Doctoral Dissertation

Artificial Intelligence and Immersive Systems Techniques for Precision Physical Rehabilitation

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Abstract

Stroke represent one of the leading causes of mortality and disability worldwide, currently affecting a significant portion of the global population. It is estimated that the number of people in the European Union facing a stroke will increase by 27% in the next two decades. Economically, the cost associated with stroke treatments and post-stroke recovery is substantial, reaching €800 billion annually in the European Union. Specifically, the average cost for a stroke-affected patient in Spain is estimated at €27,711 per year. This issue can be extrapolated on a global scale and is particularly relevant in low- and middle-income countries, generating unmet medical needs.

The previously presented data highlight an unresolved clinical challenge. Therefore, it is evident that we face a global challenge demanding an immediate and long-term response to enhance the quality of life for individuals affected by strokes. Physical rehabilitation is crucial for regaining mobility, improving independence, and ensuring the autonomy of these individuals. This, combined with telemedicine solutions, especially those designed for remote rehabilitation, aims to address the aforementioned challenges. However, it is not sufficient, as there are a series of barriers to overcome, particularly those inherent to the tools used.

This doctoral thesis proposes a set of rehabilitation solutions and environments aimed at facilitating physical therapy for patients with neurological diseases, presented through a series of publications in indexed scientific journals and international conferences. As an innovation, these proposals are based on the use of Artificial Intelligence techniques to provide personalised treatment and the application of immersive technologies to artificially recreate an environment that fully engages the patient in rehabilitation. This personalisation revolves around the definition of a specialised language called *Personalised Exergame Language* (PEL), which is used to define exercises based on the patient's condition and serves as a basis for automating their generation in the rehabilitation environments where they are used. The validation of these proposals has been carried out through various evaluations with patients, allowing for the improvement and evolution of the initial proposals throughout this research. To achieve this, various dimensions related to the impact of motivation on exercise performance, usefulness, ease of use, and patient determination in utilising the different proposals have been analysed.

Finally, an analysis of the results presented in the scientific publications is conducted to validate the initial working hypothesis of this doctoral thesis: the use of artificial and immersive techniques enhances motivation and drives autonomous rehabilitation at home.

Resumen

Los accidentes cerebrovasculares (ACV) representan una de las principales causas de mortalidad y discapacidad en el mundo, afectando en la actualidad a una parte significativa de la población mundial. Se estima que el número de personas en la Unión Europea que se enfrentan a un ACV aumentará en un 27% en las próximas dos décadas. En términos económicos, el coste relacionado con los tratamientos y la recuperación posterior al ACV es considerable, alcanzando los 800 mil millones de euros anuales en la Unión Europea. Específicamente, el coste promedio de un paciente en España afectado por un ACV se estima en 27,711€ al año. Este problema se puede extrapolar a escala mundial y es especialmente relevante en países de ingresos bajos y medios, lo que ha generado unas necesidades médicas que aún no han sido cubiertas.

Los datos previamente presentados exponen un reto clínico no resuelto. Por lo tanto, es evidente que nos enfrentamos a un desafío global que exige una respuesta inmediata y, a largo plazo, que permite mejorar la calidad de vida de las personas afectadas por ACV. La rehabilitación física es esencial para recuperar la movilidad, mejorar la independencia y garantizarla autonomía de dichas personas. Esto, junto con soluciones de telemedicina, especialmente aquellas diseñadas para la rehabilitación a distancia, tratan de abordar los desafíos anteriormente mencionados. Sin embargo, no es suficiente, ya que existen una serie de barreras a superar, especialmente aquellas inherentes a las herramientas utilizadas.

Esta tesis doctoral propone un conjunto de soluciones y entornos de rehabilitación orientados a facilitar la terapia física de pacientes que padecen enfermedades neurológicas, presentados a través de una serie de publicaciones en revistas científicas indexadas y conferencias internacionales. Como novedad, estas propuestas se basan en el uso de técnicas de Inteligencia Artificial, para ofrecer un tratