patient feedback, and the VTA. We complete this description in chapter 7 with methods built into IGER to address long-term patient motivation.

5.3 Input Abstraction

We first address the issue of multiple-device support as interaction is the basis over which the rest of the platform is built. As we previously noted, exergames for physical rehabilitation present very varied tracking requirements, in comparison to traditional entertainment games, as well as strict accessibility requirements. Special hardware, capable of supporting such requirements, should thus be preferred. However, as we aim to design a game engine and not a single exergame, we also need to support efficient development of exergames for different conditions. This is very important for post-stroke rehab, as patients may possess very different impairments, but is also relevant to the support of radically different pathologies. For these reasons, instead of focusing on integrating a single device, we designed an architecture that supports several different devices.

5.3.1 IDRA: Input Devices for Rehabilitation Abstraction

To support multiple devices for multiple exergames in a flexible way, we designed and developed an abstraction layer between the input devices and the exergames. Our abstraction layer supports multiple input devices with the possibility to use them together in the same exergame. This allows the therapist to choose the devices that best suit the patient's condition and better support the specific therapy. An abstraction layer allows us to avoid conflicts between devices and to be able to play all exergames regardless of the chosen input device (under reasonable limits). We dubbed this abstraction layer *Input Devices for Rehabilitation Abstraction*, or IDRA.[3]

IDRA achieves separation between the games and the input devices used (i) to play those games, (ii) to monitor constrained movements, (iii) to navigate the interface, and (iv) to collect and record input data.

IDRA is composed of one *input manager* and an *input handler* for each supported device.

5.3.2 The Input Handler

The *input handler* functions as an abstraction, representing a generic device, so that the system can communicate with an input handler without knowing the details of the device it is abstracting. Each handler achieves abstraction of the device it supports through inheritance. We developed one handler for each device we support (for example, a Kinect handler for the Kinect sensor), and each specific handler is responsible for managing all aspects of its input device: it handles connection and disconnection, calibration, position checks, and holds information on the device's physical setup. Each device is also tied to record and playback functions (see section 5.6). Handlers expose common methods related to all these functions, so that the system can access them in an abstract way, regardless of the actual physical device. Runtime behavior is controlled by a Finite State Machine (FSM), which controls whether the handler is in a *disabled*, *setup*, *connected*, *calibrated*, or *ready* phase.

5.3.3 The Features Request System

We need a reliable way to support many different devices for use with different exergames, from visual trackers, to pressure sensors, to haptic devices. However, an exergame cannot know beforehand if the chosen input device can support the needed capabilities. We thus designed a system for pairing the exergames with the input devices' capabilities in an abstract way: the feature request system.

With the term *feature*, we refer to any single stream of data tied to the device. This can be, for example, a 2D or 3D position, a measure of the

[3] *Idra* is the Italian name for the Lernean Hydra of ancient Greek mythology, a reptilian monster that could grow multiple heads from severed ones, a fitting metaphor for our abstraction layer.

patient's COP, a video stream, and so on. We separate features into input and output features: input features regard the streams of data that go from the device to the application (positions, rotations, sensor values, applied forces, etc.), while output features regard the streams of data that go from the application to the device (LEDs, sounds, vibrations, force feedback).

Features are defined inside input handlers and can be requested at any time by the application code. For each supported feature, the handler creates an instance of the *Feature* class that holds all the requests made to it (initially, none). A specific feature can be requested by name to an input handler and the request is fulfilled if the feature is available, adding the request to the feature's request list. This also links the feature's output stream to the callback specified by the request. When enabled, the input handler is pooled periodically at runtime and is tasked with collecting raw input data, process the data into values corresponding to the features, and route these values to the eventual callbacks.

Input features are requested with the following parameters:

- Feature: the name of the feature to be requested (*Pos* for position, *Rot* for rotation, *Cop* for center of pressure, etc).
- Callback: the function the data stream corresponding to the requested feature is routed to.
- Affine: the output affine matrix the data will be filtered with, if needed.
- Extra Parameters: parameters that are passed to the callback.
- Rollback Feature: the feature that should be used if the requested one is not available.

Output features are requested in a similar way, but they do not need any callback.

Note also that any feature can be unregistered at any time to free memory and computational power, and that features that are not explicitly requested are disabled by default.

Our system makes extensive use of feature requests during the initialization of exergame: these are made by the exergame through its avatar, which requests features related to the motion needed to animate it and interact with the virtual world. Feature requests are however not limited to avatars, and are made throughout the whole application when needed, for example to navigate the menu scenes.

As an example, the *Fruit Catcher - Lateral Weight Shift* exergame can be played either with the Microsoft Kinect or the Nintendo Wii Balance

Board, among other input devices. The exergame shows a 3D avatar in third person, which requires two features: the position of the player and the orientation of her body segments. The exergame requests these features to the specific input handler, chosen at configuration time. If using a Kinect handler, both features are available and the player will see her avatar mirroring all her movements. If using the Wii Balance Board handler, however, orientations are not available. The exergame then rolls back to a simpler feature, 2D positional input, using it to interpolate between pre-defined skeletal animations.

5.3.4 The Input Manager

The *input manager* is a singleton class responsible for setting up, organizing, and potentially deleting the input handlers that are requested to it. By reading the configuration of the current session, the manager retrieves the unique IDs associated to the chosen input devices and creates one handler for each of them. The manager also connects to the navigation device (as chosen through configuration) and starts logging its data. After the first exergame configuration is loaded, during a specific setup scene, the manager checks which devices need to be setup and which need to be disconnected (or even removed from the playing area). During this phase, the newly setup devices are connected and initialized. As each exergame starts, it requests the needed features to the input handlers based on the nature of the exergame itself. When the last exergame for the current session ends, all devices are disconnected.

5.3.5 Device Roles

Through configuration, one device can be assigned to one or more *roles* which determine how the device is used throughout the application. Due to this, the choice of what device to use is completely abstracted from the actual exergame implementation. A device may be assigned to one of the following roles: gameplay, monitoring, logging, and navigation (see figure 5.2).

Gameplay

A device assigned to the gameplay role is used by the patient to interact with the virtual game world. This device controls the player's avatar. The gameplay role is configured independently for different exergames and there also may be more than one device assigned to the same exergame, if it has multiple avatars. The devices are assigned in sequence, with the first configured

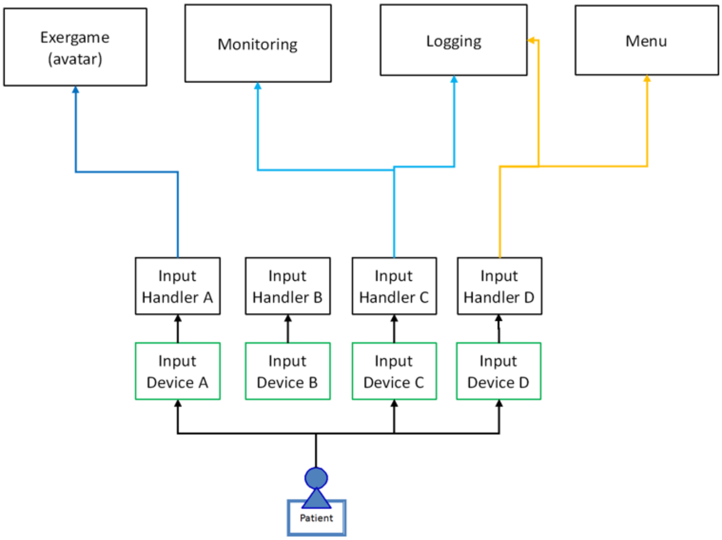

Figure 5.2: *An example of device roles assignment. Device A is assigned to the exergame's gameplay, device C is used both for monitoring and for logging its data, while device D is used for menu navigation and for logging its data. Device B is not used at all.*

device assigned to the first avatar, the second configured device to the second avatar, and so on.

Monitoring

A device assigned to the monitoring role is used during the exergame to monitor the patient's movements (see section 6.1). The role may be configured independently for different exergames and there may be more than one device assigned to the same exergame, if it has multiple monitors. The devices are assigned to the different monitors in sequence and checked for support as follows: for each configured monitor, the corresponding feature is requested to the first device; if the device can support the feature, then the feature is assigned to it, otherwise the request will be passed to the next device, until no more devices are available. Features that cannot be supported by any of the devices are ignored and a warning is logged.

Logging

If a device is assigned to the logging role, all its data streams are logged into binary files that may be used for playback or assessment. Multiple devices can be logged at once. Refer to section 5.6 for further information on logging.

Navigation

One device must be assigned to the navigation role and it is used to navigate the PS interface. We refer to section 5.4.3 for further information on the navigation methods.

5.3.6 Supported Devices

From the literature, we gather that there can be many different choices as interaction devices for physical rehabilitation exergames. Our choices are dictated by the following criteria. Input devices should, first of all, be useful for **tracking** the needed movements to perform correct rehabilitation. We aim for **off-the-shelf** devices, referring to devices that are readily available on the market, making their use more maintainable as they can be safely replaced with new purchases should a device malfunction. Their market presence also makes the hardware more stable, guaranteed throughout heavy testing. As mentioned in our introduction, the rise of **low-cost active gaming** devices produces a golden opportunity for rehabilitation, and we thus focus on these devices. At last, we aim for **non-intrusive** devices, and we made this choice for accessibility reasons: the patient should be able to play freely, without the need for a troublesome physical setup. For this reason, we avoid wearable devices. At last, we aim for devices that can support **natural user interfaces**.

Aided by our abstraction layer, we support many different devices. We integrate our system with balance boards (specifically, the Nintendo Wii Balance Board, of which we proved the accuracy in [59]) camera sensors (the Microsoft Kinect sensor and the LEAP Motion Controller[4]), and haptic devices (the Novint Falcon[5]). By request of therapists, who found the Nintendo Wii Balance Board to be too thick for it to be considered safe for autonomous rehabilitation, we integrated as an alternative the Tyromotion Tymo platform,[6] although the device misses the low-cost and off-the-shelf criteria. For research purposes, we integrated the system also with pressurized insoles[7] and additional haptic devices.[8]

We focus our discussion on the Microsoft Kinect, as it has revealed to be a powerful device for rehabilitation purposes and we used it with most

[4] www.leapmotion.com
[5] www.novint.com/index.php/novintfalcon
[6] tyromotion.com/en/products/tymo/overview
[7] Moticon OpenGo Insole Sensor System (www.moticon.de/en/system/sensor-insole)
[8] Phantom Omni (www.dentsable.com/haptic-phantom-omni.htm)

of our posture and balance exergames.

The Microsoft Kinect Sensor

The Microsoft Kinect sensor is capable of real-time whole-body motion tracking and audio recording [181]. It was released in November 2010 to be used with the Xbox360 gaming console as a natural input device for its games, betting on a hands-free paradigm. The result is an advanced sensor at a low cost (currently around 120 €). Many games were published for the console that made use of the Kinect's capabilities, allowing players to use their whole body to play. In early 2012, the Microsoft Kinect was also released for the Windows platform with a license for use in commercial software at a higher price tag (around 250 €), in an attempt by Microsoft to allow developers to create a market of Kinect-enabled applications not strictly related to gaming. In late 2013, the Kinect for Xbox One was released, bundled with the new console, as an improvement over the first Kinect. Despite the power of the hardware, the Kinect has thus far been far from the success Microsoft had hoped, at least for what concerns the gaming market, to the point that Microsoft decided to now ship the Xbox One without a bundled Kinect [66].

Thanks to its capabilities, the Kinect has been a recent favorite in research. A recent review on its use in elderly care identified 48 studies where the Kinect is used for fall detection and prevention, rehabilitation and/or exergaming [205]; during our review we counted, in 2013 only, 19 papers that use it as a foundation for new rehabilitation exergames.

We chose the Kinect as the main device around which we developed most of the exergames for posture and balance rehabilitation. The device fulfills all of our criteria, providing a low-cost and hands-free approach to exergaming, while also guaranteeing the correct tracking of multiple exercises with good accuracy. The sensor was indeed proven to be accurate enough for rehabilitation purposes [143, 153]. In addition, its speech recognition capabilities prove useful for use with interface navigation.

As we mentioned in section 2.3, camera tracking devices have issues with light conditions and occlusions, and the Kinect suffers from these problems [143]. Indeed, during our tests with patients the most common failures were related to foreign objects in the play space (such as a chair) or direct light from a window. For this reason, initialization procedures should be well designed to minimize these problems, and patients should be trained correctly to avoid such situations.

To take advantage of the Kinect's capabilities in our Panda3D environment, we developed a library, first written in C++ and then converted to C#, that makes use of the official Microsoft Kinect SDK[9] and is usable through Python by using the Python.Net extension module.[10] Our library provides a full wrapper around the SDK capabilities, as well as improvements made on skeleton joint orientation estimation, tilt compensation, player selection, automatic calibration, color-to-depth mapping, and CUDA-enabled player silhouette smoothing (see figure 5.3).

Figure 5.3: *The smooth silhouette of the player extracted from the background using our method in [158].*

5.4 The IGER User Interface

In this section, we detail our design of IGER's graphical user interfaces, interaction modalities, and scene flow. The glue that ties the whole interface together is its focus on accessibility, as requested by our guidelines. Our system thus shows a clear graphical design, uses NUIs extensively both for menu navigation and for the gameplay, it is based on hands-free gaming devices for interaction, and is configurable for each patient. The current interface of IGER is the result of continuous prototyping and testing with elders, post-stroke patients, and therapists, in order to make the interface as accessible and usable as possible.

[9] www.microsoft.com/en-us/kinectforwindows/develop
[10] pythonnet.sourceforge.net

5.4.1 Graphical User Interface

Our graphical user interface (GUI) is designed to provide clear and immediate feedback, using a simple and consistent color scheme, as well as requiring only little user input. Moreover, we chose a colorful design to maximize the attractiveness to the patient and to be coherent with our games' graphical design, while still maintaining a clear style to avoid overwhelming the patient with visual noise.

In a typical scene, the graphical interface presents information through clear text notifications, while a set of buttons is placed in the lower half of the screen with the actions the patient can take. For accessibility reasons, we favor a deep interface design, with multiple screens showing only a few select buttons, as opposed to a wide interface design that shows more buttons in the same scene and is thus harder to navigate [2].

All GUI elements share a consistency in style by design: all text is surrounded by a light blue background, and all buttons possess a dark blue inner background. Buttons are triggered through a hovering motion: when hovered, a button gets bigger to acknowledge the interaction and help in maintaining the focus; after a short filling animation, the button is triggered and the associated action (usually a change of scene) is performed. Where possible, we use small icons to signal specific concepts to the user. For example, each game and each exercise is assigned a specific icon, so that they are easily recognizable in the menus. Note that in most scenes the Virtual Therapist Avatar (VTA) is also present (see section 6.2.3). We based our GUI implementation on Panda3D's *direct GUI* system, adding to it a set of common utilities and a consistent thematic style. Examples of our scenes can be seen in figure 5.4 and 5.5 where all the interface elements are recognizable.

5.4.2 Scene Flow

In this section, we detail the design of the flow of scenes that patients pass through when using the Patient Station (PS) during a typical session. We remark that any of these scenes, apart from the exergame, can be disabled by the therapist through configuration, so that she can select what information is shown to the patient.

The **setup scene** is an utility scene shown to the patient before any exergame starts or when the system is first started. This scene is responsible for connecting and initializing all the devices that will be used during the next exergame. It supports automatic calibration, if the devices require it, for example, by measuring the patient's weight with a balance board or the

Figure 5.4: *The game introduction scene, showing how the exergame will look like when started.*

Figure 5.5: *The schedule scene, listing the exergames that will be played for the current session.*

patient's height with the Kinect. It also handles the physical setup of the devices, for example by asking the patient to place (or remove) a pressure board or to make sure that the sensors are correctly placed. Following feedback from patients and therapists alike, we designed this scene to require the least amount of input from the patient, performing all the calibration and connection checks in the background and asking the patient to act only if strictly needed, and we guide the patient with visual and audial feedback to do so. We thus reduced the time needed to setup the exergames while making sure to setup everything correctly, increasing the accessibility of the whole application.

The **welcome scene** informs the patient about the progression of her rehabilitation and functions as a daily welcome. Icons for the last days are color coded according to the tendency of the rehabilitation: a blue rectangle signals that a session was completed, a gray rectangle that there was no schedule for that day, and a red rectangle that a session was not completed. In the middle of the scene, we show a graph representing the rehabilitation progression, using the daily performance of the patient as data: a green rectangle signals positive performance, a red rectangle signals negative performance, and a yellow one signals average performance. The VTA comments on the current progression, congratulating on a good performance streak and inciting the patient if performance is low.

The **farm scene** is tied to the reward system (see section 7.4). It shows through 3D graphical elements what the patient has achieved, functioning as a graphical reminder of the rehabilitation progression. From this scene, the patient can continue to the current schedule or go back to the previous scene.

The **schedule scene** (figure 5.5) shows to the patient her progress in the current daily session, if there is one. It lists details on which exergames are to be played next, the exergame duration and what exercise and game they are composed of. The total remaining time for the session is also shown. The therapist may also write a message for the patient that is read by the VTA. From this scene, the patient can continue to the current exergame (play button) or shut the system down (exit button).

Before starting the actual exergame, the **game introduction scene** (figure 5.4) is displayed to the patient. This scene presents additional information on the next game to play and functions as a short instruction reminder for the what will be done during the exergame (an idea inspired by the *Mario Party* series[11]). A video in the middle of the screen shows a sample gameplay session, while the words on the top and the VTA's speech explain

[11] http://marioparty.nintendo.com/

what is the purpose of the exercise and what is the game's goal. From here, the user may access the instruction scene, go directly to the exergame, or go back to the previous screen.

The **instruction scene** shows image, audio, and video instructions to the patient, telling him what are the goals of the game and what he can and cannot do according to the exercise. Following the feedback we received from early usability tests, we agreed that the instructions should tell the patient the goal of the rehabilitation exercise, the goal of the game, how the exergame works (what actions can be done to reach the goal), and what constraints on the movements are active.

In the **exergame scene**, the patient performs the actual exergame. If coming from the instruction scene, the game will be started in a *tutorial* mode (see section 5.5).

The **score scene** shows the results of the current exergame after it is finished. Based on the different elements of the score system (see section 7.2), separate sections show how the patient fared in terms of exergame performance, monitoring constraints, bonus points, and difficulty progression. The icons and numbers in the lower part of the screen show the points earned during the exergame that are added to the total points of the patient for reward purposes.

The **summary scene** is shown when the last exergame of a daily session is finished. It shows an overview of the current session, highlighting good and bad performances in the different exergames. The VTA comments on the results.

The **exit scene** is at last shown to the patient as the application shuts down and the session data is sent back to the Hospital Station. The VTA appears in the middle of the scene, saying goodbye to the patient and inviting her to come back later for the next session.

5.4.3 Natural User Interaction

To support NUIs during exergaming, we employ a diverse set of natural input devices through our input abstraction layer. However, we also support NUIs for navigating the system's interface and menus, which are addressed in this section. Our interface supports two alternative navigation methods: speech control and gesture control. In order to support these methods, we designed a generic navigation system named *command system*.

The Command System

The command system acquires commands from the users to navigate the various menu scenes. We designed this system to provide the user with a consistent visual interface, independent of the actual input method.

To the user, the command system appears as a set of buttons, with one button for each possible action that may be selected for the current scene. Each action is given an explanatory name. The consistency of this solution allows the user to easily interpret the different options regardless of the current scene. It is up to the handler of the specific input device used for navigation to determine how the interaction with the buttons is done. The command system optionally supports a cursor, if the input device used to navigate the commands requires it. As an added benefit, the system is easy to set up for the developer, allowing the creation of new menus with ease.

Input handlers that support the command system need to define the *Commands* input feature. The input handler should implement the logic to respond to when the commands declaration is started and ended, when a single command is added, and when a command is removed.

Speech Control

Speech control lets users navigate the interface using their own voice and is integrated with the command system. Looking at the options on the screen shown by the command system, the user needs only to speak the name of the option and it will be highlighted and selected automatically. Optionally, a small microphone appears in a corner of the screen when voice commands are available. The microphone grows, shrinks and changes color based on the status of the recognition, giving the patient immediate feedback. Speech control is useful for patients with upper limb impairments, who would find it too hard to navigate the interfaces using hand gestures. Speech control was reported as the preferred method during preliminary usability tests, with patients also mentioning the fact that communicating via voice made the application feel more social.

We implemented speech control using the Microsoft Speech SDK and the Kinect's microphone array, which provides high-quality noise suppression and sound directionality. The speech recognition engine relative to the chosen language is loaded when the application is started. We automatically build a grammar from the words chosen by the command system that determines what sentences are allowed. By using a constrained grammar paired with carefully chosen words that do not sound alike, we minimize recognition errors. The speech control system is enhanced with directionality information to make sure to get only the commands uttered from the person standing in front of the screen, i.e. the patient that is currently playing, aiding in noise suppression.

Gesture Control

Gesture control lets the user navigate the interface using her body movements. We created a gesture control mechanism which assigns the cursor's position (a virtual hand) to the movement of a chosen input device, and the cursor is used to interact with the command system buttons. To support gesture control, an input handler needs to define the *Cursor* feature. As examples of navigation devices, we explicitly support gesture control through the Microsoft Kinect (using the user's hands) and through the Novint Falcon.

5.5 The Abstract Virtual Exercise Environment

We detail here our design for the core of IGER: the exergames' software architecture. Our architecture follows the pipeline we detailed in chapter 4. More precisely, we remind the reader that a software implementation should be provided for each *Virtual Exercise Environment* (VEE). We thus implemented each VEE into a separate class, derived from the base *Abstract Virtual Exercise Environment* (AVEE) class, which defines a generic VEE and functions both as a common interface for communicating with the other modules and a shared structure that all specific VEEs must abide to.

Each specific VEE class implements multiple exercises, thus representing multiple exergames. The exercises are supported by defining conditional mechanics, so that they follow the selected exercise's action sequence. Due to time constraints, in the current implementation we paired each VEE class with a single game, and the class thus also defines the game's aesthetics, mechanics, and goal, although per our pipeline the two implementations can and should be separated.

Among the main functions of the AVEE, we report the control of the exergame logic flow, the control of the virtual camera, the setup of shared graphical elements (skybox, terrain, etc.), the automatic clean-up of the virtual world, automatic collision detection, automatic support for training modalities, consistent message notifications, player calibration checks, pauses, and count-downs. In particular, the support for a training modality, which we call *tutorial mode*, allows each exergame to be played alongside verbal instructions and fake pre-defined trials. The AVEE is also integrated with the feedback, monitor, adaptation, and scoring modules, so that new

VEEs created through this abstract class can use these modules out of the box. The use of the AVEE obliges each game to conform to a predefined structure based on our exercise parameterization, which is then extended by the derived class to provide the specific mechanics depending on the supported exercises.

5.5.1 Exergame Control Flow

The AVEE class controls the overall flow of each exergame according to a set of phases that can be further extended to implement specific behavior:

- In the **build world** phase, the exergame setups the virtual objects and agents that will appear during its execution. It may also specify the virtual camera views.
- In the **ready check** phase, the exergame specifies the particular requirements for the player to be considered ready to play. The definition of these checks is handled by the input handler chosen for gameplay.
- In the **position check** phase, the exergame can specify where the player should be positioned, if needed.
- In the **start**, **perform**, or **end repetition** phases, additional exergame logic can be specified for the initial, running, or final phase of a repetition.
- In the **start**, **perform**, or **end trial** phases, additional exergame logic can be specified for the initial, running, or final phase of a trial.
- In the **clean-up** phase, additional actions to be performed when the game ends can be specified.

5.5.2 The Exergame Sequence

Each VEE is structured into three hierarchical levels to provide the temporal sequence needed by exercises: the whole exergame itself, the repetitions, and the trials. This structure mimics the action sequence we previously detailed. From a game engine perspective, our exergame scene is contained into a single node, called *level node*, which contains all the virtual game objects. The 3D scene is composed of multiple virtual objects derived from the same class, following an object-oriented paradigm. All virtual objects present the same structure, following the guidelines contained in [130].

To conclude whether a trial was a success or not according to player movements we introduce specific virtual objects named *targets*. We assign one or more targets to each trial, and each target is placed according to the action sequence. When (and if) the last target of a trial is reached, the trial ends with a success; if a target is instead missed, the trial ends with a failure. Targets are also affected by the parameters of the exercises. To check whether targets were hit or not by the patient, we use *effectors*. These virtual objects are tied to the patient's movement and are introduced into the virtual environment through the player's avatar. Collision is handled through the game engine's internal physics engine.

Our virtual objects expose methods that help the developer in creating them with a few lines of code: they provide functions for setting with ease their 3D model, texture, color, materials, animation, and any sound effect to be attached to it, and do so automatically whenever possible. We also provide an automated level-of-detail mechanism.

5.5.3 The Avatar

Patients are represented into the exergame's virtual environment through their *avatar*. Each exergame instance requires at least one avatar, tied to one or more virtual effectors, through which the player interacts with virtual objects. The avatar is the means through which the exergame communicates with the input devices selected for the *gameplay* role, and thus it is directly animated according to the movements of the player.

An avatar may be as simple as an inanimate object (a bat, a net, a floating hand), the hands of the player in a first-person view, or even a fully animated 3D model that allows the player to move naturally into the virtual environment in third person view (humanoid avatar). We also support a *silhouette* avatar, a projection of the player's image on the screen as if it were a mirror.

To make sure the best representation of the player is used in a game, the avatar component supports several properties that can be set at design time inside the specific exergame's code. Among these, a property named *focus* is used to correctly map the input devices to the movements of the avatar and it selects which input feature should be used. Each different focus allows the creation of an accurate relationship between (a) the actual input device, (b) the avatar chosen for animation, (c) the input features supported by the device handler, and (d) the interaction logic within the game: this makes sure that any device can be used for any game, regardless of the chosen avatar, effectively completing the separation of input devices and game logic.

For example, when playing a game using a pressure board (a) with a 3D-body avatar in third person (b), a focus set on *body* will make sure that the trajectory of the COP obtained from the pressure board (c) will control and animate the full body of the avatar (d), while a focus set on *right hand* will move the hand of the avatar using that same input feature. The *focus* implementation is based on the strategy design pattern [61].

The 3D Humanoid Avatar

The 3D humanoid avatar is the most complex among the avatars we support and represents a humanoid body that mimics the movements of the player. Different 3D models can be rigged to the skeleton (i.e. animated using the chosen skeleton as a basis), so that we can support several different avatars for different games with different fantasies (see figure 5.6).

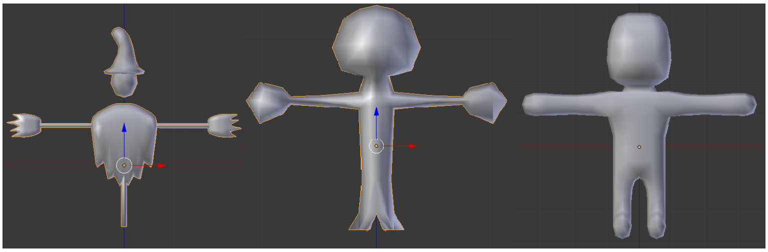

Figure 5.6: *Examples of humanoid avatars we created. From the left to right: the Scarecrow, the Tree, the Human.*

The avatar is built with a skeleton that mimics the one obtained through the official Microsoft Kinect SDK, allowing us to directly assign the quaternions returned by our Kinect library or by the Kinect SDK to the bones of the avatar to animate it with the true movements of the patient.

We also support single-movement avatar animation, using a single input stream (for instance the projection of the center of mass returned from the Nintendo Wii Balance Board) and interpreting it according to the given exergame in order to move the avatar, such as moving it around the play area or rotating the avatar's back.

As a middle ground between the two types of animation, we also support pose interpolation. A snapshot of the avatar's joint orientation can be saved to a file, and we refer to this as a single pose. Two or more poses can then be assigned to an avatar, and a single input stream interpolates between the poses to animate the avatar.

We associate different material patches to the different body sections of the avatar, allowing these parts to be colored differently. The body sections are identified by different vertex groups, defined during the avatar's mesh creation. This turns out to be very useful for monitoring feedback (see section 6.2.2).

5.6 Tracking and Data Recording

As mentioned in our guidelines, data tracking functions as an important basis to support further technology-enabled features for rehabilitation and should thus be inserted into any exergame. We separate the data tracking capabilities of IGER into different subsystems which are tasked with recording different data: motion data, exergame results, event logs, and physiological data.

5.6.1 Motion Data Tracking

By our design, all input handlers support recording and play-back functions. The motion data collected from the input device can be saved as a binary file using a *sensor recorder*, or a file can be read and interpreted by the device to play back its contents using a *sensor player*. As an example, figure 5.7 shows a plot of the motion data extracted from a recorded exergaming session using a Tyromotion Tymo balance board.

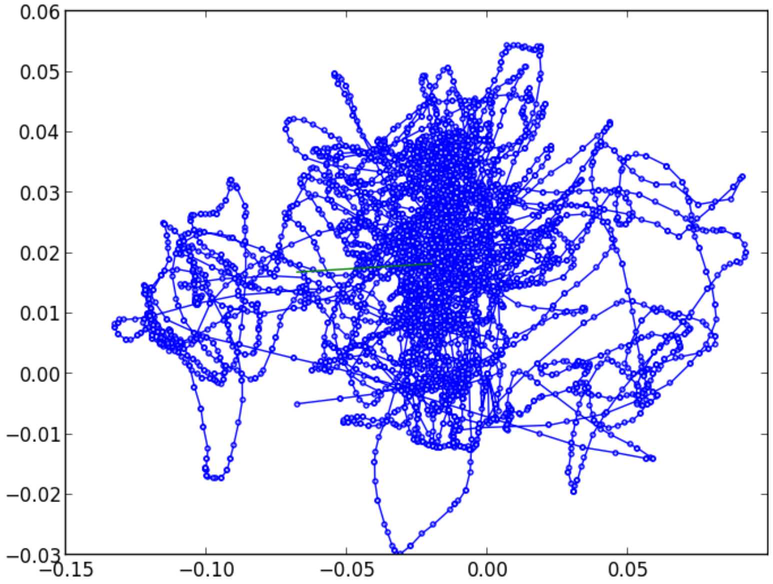

Figure 5.7: *A graph extracted from a recorded session that shows the trajectory of the COP of the patient on the Tymo balance board while playing Fruit Catcher.*

A sensor recorder is created by specifying the data format, the sampling frequency, and the array of values that must be recorded to file. For folder organization purposes, the recorder is also passed as arguments the device ID, the patient ID, the session ID, and the output file path. By default, all devices record at a sampling frequency of 30Hz.

Data recording can be started, stopped, paused, and resumed at will. The start of a recording creates a repeating task that saves a snapshot of the input device's state into a frame structure at the chosen sampling frequency.

The recorded data is written into a binary file with the extension *.rbf* (which stands for *Rewire Binary Format*), which is composed of a header part and a data part. The details of the recorder are packed into the header, including the arguments passed to the sensor, the start and stop recording timestamps, the packet size, and the number of frames recorded. A list of all recorded frames is kept into memory during execution, and the data is saved to a file only at the end of an exergame instance in order to not slow down the gameplay.

Each input handler is responsible for defining the correct data format for its device. For example, the Kinect handler reports the position of its twenty body segments as a sequence of 60 float values per frame, i.e. 20 body segments multiplied by three axes, while a pressure board handler reports the values of its four pressure sensors as four float values per frame.

When needed, the application starts the recording of a device through its input handler depending on the role of the device: the *navigation* device is recorded during the duration of the whole session, while *logging* devices are recorded during the execution of the exergame they are assigned to. For this reason, multiple data files are created, one for each device and for each exergame in the session. To favor communication with the Hospital Station (HS), the recorded data files are organized in folders based on the patient's ID number, the specific session, and the specific exergame. Each file is also assigned a timestamp.

A sensor player is created similarly to a sensor recorder, but an input file must be specified. The player can be paused at any time and it can be resumed or even reset. It can be useful for reviewing the actions of the player during a previous session as a replay feature.

5.6.2 Results Logging

Another specific module handles the results of each exergame, saving summary values regarding exergame performance under the form of motion accuracy, reaction times, and fulfillment of constraints related to monitoring. While these data are not as comprehensive as motion data and only function as summaries, they can be useful to get a quick snapshot at the progression of the patient over multiple instances of the same exergame. At the end of each exergaming session, the module creates an XML file with the recorded data, saving it in the local patient folder.

5.6.3 Event Logging

We designed an utility for registering events related to the flow of the application, to gameplay, and to patient monitoring. The important events that are triggered during the course of one session are written to a log file with their timestamp. For instance, events concerning alarms of the monitoring system (section 6.1) can be compared to the actual motion data to detect what was the cause for the monitors triggering. When an event happens, it is logged with additional information: the event's ID, the current timestamp, an optional message, and optional custom parameters.

An event logger is created when the application is first started each day and is accessible to the whole application as a singleton. Each event instance is saved into an XML log file as a separate XML element and the file is saved at a fixed frequency to disk (currently, once every second).

5.6.4 Physiological Data Tracking

As we mentioned in the guidelines, a good addition to any exergame is physiological data monitoring. In the REWIRE project, this function is performed by an external wearable system named *Lifestyle System* (LS) that collects physiological data during the day. We created a graphical user interface that guides the patient in the setup of the LS and in the collection of its data, saving the data in the patient's local folder. Since the LS was outside the scope of our work, we were not able to use this data inside IGER, and our system only routes the data to the HS for assessment purposes.

5.6.5 Assessment

Although IGER does not have assessment capabilities *per se* as it is only used by the patient and no automatic assessment was planned, all the recorded data files, including motion data, event logs, physiological results, and game results, are sent to the HS at the end of a session. These results can then be displayed to the therapist, who can review them and use them for assessment.

5.7 Configuration

Configuration of the therapy session is of utmost importance, as explained by our guidelines. Much like assessment, in our system no automation is performed for configuration, leaving this task for the therapist to perform. Bearing this in mind, we designed IGER and the Patient Station (PS) to be manually configurable from the start, allowing the therapist to perform configuration remotely. We thus support configuration of the therapy as a whole, of the single exergames it is composed of, of the general application, and of its user interface.

5.7.1 Schedule Configuration

Through the HS, the therapist is able to configure the daily schedule of the patient, deciding when and how the patient will perform her exercises and defining daily sessions. Exergames are ordered according to the taxonomy they belong to, so that the therapist can choose the exercises with ease based on the patient's progression in the therapy. According to our exergame definition, we allow therapists to configure only the *exercise* part of an exergame, and we let them select a game among those that implement the given exercise.

To make configuration easier for the therapist, we devised a graphical user interface to configure exercises, although the actual implementation was carried out by the HS developers. The design phase was carried out following several discussions with therapists, trying to match their configuration needs. A mock-up of this configuration interface can be seen in figure 5.8.

Referring to the figure, the therapist first selects the exercise (A) and a suitable game (B). After the exergame is selected, we allow a dual approach for configuring the exercise's parameters. As a first choice, we allow the therapist to configure an exergame using only a few details, such as its duration and a generic difficulty level (C), while the rest of the parameters are hidden and default to predefined choices. The *difficulty presets* form allows the therapist to easily select the difficulty of the current exercise in a simple scale from 1 (easier) to 5 (harder). As an alternative, we allow advanced options to be accessed if the therapist wants complete control over each parameter (D). We remark that our exercises are heavily parameterized and that all of their parameters can be modified through this interface. We also allow the therapist to configure the monitoring module (E) and the adaptation module (F). We refer to the respective sections for more information on what parameters can be configured for these two modules.

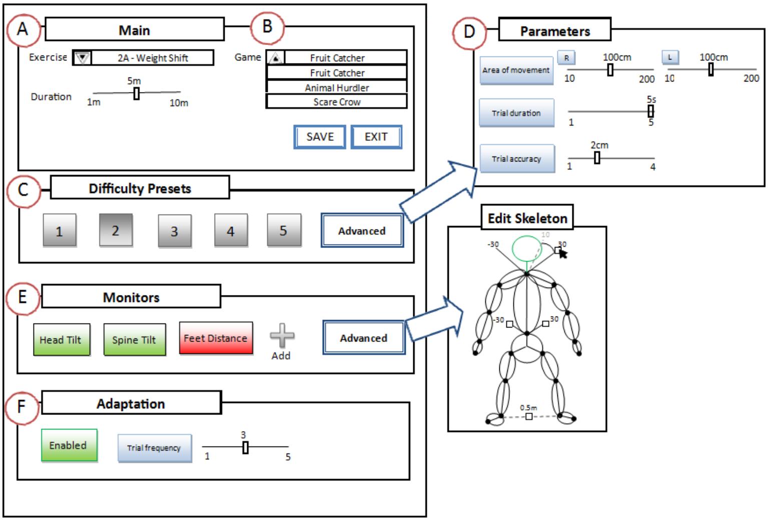

Figure 5.8: *A mock-up of the configuration interface. The different forms correspond to different parts of the rehabilitation procedure: the Main form; the Difficulty Presets form; the Monitors form; the Adaptation form.*

5.7.2 System Configuration

The configuration capabilities of IGER enable a customization of the whole system to the specific patient that will use it. This system-wide configuration is usually performed at installation time, but it may also be modified from the HS by issuing details on the parameters to override the system's local configuration.

For instance, through system configuration we select whether the patient will use the left or the right hand for the navigation of the interface while using a gesture control scheme, whether to use the speech control system or not, or what language to use for localization.

5.7.3 Patient-side Configuration

IGER supports limited configuration options for the patient, as most options are left for the therapist to choose via system configuration. We leave some cosmetic choices to the patients: the choice of which Virtual Therapist Avatar to use (see section 6.2.3), accessible through a configuration option in the *welcome scene*, and the possibility to load their own music tracks to listen to while playing the exergames.

5.7.4 Interface Design

As the system is started up, IGER accesses the HS to retrieve the daily updated configuration of the PS and the daily schedule. All the data pertaining to the parameters configured for exercises, sessions, and the system itself are locally stored in XML files to be accessed by IGER when needed, and the configuration values are instead held at runtime into specific python classes. The XML configuration files function as an interface between the PS and the HS, and the specification of these files is the result of our joint work with the HS developers. This specification is generic and independent from the specific exercises' nature, so that different exercises can be supported and so that we can add new exercises with ease.

CHAPTER 6

The Virtual Therapist: Enabling Autonomous Rehabilitation

IGER makes use of computational intelligence (CI) techniques to provide the features that allow us to mimic the role of real therapist, hence why we term our game engine as *intelligent*. In our system, due to the lack of human supervision during the actual exergaming session, computational intelligence is a necessity to provide a good degree of autonomous rehabilitation. In this chapter, we go into detail about the elements of the Virtual Therapist (VT) that enable autonomous rehabilitation at home and about the CI methods that help us achieve this goal. In particular, we employ fuzzy logic to leverage the knowledge of real therapists on what movements are permitted and which are prohibited during exercising in order to support real-time monitoring of the patient; we use Bayesian logic, in the form of the QUEST Bayesian adaptation method, to support on-line parameter adaptation; at last, we use ad hoc methods to support clear and immediate patient feedback, as well as text-to-speech technology and procedural animation to support a Virtual Therapist Avatar (VTA).

6.1 On-Line Monitoring

One of the main functions of the VT is the on-line monitoring of motion constraints, introduced to mimic this very important task typically performed by the therapist.

By watching the actions of therapists during several rehabilitation sessions, we were able to summarize the monitoring procedure. The therapist observes a set of predefined movements, making sure that each movement is always correct during the execution of the exercise. Different movements are valued differently according to their importance in the therapy, so that the therapist will give higher priority to the monitoring of some specific movements, weighing errors related to them more than others. Whenever one or more of the movements is considered wrong or harmful, the therapist corrects the posture of the patient, either by verbal feedback or physical aid, before letting the patient continue with the exercise. As an approximation, the therapist can be seen to monitor each of the predefined movements separately from the others. At any time, the most pressing error is taken into account for feedback, in order to not overwhelm the patient with too much feedback at once. This model of the therapist's monitoring can be seen in figure 6.1.

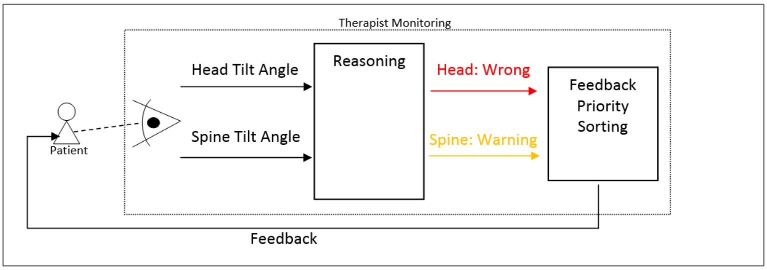

Figure 6.1: *A model of the therapist's monitoring.*

To mimic this behavior, monitoring is performed by the VT through a set of software modules called *monitors*, and one monitor is created for each specific movement that needs supervision. To each monitor, we assign a specific soft constraint, defined through (i) the chosen tracked movement (or, more precisely, a chosen *input feature*), (ii) the range of values over which the movement can be considered to become progressively less correct, and (iii) the severity degree of the movement, so that priority checking is embedded into the monitor itself. The constraints are checked by the game engine at runtime against the movement data acquired from the input devices and the result of this comparison is a specific alarm level for each monitor that is then sent to an alarm aggregator that mediates how to show the possible errors to the patient. In addition, a global alarm level is generated that can be seen as a summarizing value related to general movement correctness. Our monitoring model can be seen in figure 6.2.

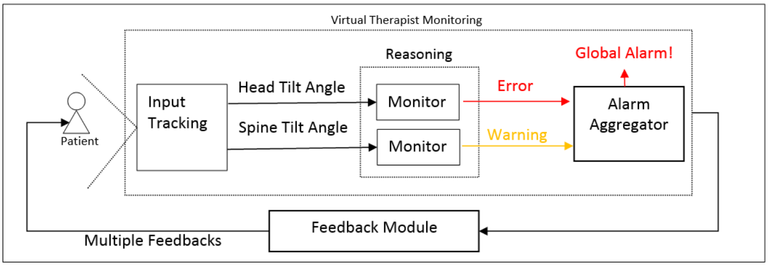

Figure 6.2: *The model of our virtual therapist's monitoring.*

As mentioned in our section on exercise parameterization, monitoring constraints are part of the definition of an exercise, and they were thus defined *a priori* with the help of our clinical partners for each exercise. However, monitoring constraints are not directly addressed by the exergame mechanics, and they are instead consistently addressed throughout all exergames by the monitoring system.

A large effort was put into the design of a monitoring architecture that can be easily configured by therapists. The monitors associated to each exercise can be configured as a set of soft constraints that the patient must fulfill when executing the rehabilitation tasks regarding a specific, predefined, movement. This is done through a visual interface, allowing easy customization of the monitors to the specific characteristics of the patient and of the rehabilitation task.

To support an arbitrary number of monitors, we designed monitoring capabilities with flexibility in mind. This is obtained through our input abstraction layer, making sure that multiple monitors that use different devices can coexist. The use of a combination of low-cost tracking devices for our exergames, in particular, provides us with the means to closely monitor the required movements of the patients, as the same devices that are used during the game to track their actions and transfer their movements to the avatar can be used to monitor that movements are correctly performed.

6.1.1 Monitoring with Fuzzy Logic

We implemented two alternative monitoring solutions. The first solution allows us to define several simple monitors and attach them to variables whose changes we want to keep under control. These monitors can easily keep track of the value of these variables and, in case the limits are exceeded, an alarm is raised according to the predefined severity level specified by the monitor.

However, monitoring performed by a real therapist can be hardly converted into crisp reasoning. To better model the therapist's reasoning, we introduced monitoring based on *fuzzy logic*. Fuzzy systems are the most suitable framework to represent expert knowledge [127] and they are thus a good addition to our toolset. Our fuzzy system takes the monitoring configuration and uses it as the knowledge basis on which to infer what alarms to rise according to the tracked movements.

For each monitored input movement, the minimum and maximum values defined during configuration transparently determine a range of continuous values that are automatically mapped into fuzzy input variables, with a sequence of fuzzy sets associated to progressive severity.

For example, we may create a constraint that the patient's head must not be tilted on the frontal plane. The tilt is computed as the angle of the head relative to a rest position, parallel to the world's up vector and computed around the patient's front vector. A minimum value of 10 degrees (up to which the movement is considered correct) and a maximum value of 30 degrees (the value at which the movement is considered wrong) are set at configuration time. The tilt angle, as tracked by the input devices, is fuzzified into the *head tilt* input fuzzy variable. A set of four membership classes (*ok*, *risky*, *bad*, and *wrong*) is automatically generated, equally spaced in the variable domain on the defined range. We may add a second constraint: the patient must remain upright and thus her spine must not be tilted more than 10 degrees on the frontal plane. The monitored variable is defined as the angle between the patient's spine and the world's up vector around the front vector and is fuzzified into the *spine tilt* fuzzy variable. The maximum tilt acceptable would be of 10 degrees (with a default minimum of 0 degrees) and four fuzzy classes are generated once again automatically. The fuzzy input variables we described can be seen in figure 6.3.

Similarly, we define monitors for several different body segments, and in particular we support the monitoring of spine and neck (sagittal and frontal motion), shoulders and legs (sagittal, frontal, transverse motion), knee, and elbow. We also define monitors that take explicitly into account the COP of the patients or their weight distribution.

We define a single fuzzy output variable for each monitor: the alarm level. This variable is populated with five fuzzy sets: *silent*, *log*, *warning*, *error*, and *shutdown* (figure 6.4).

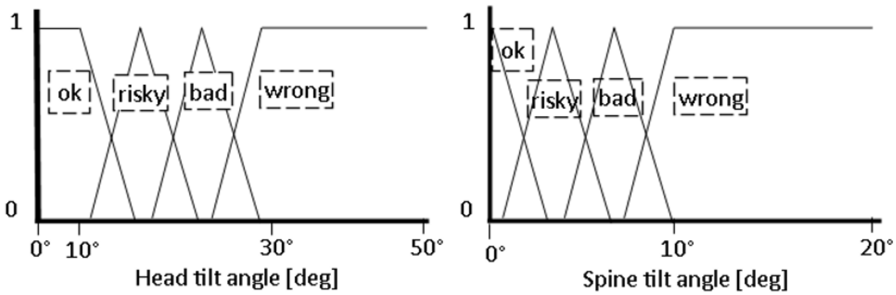

Figure 6.3: *Head tilt angle and spine tilt angle, fuzzified for monitoring.*

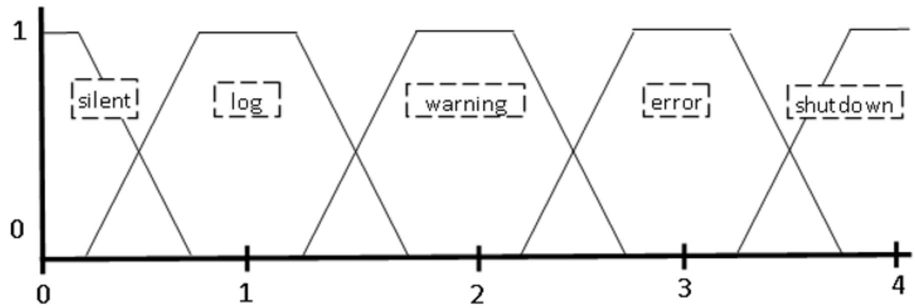

Figure 6.4: *The alarm level fuzzy output variable.*

We generate automatically a set of fuzzy rules that map the input variables to their alarm level output according to the knowledge that is encoded into the monitor configurations. During the configuration phase, a severity degree is attached to each monitor, and this can take one of the following values: *log*, *warning*, *error*, or *shutdown*; this mimics the sets defined over the alarm level fuzzy variable and this relationship is used when creating the fuzzy rules. A single rule is created that maps all the input variables, when set to the input fuzzy class *ok*, to the output fuzzy class *silent*. This makes sure that no alarm is raised only if all monitors constraints are fulfilled. A new rule is created for each input variable so that when it is set to the input fuzzy class *wrong*, the output is set to the fuzzy output class linked to the monitor's severity. For instance, a severity degree of *log* determines a mapping from the input's *wrong* set to the output's *log* set, while a severity degree of *error* determines a mapping from the input's *wrong* set to the output's *error* set. Similarly, new rules are created for each input variable that map their *risky* and *bad* classes to corresponding classes of the output.

Again, this is based on the severity degree, interpolating linearly between the output's *silent* class and the class linked to the chosen severity degree. Note that all the rules are set to have the same weight (fixed to 1) so that no additional priority is assigned.

The aggregated output is obtained through the use of the fuzzy logic operator OR on all rules, thus considering the maximum value of all their outputs. As all the rules have the same output variable, following aggregation, the output is basically always controlled by the input that has a higher value and higher severity degree. The fuzzy system thus prioritizes the most pressing and severe error, so that the feedback can react accordingly, temporarily ignoring less important errors. The alarm level fuzzy variable is at last defuzzified according to the rule outputs, converting the fuzzy output into crisp numbers. The system's final crisp output is termed *global alarm level*, obtained by performing a weighted average on the output fitness values. This results in a numerical value that can be used by the rest of the application as a summary alarm indicator.

Continuing our previous example, let us consider the case in which the head tilt has a value of 25 degrees, while the spine tilt has a value of 10 degrees. Let us suppose that the head tilt monitor has its severity set to *error*. In this case, the head tilt input fuzzy variable maps the head tilt crisp value to the *bad* fuzzy set with fitness 0.5 and to the *wrong* set with fitness 0.5. Similarly, let us consider the spine tilt monitor to have its severity set to *warning*, so that the input fuzzy variable maps the spine tilt crisp value to the *wrong* fuzzy set with fitness 1. When the fuzzy rules are checked by the inference engine, we are concerned with just a few rules: the rule that maps the head tilt input's *wrong* set to the output's *error* set, resulting in an output of *error* with fitness 0.5; the rule that maps the head tilt input's *bad* to the output *warning*, resulting in an output of *warning* with fitness 0.5; and the rule that maps the spine tilt input's *wrong* set to the output *warning* set, resulting in an output of *warning* with fitness 1. Following the example, the aggregated outputs will be *warning* at 1.0 and *error* at 0.5. By considering the crisp values of the two output sets' origins during the defuzzification through a weighted average (2 and 3 respectively), the global alarm level is set to

$$(1.0 * 2 + 0.5 * 3)/(1.0 + 0.5) = 3.5/1.5 = 2.33 \tag{6.1}$$

which corresponds to an alarm level a bit higher than a warning. The example can be also seen in figure 6.5, where our fuzzy system monitoring is summarized.

Our monitoring module performs an additional step, not related to its

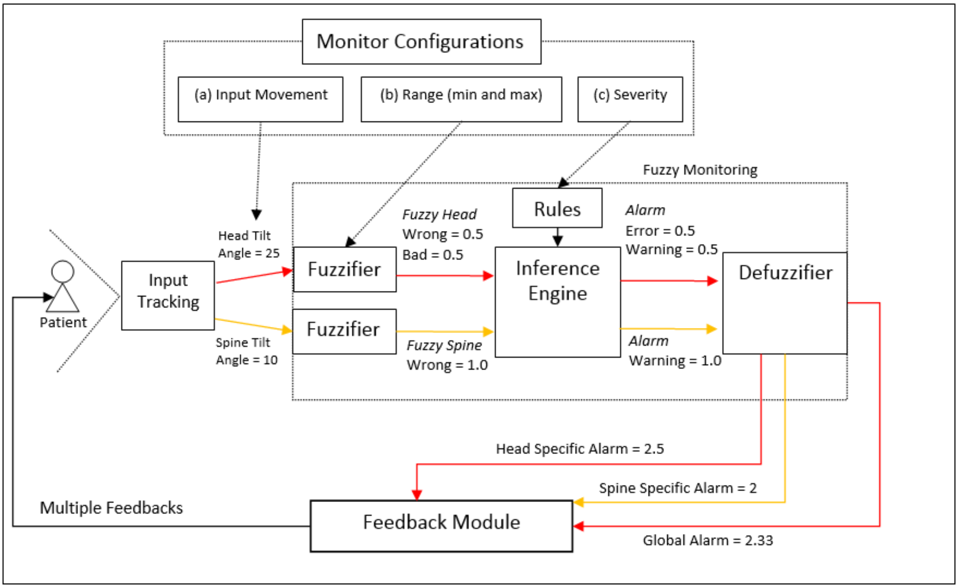

Figure 6.5: *A visual model of our fuzzy monitoring system, showing an example of monitoring flow.*

fuzzy nature. Before being inserted into the fuzzy system, the crisp input values are also normalized between their defined minimum and maximum and multiplied by a value corresponding to their severity degree (1 for log, 2 for warning, 3 for error, and 4 for shutdown). This value is referred to as the *specific alarm level* of the monitor, and is used for mapping the monitor's values to specific monitoring feedback.

6.2 Patient Feedback and the Virtual Therapist Avatar

We place particular emphasis on the feedback given to the patient throughout the rehabilitation session, be it feedback about the gameplay progression, monitoring effects, game state, or generic useful information. We provide clear, direct, and consistent feedback as a result of our iterative prototyping method, checking with patients whether feedback was clear or not as we developed it.

We provide feedback through three different linked modules: the *alarm module* is in charge of analyzing monitoring results and pause the exergame if needed, the *feedback module* is in charge of providing general feedback to the patient regarding her gameplay and monitoring performance, while the *Virtual Therapist Avatar* (VTA) functions as a guide throughout the application.

6.2.1 The Global Alarm

When a monitoring constraint is violated, the system issues an alarm. The global alarm value is a single value that encompasses the state of all monitors at once: if this value is low, the monitors are not detecting any erroneous movements, if the value is high, at least one monitor is detecting an erroneous movement. We defined five alarm severity levels, with each triggering a different behavior of the VT (see table 6.1).

Alarm Level	Assigned Value	Effect
Silent	0	No alarm. No action is performed.
Log	1	A notification of the alarm cause is added to the exergame log.
Warning	2	A warning is issued to the patient under the form of audial and visual feedback, reminding her to correct the bad behavior. The event is also logged. This level is basically associated with violating soft constraints.
Error	3	In addition to issuing a warning and logging the event, the game is paused. The player is then given an explanation of the cause of the error and the option to resume the game. This level basically identifies a hard constraint.
Shutdown	4	This is reserved for very dangerous situations. The game is shut down and a warning is sent to the therapist, prompting her to contact the patient.

Table 6.1: *The possible alarm levels triggered by our monitoring module.*

When an *error* alarm is triggered, the game is paused and a text message is shown in the middle of the screen with details on the erroneous movement. The underlying game is shown, blurred, on the background, so the patient can reposition herself if needed. The pause messages are associated to the violated constraints and, while sacrificing some immediacy compared to icons and sound, better explain the problematic movements.

6.2.2 The Feedback Module

The feedback module provides consistent visual and sound elements to give patients information on their performance as they play. To achieve consistency, the feedback software module is decoupled from the single exergames allowing us to reuse the same visual and sound elements. This allows the patient to understand clearly and unambiguously, regardless of the current exergame, whether she completes successfully an exergame trial (a green tick appears and a tuned sound is played) or she fails (a red cross appears and a dissonant sound is played). This decoupling also allows us to show timing, scoring, starting, ending, and pause information out of the box for any exergame created through IGER.

To improve clarity and consistency, throughout the system we use color-coded feedback inspired by semaphores: a green hue is always associated with positive performance, a yellow hue with a average performance, and a red hue with negative performance. The use of color-coding allows the patient to get an intuitive and non-intrusive idea of what the system is communicating.

Monitoring Feedback

We largely focus on feedback related to on-line monitoring as it is related to patient safety and immediate and clear feedback is required for the patient to react in time, should the need arise. Since monitoring is related to *input features* (see section 5.3.3), we assign a specific feedback element to each feature at design time. Binary features, such as signaling whether the foot is kept on a pressure board, are shown using a binary led visual feedback. Continuous features, such as the force exerted on a pressure board, are shown using a colored bar with a beacon signaling the current value. Positional features, such as the Center of Pressure obtained from a pressure board, are shown with a rectangular working area and a beacon signaling the current position of the patient. Features tied to rotations of the different body parts (head, spine, elbow, knee, etc.) are paired to a feedback placed directly on the patient's avatar mesh, coloring the different body parts according to the current value (figure 6.6). Among these feedback elements, the avatar was deemed by patients and therapists alike the most intuitive and useful feedback for monitoring, as it is clear and immediate (it is placed in the visual focus zone) and non-intrusive (it adds no new virtual object to the 3D scene), allowing the patient to discern exactly what body part is affected.

6.2.3 The Virtual Therapist Avatar

Following our goal to mimic the therapist role, and considering the great social and motivational effect given by the presence of an actual therapist, we introduced the Virtual Therapist Avatar (VTA) into our system. Just as the player is present into the exergames with her avatar, the VTA rep-

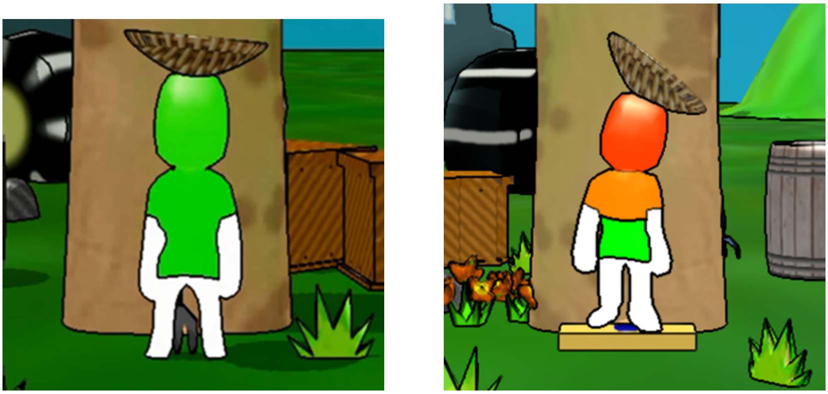

Figure 6.6: *Examples of the effect of monitoring posture on the avatar mesh. Left: the monitoring constraints are fulfilled. Right: the monitoring constraints are violated. Notice that the elements follow the green-yellow-red color code.*

resents the real therapist when she is not available. The VTA appears in the application either during or between exergames, and is responsible for accompanying the patient alongside her training, reproducing the behavior of a real therapist as much as possible. In respect to simple visual or audial feedback, the VTA provides a more natural way to communicate with the patient and we thus integrate it with our feedback and alarm modules: it appears when an exergame is paused due to errors reported by the monitors to explain what went wrong and what the patient should do, during the introduction of an exergame to explain its rules, and during the course of the exergame to motivate. The VTA also appears to welcome the patient as she starts the rehabilitation session and to salute her when she leaves, to remind the patient of her progression inside the rehabilitation, and to congratulate on achievements and rewards.

We introduced the VTA in two different forms, allowing the patient to choose the best one according to her preference (see figure 6.7). The first form is a 3D model of a realistic female virtual therapist, allowing the patient to feel the presence of a more serious character supervising her activity. We animate the therapist's face, giving her different facial expressions and occasionally making her head tilt and her eyes blink. The second form is a 3D mascot, similar to what Nintendo does with its Wii Balance Board avatar in the Wii Fit games. We named the mascot *Piggy* for obvious reasons. The mascot can be beneficial as a motivator due to its funny aspect and motion, enhancing the playful aspect of the application. The rationale for the two different forms stems from an interesting argument: should the

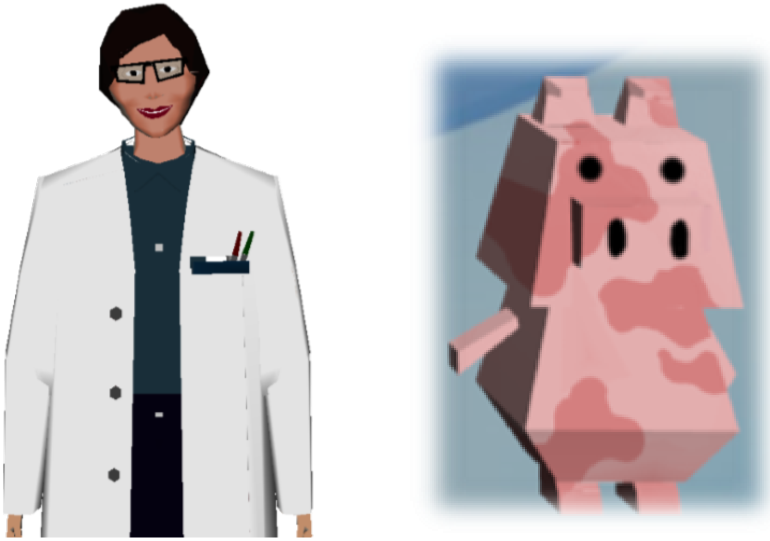

Figure 6.7: *The different choices of Virtual Therapist Avatar. Left: the 3D model of a realistic therapist. Right: Piggy, the 3D mascot.*

exergames feel more like traditional therapy, or more like a gaming system? We left this choice to the patient.

6.3 On-Line Adaptation

On-line adaptation has implications both for motivation and for accessibility, as explained by our guidelines. Through a specific software module, we perform on-line adaptation by measuring the patient's performance and then modifying the exercise's parameter values accordingly while the patient plays an exergame. These parameters are related to the domain of the exercise, and thus directly affect the skills required to complete it, i.e. they affect the exergame's difficulty.

In our system, it is up to the therapist to select appropriate adaptation parameters for each exergame, chosen among those exposed through the exercise's parameterization. Using the configuration form, parameters can thus be either manually configured or enabled for adaptation. Examples of adaptable parameters chosen by our therapists for posture and balance rehabilitation are the trials' duration (related to reaction time) or the area of movement (related to the exercise's movement boundaries), both of which directly translate to an increase in the exergame's difficulty.

The on-line adaptation module is in charge of tracking the patient's performance at runtime. At the end of each repetition, we compute the current performance p as the ratio between the number of successful trials N_s and the total number of trials N_{tot} in the repetition:

$$p = \frac{N_s}{N_{tot}} \tag{6.2}$$

This value represents the *success ratio* of the patient and can thus be used as a generic exergame performance indicator, used to determine the consequences of adaptation and modify the parameters accordingly. We support two alternative methods for adaptation: a heuristic method and a Bayesian approach.

6.3.1 Heuristic Adaptation

The first method is similar to the solution first proposed in [87] and performs adaptation based on heuristics.

We define the n game parameters $x(i) = [x_1; x_2; \ldots; x_n]$ selected for adaptation and their variation introduced at each adaptation step $dx = [dx_1; dx_2; \ldots; dx_n]$, chosen in the direction of difficulty increase. These parameters are defined by the therapist. We also define a desired target performance ratio p_{end}, fixed to 80% for all of our exergames.

At the end of each repetition, the parameters x are updated as follows. If p is higher than p_{end} the patient is over-performing and x is therefore incremented by dx, increasing the difficulty of the next repetition:

$$x(i+1) = x(i) + dx \tag{6.3}$$

If p is lower than p_{end} the patient is under-performing and x is therefore decreased, making the game easier at the next repetition:

$$x(i+1) = x(i) - dx \tag{6.4}$$

As a result, the exergame modifies its challenge level to match the skills of the patient.

Although the algorithm is simple to implement and can provide acceptable results, dx is not immediate to define and requires some tuning. Small variations generate slow adaptation, and thus do not work correctly, while large variations could produce heavy oscillations, thus avoiding any convergence. In addition, this method provides no soft or hard limits on the final values, an unacceptable risk for most therapists. To account for these drawbacks, we explored a novel method as an alternative.

6.3.2 Bayesian QUEST-based Adaptation

Our alternative parameter adaptation algorithm is built upon the QUEST Bayesian adaptive method [203] that is widely used in psychophysics to adapt a psychometric threshold for audio, visual, or tactile stimuli. The method is based on prior knowledge of the threshold and the observation of a set of single-outcome tests, usually expressed with a binary result, that refine the initial knowledge towards a more likely threshold value.

This method is based on three assumptions. First, the function that relates the parameter to the performance must have the same shape under all conditions, an assumption easily fulfilled by considering an adequate performance function. Second, the subject's threshold should not vary from test to test, and third, individual tests must be statistically independent. These two assumptions mean that we assume each patient to possess a fixed difficulty threshold at which her performance is adequate, and that this does not change during the gameplay, thus assuming that no learning is performed. This can be safely done due to the short gaming sessions and to the fact that adaptation is reset at each session.

The QUEST method was modified here to adapt the exergame's difficulty in real-time. In our method, the therapist identifies a single parameter x related to the difficulty of the exercise. We then adapt the value of x as a function of the outcome of each repetition (also called *test*), so that the desired performance ratio p_{end} is reached. x thus represents the *adaptation threshold* of QUEST.

To start, we define the prior probability density function (pdf) of the parameter, $f_x(x)$, which functions as the initial guess and thus determines the probability at which, according to our guess, the actual threshold is x. It is assumed here as a Gaussian function centered in μ_{prior} and with standard deviation σ_{prior} and is defined at configuration time according to the mean and standard deviation chosen by the therapist. Let $o \in (S, F)$ (where S is a success and F is a failure) be the observed binary outcome of a repetition, we define the data $D = [o_1; o_2; \ldots; o_n]$ as the sequence of observed outcomes of a set of n subsequent tests. We also define $f_D(D)$ as the pdf distribution of D, computed from the data itself.

The selected parameter is modified on a per-repetition basis. The outcome o of a given repetition is S (or F) if the repetition's performance ratio p is higher (or lower) than a chosen minimum performance (for our exergames, this is fixed to 80%).

We thus aim to compute the value of x, x_{end}, that is expected to be the threshold at which the posterior pdf of the parameter given the data,

$f_{x|D}(x|D)$, converges to p_{end}. Considering explicitly the dependency between x and D through the Bayes theorem, we obtain the posterior pdf as

$$f_{x|D}(x|D) = \frac{f_x(x) f_{D|x}(D|x)}{f_D(D)} \tag{6.5}$$

Our goal is thus to compute this pdf at each repetition, and we use QUEST to compute this posterior pdf efficiently. On the right side of equation 6.5, the term $f_D(D)$ is constant, and we are left with the other two terms to obtain

$$Q(x) = f_x(x) f_{D|x}(D|x) \tag{6.6}$$

where $Q(x)$ is named *QUEST function*.

The term $f_{D|x}(D|x)$ indicates the pdf of the previous repetition outcomes given the value of the parameter. Under the assumption of statistical independence, by defining the performance function $p_x(x_i)$ that determines the probability that, given a threshold x, using parameter test value x_i the repetition i was a success, we can rewrite the term as a production and obtain

$$Q(x) = f_x(x) \prod_{i=1}^{n} p_{r_i|x}(x_i) \tag{6.7}$$

Where $p_{r_i|x}(x_i)$ is the probability that test i, with actual threshold x and using the test value x_i, has outcome r_i that is either 0 (miss) or 1 (hit). From this, we obtain an iterative method to compute the QUEST function $Q_i(x)$ at each test i:

$$Q_i(x) = Q_{i-1}(x) p_{r_i|x}(x_i) \tag{6.8}$$

Since we are working under the assumption that $p_x(x_i)$ maintains the same shape between different repetitions, we can rewrite it through a canonical function $\Psi(x_i - x) = p_x(x_i)$. We define a success function $S(y)$ and a failure function $F(y)$ as

$$\begin{aligned} S(y) &= \Psi(-y) \\ F(y) &= 1 - \Psi(-y) \end{aligned} \tag{6.9}$$

which allows use to rewrite $p_x(x_i)$ as

$$p_x(x_i) = \begin{cases} S(x - x_i) & \text{if success} \\ F(x - x_i) & \text{if failure} \end{cases} \tag{6.10}$$

Thanks to this, the Quest function $Q_i(x)$ at test i can be obtained iteratively from $Q_{i-1}(x)$ by shifting $S(y)$ (or $F(y)$, if the outcome was a failure) by intensity x_i and multiplying the result:

$$Q_i(x) = Q_{i-1}(x) * \begin{cases} S(x - x_i) & \text{if success} \\ F(x - x_i) & \text{if failure} \end{cases} \tag{6.11}$$

At each adaptation step i, the parameter value x_i is chosen as the mean of $Q_{i-1}(x)$, as suggested by [104]. After the test, the Quest function $Q_i(x)$ is updated and the next test can start.

To define a suitable performance function $p_x(x_i)$, as suggested by [203], we use a Weibull function:

$$p_x(x_i) = \delta\gamma + (1 - \delta) * (1 - (1 - \gamma)e^{-10^{\beta x_i}}) \tag{6.12}$$

where δ is the percentage of success at maximum intensity (i.e. maximum difficulty, in our case) and should be a small value that accounts for the unlikely case where the patient succeeds in a very difficult exercise purely by chance, γ is the probability of failing at zero intensity (i.e. minimum difficulty), and β is the slope of the psychometric function and it is here set equal to 3.5 according to the two-choice case [203]. δ is set to a very small value (0.01) and so is γ (0.001), although we note that the parameters could be changed according to the exercise's nature.

Since our aim is to achieve a fixed success ratio, at each step we shift the performance function so that the expected percentage of successes is equal to p_{end}. We thus interpolate $p_x(x_i)$ in order to find the correspondent parameter value x_{end}:

$$p_x(x_i) = \delta\gamma + (1 - \delta) * (1 - (1 - \gamma)e^{-10^{\beta(x_i + x_{end})}}) \tag{6.13}$$

This method has several benefits. We obtain fast convergence towards a parameter value that is supposed to maintain the chosen success ratio (see figure 6.8), while providing therapist-controlled soft limits defined by the a priori term. Adaptation is configured with ease by the therapists as they need to define just two intuitive parameters: the mean and standard deviation of the guess. We choose to adapt only one parameter at once although the Bayesian adaptation scheme proposed here could be extended to multiple parameters. This was ruled out here as therapists usually aim at a single goal associated to one critical parameter at a time. Moreover, such an approach would require an estimation of the contribution of each parameter to the overall difficulty level.

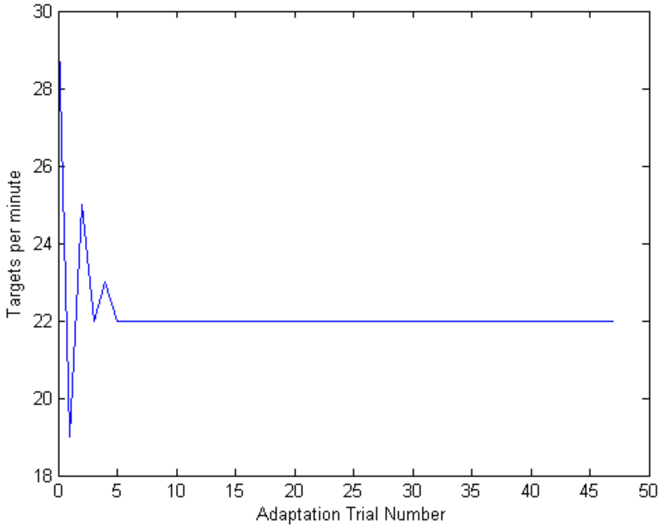

Figure 6.8: *An example of convergence of the modified QUEST adaptation method. We adapt here the trial frequency.*

6.3.3 Adaptation Supervision

Apart from giving feedback to the patient, the global alarm triggered by monitoring is also used to supervise the adaptation module. This is needed because monitoring and adaptation have somewhat conflicting goals: adaptation makes sure that the challenge of the game is on par with the player's skills, while monitoring makes sure the exercise is performed correctly. If the patient is focused on the game, she may be able to get a high performance score and thus make the game even harder, but this may also make the player neglect the constraints of monitoring, especially if she enters a *flow* state. In this case, adaptation must be stopped, as the correctness of the exercise is more important than the motivational effects given by the increased challenge.

We define four possible results following the interaction between adaptation and the alarms, summarized in table 6.2. In particular, note that adaptation is blocked or limited if patient performance increases but monitoring constraints are violated.

	Alarm level				
	Silent	Log	Warning	Error	Shutdown
Increasing performance	Increasing difficulty: full	Increasing difficulty: partial	No adaptation	No adaptation	No adaptation
Stable performance	No adaptation	No adaptation	No adaptation	No adaptation	No adaptation
Decreasing performance	Decreasing difficulty	Decreasing difficulty	Decreasing difficulty	Decreasing difficulty	Decreasing difficulty

Table 6.2: *The effect of patient performance and alarm level on adaptation.*

CHAPTER 7

Long-term Patient Motivation in IGER

In this last chapter regarding IGER, we detail the systems we designed to address long-term patient motivation. Following our prior discussion on patient motivation, we focus on both intrinsic and extrinsic motivational methods to provide a compelling rehabilitation experience, able to maintain patient interest for the full duration of the therapy.

We designed the *variations module* to improve motivation in the single exergames by providing randomized variations in the virtual environments, which in turns increases their longevity since each play session is different from the others. We also address long-term motivation using extrinsic motivators by considering all the exergames as a larger whole, designing two different, yet linked, systems: the *scoring system* and the *reward system*.

7.1 Environment Variations

In order to increase the long-term appeal of our games through *curiosity*, we introduced a set of software modules to provide variations in the games based on Procedural Content Generation (PCG), creating ad hoc algorithms for the purpose. Through PCG, we obtain an endless number of variations for a specific aspect of the game, it is thus a relatively simple way to increase the long-term appeal of a game.

As an initial solution, we introduced a controlled randomization of the scenery by defining some parameters that govern the virtual environment, with no actual effect on the gameplay. For instance, we parametrize the position of scenery objects (such as barrels, trees, or flowers), the light conditions (night or day) or the selection of in-game music. This is based on the method of vector parameters: we set lower and upper limits for the parameters and use a pseudo-random algorithm, initialized with a random seed, to set their values at runtime. This produces small variations into the game without affecting the gameplay, and thus without affecting the exercise underneath.

As a second PCG technique, we employ maze generation algorithms to create paths for some of our exergames, namely *Animal Hurdler* and *Horse Runner*. The path generation algorithm takes as input a few parameters and generates a randomized but constrained path over which the avatar can move. The path is composed of sections, either straight or curved. From the starting parameters, we generate a direction matrix using an algorithm based on recursive backtracking, modified to avoid dead ends and produce a non-branching path, thus making sure that a navigable path of the chosen length is always generated. The direction matrix holds a grid representation of the path, from which we extract an array holding the direction that must be taken at each step to travel the path. After we create the path, we generate its physical representation in the virtual world, using the resulting array of 3D points to instantiate and position graphical assets, populating the path with environmental meshes (trees, objects, and creatures). Figure 7.1 shows an example of generated path.

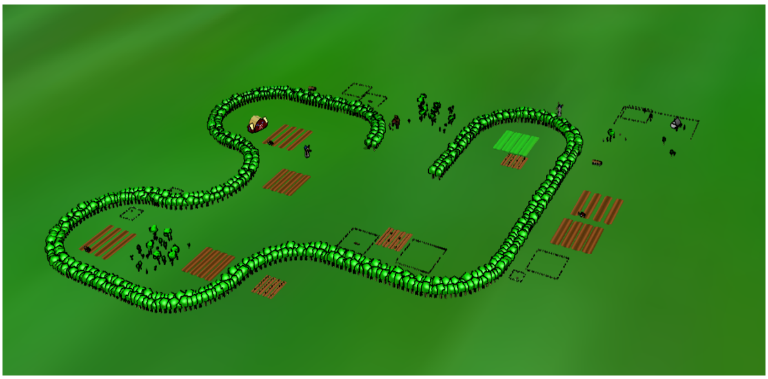

Figure 7.1: *An example of generated path, highlighted by the trees that cover it, used in the Horse Runner game. Environmental meshes like fields and barns are also added around the path.*

7.2 The Score System

The score system of IGER, at its core, measures the performance of the player and translates it into easily interpretable numerical values. We designed a score system specifically for rehabilitation exergames. The score takes into account both the performance of the player in the game and the rehabilitation nature of the exergames, and these two aspects concur to determine the points assigned to each action. Whenever a trial is completed, a score is assigned to the patient based on her performance, adding a predefined set of points in case of a success and removing points in case of a failure. The score is displayed to the patient during play with a numerical value and a success (or failure) visual and auditory feedback. A save/load feature is integrated into the scoring system, allowing a player's score to be carried over to future game sessions and to compare her current score with previous values.

We designed a score system that takes into account multiple elements to compute the final score. This is necessary because of the highly customizable nature of exergames, and because the system must be fair to the patient. For these reason, we take into account all customizations that can modify the challenge of the exergame and assign points accordingly. Otherwise, the patient may feel cheated, as the score would not be proportionate to the challenge, thus losing all motivational benefits.

The score system takes into account a set of separate parameters to compute the final numerical score.

We define the **success ratio** S as the ratio between the number of targets hit and the total number of targets appearing during an exergame instance. The success ratio can vary from 0 (worst performance, no target was hit) to 1 (best performance, all targets were hit). We remark that this success ratio, due to the dual nature of the exergames, is directly related both to the gaming performance and the exercise performance of the patient. We also remark that this is the same ratio that is used for adaptation purposes.

The patient needs to achieve a high success ratio while fulfilling the movement constraints specified by the therapist through monitoring. We thus define the **monitoring ratio** M. For the purpose, the state of the monitoring alarm is used as a global multiplier after normalization, with a multiplier of 0 signaling that the monitoring is not fulfilled and a multiplier of 1 signaling that the monitoring constraints are all fulfilled.

We take into account the duration of the exergame when computing the final score of an exergame through the **time multiplier** T, equal to the number of minutes of play. This is implicitly taken into account during play, as a longer duration is translated into a larger number of trials.

It is important, for a score system to work, that a higher difficulty level provides a higher score to reward higher performance. In our exergame, difficulty is controlled by different factors: the **difficulty ratio** D varies according to the difficulty level chosen during configuration, the **adaptation multiplier** A varies according to on-line adaptation performance, and the **taxonomy multiplier** X varies according to the innate difficulty of the exergame based on its position inside the exercise taxonomy. These multipliers are applied on the total value at the end of an exergame and added as bonus points. They vary from 0 for the easiest difficulty to 1 for the hardest difficulty.

In addition to these parameters, we define $P_{max,m}$ as the maximum points that can be earned per minute regardless of the played exergame. We use this as an arbitrary starting point. Its value has only psychological effects, with higher numbers resulting in scores with a longer streak of digits.

Using these parameters, we can compute the score given at each successful trial as

$$P_t = \frac{P_{max,m}}{N_m} \tag{7.1}$$

where P_t are the earned points per successful trial and N_m are the number of trials per minute of the exergame instance. With this equation, we remark that the points are independent of the frequency of execution of an exergame, as frequency is not a clear indicator of difficulty. For example, a hard-to-perform but slow-paced exergame may be more difficult than a twitchy, fast-paced exergame. We define the total score P_{total} at the end of an exergame instance as follows:

$$\begin{aligned} P_{max,eg} &= P_{max,m} * T \\ P_{eg} &= P_{max,eg} * S * M \\ P_{total} &= P_{eg} * (1 + D + A + X) \end{aligned} \tag{7.2}$$

$P_{max,eg}$ represents the maximum possible points to be gained for that exergame instance and P_{eg} represents the points obtained relative to the exergame performance. This formula has the following consequences: a longer exergame nets more points; to get a high score, the patient needs to play the exergames correctly (high S and M); if a player completes the exergame with a high success percentage (high S) but she is not moving correctly (low M), she will get very little points; if the player does not complete the exercise with a high success percentage (low S value), even if she is moving correctly (high M) she will still get very little points; difficulty (through D, A, and X) increases the points earned, but can never diminish them.

As an example, the final score may be obtained as follows:

- $P_{max,m}$ = 1000, this is an arbitrary value.
- $T = 2$, the exergame lasted two minutes.
- $S = 0.8$, the patient has successfully completed 80% of trials. This means that the player is winning most of the time, but not always.
- $M = 0.8$, the patient has been playing carefully, paying attention to the monitoring constraints.
- $D = 0$, the game was played at the minimum difficulty level (easiest).
- $A = 0.5$, the game was played at a medium challenge level, due to automatic adaptation.
- $X = 0$, the exercise is part of the easiest category inside the taxonomy.

With this example, the total score is $1,920$, which can be considered a good score value.

To illustrate the ranges of possible scores, we take both the worst and best possible results. The worst result is obtained by either missing all exergame targets or disregarding all monitoring constraints. In this unlikely case, the cumulative score would be zero. The best result is instead obtained by hitting all targets ($S = 1$), while fulfilling the monitoring constraints ($M = 1$), playing at the maximum difficulty level ($D = 1$, $A = 1$, $X = 1$). Considering these values, the player could achieve a maximum score of $4,000$ points per minute.

Note that the range for the score is unrelated to the actual game, as the performance is always relative to the total number of trials. For this reason, any exergame will net the same average amount of points per minute in the 0 to $4,000$ range (with a likely value around $2,000$ points).

Although different multipliers concur to create the final score, during play the patient is just presented with two values: the number of earned points thus far (depending on P_t and the number of successes at a given time) and the monitoring multiplier. The score is shown in the lower right of the screen, while the multiplier is right below, changing color from green to red as it changes value, modifying the point value of incoming trials.

The score scene, shown after an exergame ends, gives details on how many points the patient has earned. Apart from a summary on success ratio and monitoring, during this scene the patient is also given the bonus points according to the difficulty multipliers.

7.3 The Design of the Big Farm Game

As discussed in our guidelines, the motivation factor given by the single exergames can be enhanced when considering them as a whole, for example by having the games share a fantasy. We can however make a step forward by referring to a previous comment we made regarding the separation of game and exercise, where we referred to placing the game either *inside* the exercise, as exergames are typically made, or *around* the exercises. We present here a novel solution that builds upon the latter option: we designed a game in which all exergames can be considered mini-games inside a bigger whole, which we named the *Big Farm Game*. In order to achieve long-term motivation, we add an additional layer of play through the Big Farm Game by integrating the exergames into its bigger goals, which present different time requirements and different challenges unrelated to the physical or cognitive feats that the exergames require. In practice, the Big Farm Game is affected by the results of the different exergames played during a session, effectively removing the limits we explained when talking about the separation of game and exercise, as intuitively demonstrated by figure 7.2.

For this long-term game, we decided to focus on social and exploratory challenges through collaboration, as elders especially enjoy such challenges [86, 101, 212]. In addition, its dynamics take place on a different dimension in respect to the actual exergames, so that any patient may play the Big Farm Game at its fullest regardless of her physical or cognitive disabilities.

We note that the use of both short-term goals (the single exergames) and of long-term goals mimics how rehabilitation works, with short-term, repetitive exercises that lead to the long-term goal of regaining one's lost abilities. Therefore, the patient is provided with short-term feedback through the score obtained at each session and long-term feedback through her progression in the Big Farm Game. These dynamics led us to model the Big Farm Game similarly to popular casual games such as FarmVille[1] and to use simplified farming mechanics, inspired by classics such as Harvest Moon.[2] In our design vision, in the Big Farm Game the patient builds and grows her own farm as a consequence of good performance during the single exergames. By completing the single exergames, the player obtains rewards

[1] FarmVille - Zynga - 2009

[2] Harvest Moon - Victor Interactive Software - 1996

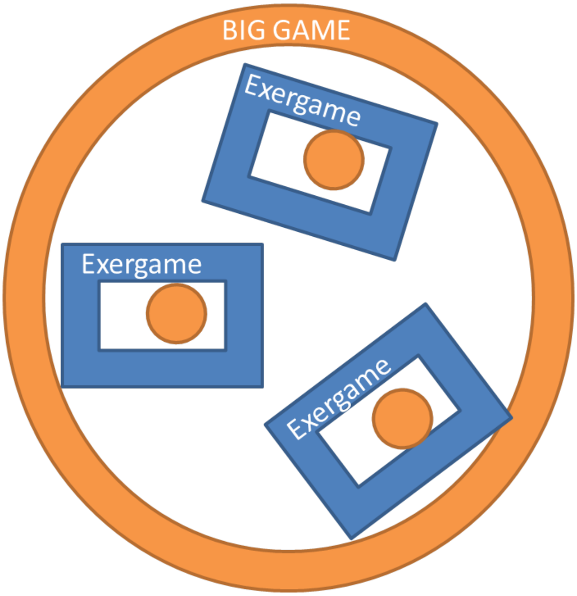

Figure 7.2: *A visualization of how a game built around the single exergames can overcome the limits of typical exergaming.*

that are placed inside a virtual farm that grows as the patient plays. This helps in providing motivation, as what is considered a boring task that needs to be performed several times during a single exercise becomes just a small piece of a big puzzle, the completion of which is the final goal.

We designed the Big Farm Game with the following criteria in mind:

- *Reward system*: the basis of the Big Farm Game lies on a reward system, allowing the patient to collect virtual rewards.
- *Social interaction*: patients can see what their friends are doing through a social network, interact with them with messages, and exchange in-game bonuses, effectively promoting collaboration.
- *Long-term growth*: the patient sees her farm getting bigger while her trees and her animals grow inside its boundaries. The patient obtains new items that are then placed around the farm, so that it is populated with time. This also reinforces the *shared fantasy* of our exergames, as player-created stories can arise as a form of *emergent storytelling* thanks to the progression of the farm, introducing a narrative into the games without explicitly developing additional content [116].
- *Personalization*: the patient is rewarded with personalized items that are procedurally generated to be unique to her. This gives the patient

a sense of uniqueness that acts as a motivational factor, as well as feeding curiosity.

- *Exploration*: the patient is able to visualize other farms around her own, thus obtaining a sense of shared progression with other patients. The patient can also explore the search space of the generated rewards.
- *Progression feedback*: the whole farm functions as an overview and feedback of the current state of the progression in the rehabilitation, with a big farm full of plants and animals reminding the patient of all her achievements. A sense of progression is indeed very important when employing virtual rewards [101].
- *Score system integration*: the rewards that can be placed inside the farm are obtained through the score system. The score is directly translated into a virtual currency that is then used to purchase the rewards. This makes sure that the farm is an interpretation of the progression of the patient, and that reward is proportional to investment [110].
- *Automation*: most trivial actions, such as placing items in a believable position inside the farm, are automated by the system so that any patient may use it. The interface will thus be rather simple, requiring that patients, for the most part, only answer specific yes/no questions with a gesture.

Although we designed it and created most of its modules (the farm virtual scene, the PCG generator, and the reward system), the Big Farm Game is still currently in development and it has not been used for the clinical validation of the system. However, to test some of our design choices with actual patients, we created and introduced a partial reward system into the current version of IGER, allowing patients to interact with it and give us initial feedback.

7.4 The Reward System

Following our Big Farm Game requirements, we built generic support for reward systems inside IGER through inheritance. IGER communicates with the reward system at two different points: it shows the obtained virtual rewards in a specific scene and, at the end of an exergame, it asks the reward system to show newly obtained rewards. It is then up to the derived classes to perform the needed steps to implement the reward system.

We developed two alternate reward systems. The first, named *Icons Reward System* (IRS), functions as an initial prototype: it uses variable reinforcement schedules and collectibles to increase patient motivation. The second, named *Plants Reward System* (PRS), is still in development and functions as an improvement over the IRS. It adds progression mechanics and PCG techniques to the mix, creating a more compelling and complete reward system that fulfills all our criteria.

7.4.1 The Icons Reward System

This reward system consists of a set of collectible icons that are unlocked by completing exergames. The basis of this reward system consists in series of funny icons, with eighteen icons per each series. We currently have three series: farm food, farm animals, and farm products. Both new icons and previously obtained icons can be found, mimicking the process of stickers collection (where duplicates are common). As such, there is a possibility that the user will earn an icon she already earned and the probability of this happening increases as the player reaches completion of the series. When a series of icons is completed, the next series is unlocked.

Icons can be seen in a specific scene, with collected icons appearing in full color and yet-to-be collected icons grayed out (figure 7.3). By showing the unavailable icons in a grayed out fashion, we build up expectations for players as they will be curious about finding out what lies behind the hidden icons, although the silhouette makes them predictable enough to maintain a degree of anticipation [76].

Figure 7.3: *The scene showing the current icons collected by the patient.*

At the end of each exergame, there is a chance that an icon is obtained, and the probability of winning is dependent both on random chance and on the results of the exergame. Whenever a game is completed, a slot machine mini-game automatically starts (see figure 7.4), and the three slot cylinders spin and then slow down, halting on one of the six figures. If the three cylinders show the same figure, the patient is awarded a new icon. Due to the luck factor, the reward system uses a variable reinforcement schedule, which is known to have big motivational effects and is thus often used in games [114, 172]. Note that the winning ratio can be adjusted so to let the player win more or less with an eye on the balance of the motivational factor (higher win rates motivate the player) and the total lifetime of the reward system (higher win rates deplete the icons faster). When an icon is won, a wrapped gift box appears from the bottom of the screen and automatically opens after a few seconds, building suspense. An icon then comes out of the box with an animation and a fanfare sound.

Figure 7.4: *The slot machine mini-game appears as the game ends and allows the patient to obtain bonus rewards.*

While this reward system is simple to implement and can provide motivation for a long time, it doesn't address all our design criteria. In particular, it does not support social play, progression feedback, nor personalization.

Engagement through Variable Reinforcement

We designed the system to keep the player engaged for the full three months of the pilot test by playing on the probability of completing a series. Our aim is for the patient to earn all rewards after n exergame instances, with a single chance of earning a reward per completed exergame. We formulate our requirement as follows: how many instances n do we need to make sure that with probability $P > t$ a specific reward is earned? Or, similarly, how many instances n do we need to make sure that the probability of never earning a specific reward is $P < 1 - t$? Since we are treating a sequence of n draws with replacement, we can model our requirements through a binomial experiment, using a random variable $B(n, p)$ with a binomial distribution. The probability $P(k)$ of getting exactly k successes in n trials is given by the probability mass function

$$P(k) = \binom{n}{k} p^k (1-p)^{n-k} \tag{7.3}$$

In our case, n is the unknown value, $k = 0$ (no successes), and p depends on the number of rewards per series (3 series of 18 rewards). Also, at each exergame instance, we fix the probability of winning anything at all as 50%, without taking into account the performance of the patient which is assumed here to be average. As a consequence, the probability of earning a specific reward is

$$p = \frac{1}{18} \cdot 50\% = \frac{1}{36} \tag{7.4}$$

and the probability of *not* earning that reward is

$$q = 1 - p = \frac{35}{36} \tag{7.5}$$

We set the statistical threshold to $t = 95\%$, so that $P(0) = 1 - t = 0.05$. We thus have:

$$\begin{aligned} P(0) = 0.05 &= \tbinom{n}{0}(\tfrac{1}{36})^0(\tfrac{35}{36})^{n-0} \\ 0.05 &= (\tfrac{35}{36})^n \\ \log(0.05) &= n\log(\tfrac{35}{36}) \\ n &= \tfrac{\log(0.05)}{\log(\frac{35}{36})} = 106.34 \end{aligned} \tag{7.6}$$

Hence, we need at least $n = 107$ exergame instances to earn all rewards of one series with a probability higher than 95%, and 321 instances to earn the rewards of all 3 series. With a mean of three exercises per day, on average, a patient will take around 107 days to complete the reward system, and this means that the reward system will cover all the 3 months of therapy.

7.4.2 Plants Reward System

We designed the PRS to fulfill all our design criteria for the Big Farm Game. This reward system is built on top of the IRS and thus uses the same slot-machine mechanic to collect rewards. Instead of collecting icons, the player is awarded with a virtual newborn plant at the end of each exergame. These plants are randomly generated using a PCG algorithm, so that the structure of two plants is never the same, gifting each patient with personalized content. The plants are collected inside the farm scene, and the patients can see them before they start a daily rehabilitation session. Obtained plants are initially stubs and grow as the therapy advances. Plants are arranged inside the farm automatically, so that no input is required by the patient, effectively providing a type of automated play (which is not dissimilar from many popular *casual games* [92]). To link this system with scoring, and thus give a further motivation for patients to achieve good performances within the exergames, new plants can also be obtained by spending the player's accumulated score points. This design also includes the possibility for patients to show their farm to other patients online, in a similar fashion to online social games.

Although social features and scoring integration are still to be implemented, we created the modules that generate the procedural plant meshes and display them in the game. We implement the procedural generation of plants through parametric L-systems, as they represent a natural way to model different plant formations [118]. We developed a set of python modules that allow the user to create and manipulate parametric strings and generate rule-based parametric stochastic L-systems that use these strings. We also added a set of methods that allow the incremental modification of L-systems, introducing reasonable modifications in order to always generate parametric strings that can be transformed into plants. Another module defines a turtle graphics environment that allows the user to input a parametric string and output the 3D representation of a plant. This environment takes into account the structure of plants, addressing gravity, tropism, and branch weight. After a tree representation is produced, we use the Blender 3D graphical engine[3] to render them to screen, using a few additional visual parameters (trunk size, leaf color, leaf shape, flower type, plant age, etc.) to generate the final 3D plant mesh. We developed the system as a set of python modules that communicate with Blender, obtaining a system that, given a few parameters as input through an in-engine GUI, generates a new plant-like mesh (figure 7.5).

To create actual plant-like meshes, we paired the plant PCG tool with evolutionary algorithms. To do so, we defined a fitness function, a set of operators, and a goal. Given a generated plant mesh, we define its fitness function according to botany-inspired rules (see [144]). At each evolution step, we apply crossover and mutation operators to a population of plants

[3]http://www.blender.org/

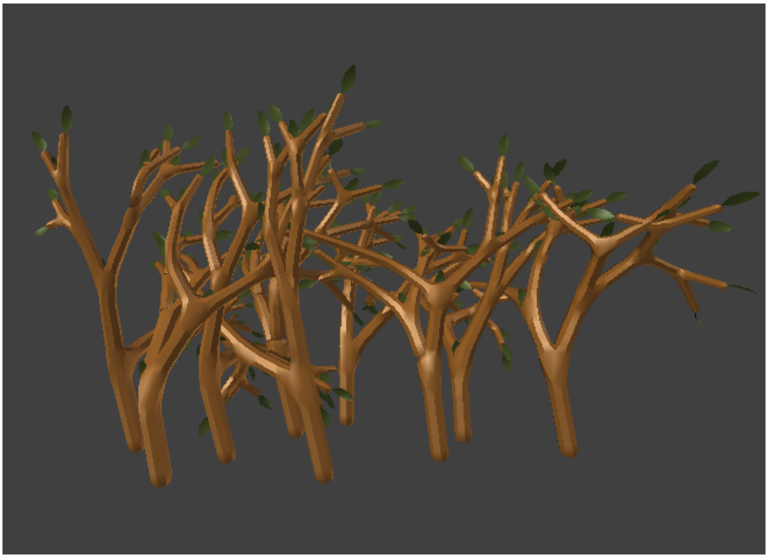

Figure 7.5: *An example of plant meshes generated with our tool. These plants share the same structure but we use stochastic variations to create some differences.*

using a set of incremental generation methods we defined, performing subsequent evolution steps and stopping when the desired fitness is reached. Since this automatic evolutionary algorithm is hard to tune and tends to produce similarly-looking meshes due to the fixed fitness constraints, we are currently experimenting with an interactive evolutionary algorithm inspired by [131], which consists of a web-based application that presents its users with a selection of generated plants, allows them to rate the instances, and then uses this information as a fitness value (figure 7.6). Due to the subjectivity of visual plant quality, this can be an interesting approach.

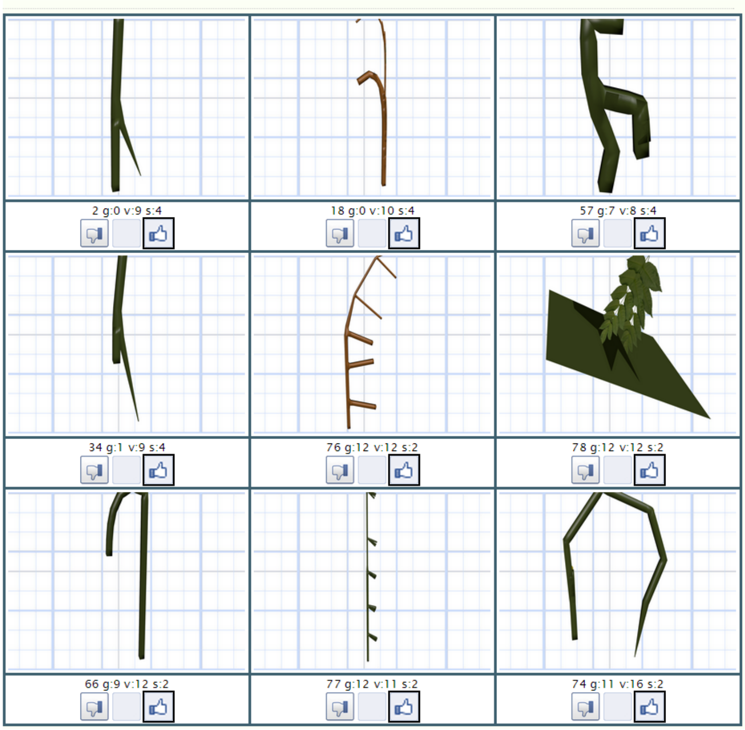

Figure 7.6: *A panel in the interactive evolutionary algorithm web-based application. The user has selected the plants he prefers, which will be used for further evolution.*

CHAPTER 8

Results and Validation

In this chapter, we discuss the results of the initial experimental validation of our system and of our exergames for balance and posture rehabilitation. The experiments involved both healthy elders and post-stroke impaired patients, they were performed in collaboration with our clinical partners who conducted several studies at different stages of the development. Initially, the exergames were used in single-session usability tests with healthy elderly and post-stroke patients to assess usability and acceptance. Then, they were used in preliminary multiple-session studies to test compliance and appropriateness; finally, the complete system was used in a pilot test of the REWIRE project to assess therapeutic efficacy. Due to the time frame of the project, we are still waiting for the final clinical assessment of the pilot test, although we received positive preliminary results from our partners. Alongside these studies, we performed dozens of minor tests by letting several people (mainly clinicians, but also the general population, comprehending children and elders alike) use our system at specific events, such as workshops, research dissemination events, project meetings, or by invitation in our laboratory. In the rest of this chapter, we detail the studies we carried out and our results so far.

8.1 Usability Study with Post-Stroke Patients

The first usability study was conducted in September 2012 with post-stroke elderly patients at the *Zentrum für Ambulante Rehabilitation* (ZAR) in Zurich. The objective was an early evaluation of the system aimed at usability and technology acceptance with actual patients and therapists.

We tested our exergames and the IGER system with two post-stroke patients (two years since the event) and two clinicians. The study comprised a single session of around two hours per user, with both patients and clinicians trying the system out. The patients were able to play three exergames: *Fruit Catcher - Lateral Weight Shift*, *Scare Crow - Stand Still*, and *Balloon Popper - Reaching*. Adaptation and monitoring were enabled, as well as speech and gesture control. Configuration was limited to the choice of difficulty level, chosen by the therapist. All the exergames were played using a Kinect, a Wii Balance Board, or a Tymo plate. Assessment was conducted through a usability and acceptance questionnaire, as well as short interviews with both patients and therapists.

All users reported that the games were fun to play and easy to learn. They reported also a good amount of challenge, thanks to the choice of difficulty. Interaction through Kinect and the balance boards, as well as gesture and speech control, were reported to be easy and fun. Monitoring and adaptability were deemed useful both by patients and clinicians. The graphical interface was however reported to be unclear and confusing. In particular, the difference between buttons and text labels was unclear and more visual feedback was requested. The instructions shown before play were considered unclear as well. Patients also asked for more feedback on their progression and more content to motivate them. This happened prior to the design of the reward system and the scoring system that handle this issue. Patients and therapists also found the initial auditory warning feedback we linked to monitoring constraints to be overwhelming and we removed it, leaving just the color-based feedback that instead received a good response.

This preliminary set of experiments demonstrated a good degree of acceptance and usability, prompting further development in the chosen direction. However, we noted issues related to the graphical user interface. Following an iterative prototyping design, we redesigned the graphical user interface to meet the patient needs. The result can be seen in our current interface.

A similar procedure was carried out in April 2013 to gather additional feedback.

8.2 Usability Study with Healthy Elders

In the second study, in December 2012 we tested the system in Lecco, Italy, with healthy elders. The goal of this study was to analyze usability and technology acceptance of the system and the exergames with elders. Complete results are published in [156].

We tested our exergames and the IGER system with seven subjects aged 68 to 82. All elders were healthy, but most had a past history of physical impairments (including stroke, heart problems, arthritis, and hip prosthesis). The study comprised a single session of around 30 minutes per user. Although different exergames were shown to the users, we focused especially on the *Fruit Catcher - Lateral Weight Shift* exergame. Adaptation and monitoring were enabled, as well as difficulty selection. All the exergames were played using a Kinect and a Wii Balance Board. Assessment was conducted through a usability and acceptance questionnaire, as well as short interviews.

All subjects found the exergames engaging and stimulating and also rated all the virtual scenarios positively. All patients reported that the exergames were very easy to learn and the visual instructions, in particular, were highly appreciated. Only one subject reported some difficulties in learning the game mechanics at the beginning, but she did not find further problems in playing after reviewing the instructions. Monitoring functions were evaluated positively by the patients and color-coding was rated as the best source of feedback. On-line adaptation was completely transparent to the subjects, who did not realize it was in effect. They all reported experiencing a proper challenge level and reported no frustration while playing. No pain nor stress were reported.

Through these experiments we validated our system and exergames for acceptance and usability by elders. This study also represented a further step in our iterative design: for example, following the elders' feedback, we switched from a hourglass to a timer clock to show more clearly the duration of the exergame. Most users asked for the possibility to choose their own music, and we also added this functionality.

8.3 Pre-pilot Study with Healthy Elders

Our clinical partners in ETH Zurich conducted in spring/summer 2013 a preliminary in-hospital study using a more advanced version of our exergames to assess usability, attrition, adherence, technology acceptance, and therapeutic effects [208].

In this study, sixteen healthy untrained elderly subjects performed three supervised training sessions each week for a period of twelve weeks. They trained for 20 minutes per session, for a total of 36 sessions. Five exergames were used for the intervention: *Scare Crow - Stand Still*, *Hay Collector - Lateral Weight Shift*, *Fruit Catcher - Lateral Weight Shift*, *Animal Hurdler - Lift Legs*, and *Bubbles Burster - 360 Weight Shift*. The focus was thus on balance and gait training. Monitoring was enabled, as well as exergame and difficulty selection through a simple user interface specifically created for the therapists. All the exergames were played using the Kinect sensor and/or a Tymo plate. Assessment was performed using the Berg Balance Scale, the 7-Meter Timed Up and Go test, and the Short Physical Performance Battery test.

Thirteen participants completed the study (18.8% attrition) without missing a single training session (100% adherence). Participants showed high acceptance of the intervention, and they expressed the intention to continue using the exergames, which were seen as easy to use and useful. They also evaluated usability of the exergame-based training intervention positively. The intervention improved gait and balance-related physical performance measures in the elderly. No patient reported adverse effects.

As this study was conducted during the development cycle of the system, we took advantage of it in our iterative prototyping design. In particular, the participants highlighted the need for additional levels of difficulty, while the VTA and scoring feedback were deemed inconsistent and were thus revised. We also changed some of the exergames to reflect the needs of therapists and patients, such as making *Hay Collector*'s interaction more direct, increasing the size of the targets in *Bubbles Burster*, changing the movement of the worms in *Animal Hurdler*, or slowing down the horse in *Horse Runner*. In addition, we took this opportunity to allow therapists to define the standard configuration settings for the different levels of difficulty of each exergame, for the choice of adaptation parameters, and for what monitors should be enabled for each exercise, to be used as defaults in the final system.

This study assessed the usability of an advanced version of the system, prompting positive preliminary therapeutic validation and providing feedback on the exercise parameters' values to be used for the final version.

8.4 Usability Study with Post-Stroke Elderly Patients

We were able to collect additional data in September 2014 thanks to a collaboration with Elena Corradini, a physiotherapy student at the university of

Parma, Italy. The objective of this study was to verify usability, acceptance and therapy appropriateness of our exergames with post-stroke elderly patients. Although the study is still undergoing, we were able to gather some initial results.

Five patients with a previous history of stroke (one to nine years since the event) participated in the study; all patients were stable walkers. Patients used the system for ten daily sessions of 30-40 minutes each. Eight exergames were used: *Scare Crow - Stand Still*, *Fruit Catcher - Weight Shift*, *Hay Collector - Weight Shift*, *Bubble Burster - Weight Shift*, *Animal Hurdler - Lift Legs*, *Wheel Pumper - Lift Legs*, *Fire Fighter - Lateral Steps*, and *Horse Runner - Sit-to-Stand*. The exergames were selected to be played as stand-alone, skipping the rest of the menu scenes. Exergames were configured to be played at a fixed difficulty setting and with a fixed duration (two minutes). All patients played the exergames using a Kinect sensor and a Wii Balance Board. Assessment was performed using TUG, the six-meters walk test, and the ten-meters walk test.

Patients showed good adherence, with just one patient missing one single session due to fatigue. All exergames were reported to be easy to use, and all the patients found the exergames and the system progressively easier to use after the first two training sessions. A patient reported feeling insecure when using the Wii Balance Board. Most of the patients expressed the intention to use the system at-home, if given the chance, mentioning the fact that it would be a good addition to a standard therapy. The exergames were deemed appropriate for training balance and posture by the physiotherapy student. Three patients revealed a post-therapy increased balance performance, one had a stable performance, and one patient is finishing the procedure. As an encouraging effect of the therapy, one patient considerably and visibly improved her standing posture, a conclusion supported by spinal cord tests. As adverse reactions, patients accused minor fatigue, and one patient reported minor nausea during the second week of training. No patient reported pain or injury.

Unsurprisingly, patients reported higher motivation while playing exergames that provided challenges matching their skills, and lower motivation and lower perceived usefulness when playing exergames that were too easy. This is a direct consequence of no personalization being performed during configuration. Several patients reported that the exergames had a higher motivational factor than the traditional exercises given by the therapists to perform at home, and also reported that immediate feedback was very useful. The presence of a Virtual Therapist Avatar (VTA) was deemed useful by the patients, especially due to its text-to-speech capabilities. However, most patients also reported that the VTA could not be a substitute for a real therapist, an observation with which we agree, as its role is to only complement that of a real therapist.

Several patients reported that they could not understand the score system. Since the therapist had not been given any explanation about scoring and the exergames were played as stand-alone, without the additional scoring recap scenes, this is however unsurprising.

This study confirms that the system can be beneficial, and that elderly post-stroke patients are willing to use the final system. Also, the need for personalization to provide adequate challenge as well as adequate efficacy is validated as being of great importance.

8.5 Pilot Test: Autonomous Post-Stroke Elderly Patients

The final Patient Station (PS) and its exergames were selected for use in a three-months pilot study with post-stroke patients at home. The objective of this study was to assess usability, adherence, acceptance, and effectiveness of the final and complete system.

During the pilot test, the complete system was employed, alongside all of our posture and balance exergames. The PS was placed at the home of the patients, who used the system autonomously for the duration of the therapy. The therapist supervised the patients remotely and asynchronously using the Hospital Station (HS) and went to their homes on a weekly basis or if some issues were found. Patients started the therapy after a period of in-hospital training, acclimatizing with the interface and the exergames. The pilot study was conducted in two separate clinical centers: the university hospital *Virgin del Rocio* in Seville, Spain and the neurological rehabilitation institute *Cereneo* in Vitznau, Switzerland. Due to the time frame of the REWIRE project, the pilot tests have not been completed yet, although the system was installed in the house of six patients in Seville. Three patients completed the at-home training program, while three more patients are currently using the system at home. Three more patients are currently performing the training in Vitznau. Patients used the system for two to three months, with daily sessions of around 40 minutes each.

From the preliminary results received from Seville, patients showed good adherence, satisfaction, and acceptance of the technology, expressing a desire to continue using the system. Patients reported that the system and the exergames represented an important motivation to complete the therapy. They also expressed a preference for some games, mainly *Horse Runner* and *Bubble Burster*, due to the higher perceived challenge. Some patients had difficulties using the system correctly at the beginning of the rehabilitation period, but after additional explanations by the clinician and an in-hospital training session the issues were solved. Although a throughout clinical testing is in the works, we were able to collect some preliminary results on effectiveness: from a subjective point of view, patients feel themselves more stable and secure in their movements and no adverse reaction to the therapy was reported.

During the pilot test we experienced some technical problems due to the at-home nature of the system, mainly related to the initial installation performed by the therapists or to hardware issues with the Tymo, the Kinect, or the computers given to the patients. Other technical issues were found in the communication between the PS and the HS, with internet connections being slow or dropping altogether, blocking out the patient for a while. Thanks to our iterative development procedure, we solved the technical problems on the go by providing more robust software solutions, less prone to shut down after hardware problems, and we provided the patients with timely updates of the system to solve emerging issues, adding features such as off-line use, multiple session support, and delayed results reporting. Many issues were solved with a better understanding of the system by therapists and patients alike. Therapists reported that indeed problems had diminished greatly after the first days of rehabilitation, after the patient got accustomed to using the system.

Following initial feedback, during the pilot test we also made a few modifications on the alarm and feedback modules. In particular, we added a cool-down timer when triggering multiple subsequent pauses as they were reported to be too intrusive, and we added a smoothing of the color values associated with monitoring to avoid a twitchy visual effect with fast movements.

This study validated the use of the system for autonomous rehabilitation at home for what regards acceptance, usability, and adherence. The clinical results are good as well, but still preliminary. We are however confident that the final clinical results will match our expectations, extrapolating from our previous studies and referring to other previous successful at-home rehabilitation studies with exergames [162].

CHAPTER 9

Conclusion

In this work, we designed and developed a *game engine for rehabilitation* and used it to create a set of carefully designed exergames for posture and balance rehabilitation of post-stroke elderly patients in an autonomous at-home setting. The game engine is now part of a Patient Station currently under clinical testing. We validated our exergaming therapy through several studies, achieving good results for usability, acceptance, and adherence, and pointing to good predictions for clinical validity.

Throughout our work, our new definition of *exergame* was a powerful tool that allowed us to better tune the exercise and game aspects independently, ultimately increasing the quality of both. The definition spawned our consistent pipeline for the creation of exergames as well as our exercise and game design guidelines, which were used extensively in this work, allowing us to create better exergames. Although most of the guidelines are based on previous work in the field, we also provided a comprehensive list, as we found much confusion in the literature about terms. The concept of *therapist supervision* played a major role in pinpointing these guidelines and clarifying the difference between automatic and supervised solutions. Through our design process we identified several dualities between guidelines, such as the duality between configuration and adaptation (both have the same goal, but function differently), or exercise adaptation and Dynamic Difficulty Adaptation (both change the difficulty of the exergame, but from the different points of view of exercise and game).

We validated the feasibility, efficacy, and consistency of our design solutions through the creation of nine exergames for posture and balance rehabilitation using an iterative prototyping design method. We also made a step forward and included our solutions in the design and development of a complete engine for rehabilitation. In particular, our efficacy guidelines allowed us to structure a complete engine that addresses all the needs of rehabilitation and to position our approach in comparison with other solutions, while our motivation guidelines were useful to complement our engine with modules to further increase patient compliance. We equipped our game engine for rehabilitation with modules to promote autonomous rehabilitation thanks to the innovative use of computational intelligence methods to achieve on-line monitoring, on-line adaptation, and effective patient feedback. In addition, our engine served as a basis for the development of our exergames, so that our pipeline and guidelines could be more easily followed due to the abstractions we introduced.

With this work we were thus able to address the research questions we presented in the introductory chapter (see section 1.5): we defined what is required to perform rehabilitation in an autonomous and safe setting through our guidelines, and we proposed technological solutions that can help in making rehabilitation autonomous. We also showed that exergames can be useful for autonomous rehabilitation, how efficacious and motivational exergames can be designed using our guidelines, and how we can efficiently develop them by leveraging a game engine.

9.1 Notes on the Results

Our exergames were validated through clinical and usability studies conducted with elders and post-stroke patients; this allowed us to assess their therapeutic and motivational effects, and to validate the effectiveness of our game engine and of our design solutions.

In general, we obtained positive feedback. In all the studies we conducted we had high acceptance both from our target population, elders and elderly post-stroke patients, and other populations, such as healthy adults or children. We believe that the simple visual style and the farm theme helped in achieving high acceptance in different populations. However, the clinical background of the application (having actual therapists behind the exercises and supervising remotely) had an important part in making sure that the system was perceived as useful therapy and not only as a pastime. This is reinforced by the 100% adherence we found in our pilot test, showing that the system was considered useful for the full duration of the study. Adherence and acceptance results also highlighted the beneficial motivational effect of our exergames, also reinforcing the high usability of our system as patients were able to use the system with relatively low effort. Although usability was rated good even for the initial prototypes, we kept improving it through iterative design and thus finally obtained a system usable autonomously for several months. In fact, a lot of our development effort went into this. At last, we note that the exergaming therapy we developed had beneficial therapeutic effects on the patients. However, our conclusions on efficacy are based on limited data, with our major issue being the limited number of people who completed the pilot test as of today.

Nonetheless, the studies highlighted some issues in using our system, which we recap here. While usability was rated high, no patient was able to use the system autonomously without some initial training: this is due to the novelty of the system, and also to its prototypical nature. The use of technology in a home environment was the source of several issues during the pilot tests as well. A last category of issues was found regarding motivation, especially concerning social issues and long-term motivation, as patients reported wanting something more from the scoring system or the icons reward system. Most of the issues have been now solved, and we feel the future use of our new reward system will address the motivation issues that arose.

We compare our results to a similar project, which used exergames and instrumented data gloves to promote rehabilitation at-home for children suffering from cerebral palsy [70]. In particular, the authors highlighted the difficulty of the at-home therapy due to the medical condition of the children, due to technology issues, and also due to motivational issues, with patients losing motivation up to stopping using the system altogether. The issues encountered with our system were instead of minor importance, and we believe this is due to the use of iterative prototyping, to the understanding of the usability needs of the patients, and to our focus on good game design guidelines to achieve a good motivational effect, further reinforcing the benefits of our solution. However, we acknowledge that problematic technical issues can happen during at-home autonomous rehabilitation, and this must be better taken into account throughout development, preparing ahead of time by providing timely technical support and adequate training.

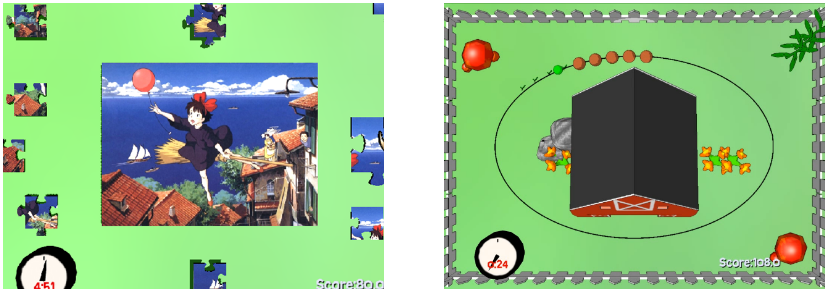

Figure 9.1: *Two exergames specifically created for neglect rehabilitation using our game engine. Left: Puzzle Maker, right: Path Follower.*

9.2 Neglect and Upper Limb Rehabilitation

To test the flexibility of IGER, we applied it to the development of exergames for other pathologies. In particular, we used it for cognitive rehabilitation of neglect patients following stroke. Following our guidelines, Elif Surer, a post-doctoral researcher in the *Applied Intelligent System laboratory* at the *Università di Milano*, created nine exergames for neglect rehabilitation (see figure 9.1 for a couple of examples). Some of these exergames take advantage of our already existing games, such as *Balloon Popper*, or produced games that were then re-imagined to use with physical exercises, such as *Bubble Burster*, All neglect exergames follow our exercise parameterization and structure with a few modifications, mainly concerning initialization procedures and the addition of cognitive parameters, and were created following our guidelines and our pipeline. All exergames were designed to be used with a Novint Falcon haptic device, as the haptic feedback is quite useful in neglect rehabilitation to help the patient in exploring the neglected area. The Novint Falcon device was thus integrated into our system and was used both as a navigation device, a gameplay device, and a logging device. A neglect rehabilitation pilot test is bound to be performed at the start of 2015. More information on the neglect exergaming therapy and the exergames created for it can be found in [190].

In addition, we also explored the use of IGER for the development of upper limb exergames. In particular, we extended the *Balloon Popper* game to support this type of exercise. When used to rehabilitate the upper limbs, *Balloon Popper* is played inside a virtual environment that uses a special interaction modality: patients interact with the virtual world through an augmented mirror modality, so that they can see themselves moving inside the game screen (see figure 9.2), making reaching tasks much more intuitive.

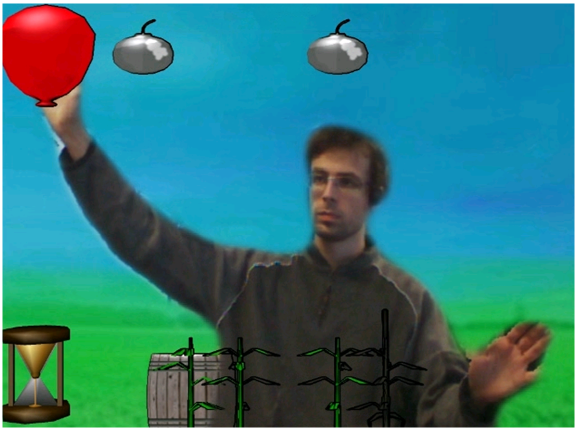

Figure 9.2: *The Balloon Popper game, played with an upper limb reaching exercise, using an augmented mirror interface.*

The use of IGER for these different pathologies reinforces its usefulness as a game engine for rehabilitation.

9.3 Discussion

We propose here some general directions for future work in the field of rehabilitation exergames, based on the current state of the art and on our experience.

9.3.1 Exploration of Game Genres

As a first interesting research direction, we point to the exploration of different game genres, as virtually no game we reviewed has role-playing or strategy elements. These genres are usually slow paced and more complex, even in their interfaces, when compared to action and puzzle games. The use of elements taken from such genres could make exergames more compelling and with a longer-lasting appeal. The integration of such genres with more active gaming could give birth to a new generation of exergames which would leverage orthogonal dimensions of play. Role-playing and strategy games also possess greater longevity due to the large amount of content (for role-playing games) and of the large possibility space created by their mechanics (for strategy games). We admit, however, that these games would require a larger development effort and are thus less appealing for research, pointing once again towards the need for a more integrated collaboration with professional game developers. Note however that direct and simple interactions should be preferred for exergames, and this should push researchers towards creating strategy and role-playing games that are simpler than their typical entertainment counterparts.

9.3.2 Computational Intelligence

Another aspect we feel is in need of more research effort is the use of computational intelligence to enable autonomous rehabilitation. In this work, we show solutions to automate parts of the therapy, and there are a few other solutions in the literature, although most of these have either limited experimental results or address only narrow functions. Nonetheless, the field of computational intelligence is large and has already seeped into game development and virtual reality rehabilitation, we thus see little reason not to extend it to exergames. We also remark that the use of computational intelligence could possibly lead to an automated loop between configuration, assessment, and the exergames, basically producing fully-autonomous rehabilitation.

9.3.3 Contrasting Preferences

Throughout our work, we noticed a trend with the feedback from therapists and patients: some of our design questions were left unanswered, often with opposing feedback being reported by different subjects. For example, patients, according to some therapists, should never be notified of their therapeutic progression, lest risking depression in case of negative performance; other therapists instead insist that the patient must be always notified of her progression. Similarly, some patients prefer to see the exergaming system as more of a toy with additional functions, while others prefer to see it mainly as a therapeutic tool. For this reason, a system that shows itself as a toy is preferred by the former type, but not by the latter, while a system that shows itself mainly as a rehabilitation tool produces the opposite result. This is reflected in the choice of Virtual Therapist Avatar (VTA) made by patients, with some patients preferring the realistic VTA because it made the application feel more serious, while others despised it for the same reason, preferring *Piggy* for a more playful feeling. Another example comes from the attitude towards the simple graphical style: some users liked our graphics, while others voiced their preference for a more realistic style. Some of these issues can be solved, as we did, by providing configuration options: this is the reason for leaving the choice of VTA to the patient, or for leaving to the therapist the choice to enable or disable specific scenes at will. However, we believe that further research, especially with quantitative studies, is required to find out whether one option is better than the other.

9.3.4 Cognitive Effects of Games

We introduce the issue of what cognitive effects games can have on the therapy, which is directly related to the separation paradigm we propose. Our work assumes that a game can be placed over an exercise to create an exergame and not affect the underlying exercise at all. While this can be true for physical actions, this assumption may be too weak for exercises that require cognitive skills. After all, a game creates a virtual fantasy, and this means that it adds meaning to the underlying exercise: the same exercise can be played through an exergame that requires the player to hit balloons with her hands, and equally with an exergame that requires her to hit ugly monsters, with an obvious difference in meaning and psychological effect. On the one hand, we mentioned that we can use the effects of meaning given by the gaming coat to promote the needed interactions, as the player will be compelled to touch objects that are supposed to be touched. On the other hand, this added meaning may change the approach of the patient to the exergame, thus voiding our assumptions on separation. This is not only related to fantasy, as the design of a scoring mechanism can have similar effects, akin to the difference between positive and negative reinforcement. We believe that further research in this direction can be quite interesting.

We also note that the use of reward systems and long-term motivational mechanisms can greatly enhance compliance to the therapy, and that these systems can also have a cognitive effect regardless of the underlying exercises. We thus regard exploration of long-term motivational mechanisms paired with ad hoc studies on their effects as a quite interesting future work.

9.4 Ongoing and Future Work

Encouraged by the results, we are now completing the ongoing work related to the REWIRE project. In particular, we plan to obtain the final results on therapeutic validation by completing the pilot study. Following feedback from the pilot tests, we plan to further refine the current system and our exergames, as well as working to further address the emerged technological issues.

A major work we are completing regards the development of the full reward system, which would help us in achieving more effective long-term motivation, to address the issue of social isolation, and to better understand the cognitive effect on patients of games, gamification, procedural content generation, and variable rewards. We thus plan to continue our research in this direction.

We are also working to further expand our system and exergame selection for different pathologies, and we are collaborating with several rehabilitation centers and hospitals for this purpose: for example, we are tuning current exergames for multiple sclerosis in a collaboration with the *Besta* neurological institute in Milan, and we are developing new exergames for hand and finger rehabilitation of children with the *San Giuseppe* hospital in Milan.

We plan to improve IGER by integrating lifestyle and physiological data with monitoring and assessment features. Similarly, we plan to explore the possibility to actually close the loop between assessment and configuration, using data mining and computational intelligence methods to analyze the results recorded during the exergaming sessions and then create a recommendation system to propose modifications in the configuration for the therapists to supervise. Due to time constraints, in this work we paired each VEE class to a single game, but we plan to neatly separate the two in their implementation as well. We also aim to explore multiplayer gaming, as the added social effect can help in fighting isolation. As we suggested previously, we aim to do this by introducing patient-patient and patient-caregiver cooperative play. We also aim to explore new input device solutions, such as the recent Kinect for Xbox One. At last, we think that our pipeline and framework can be taken as a guide by other developers for their own exergames, and we thus plan to release the IGER system as open source software.

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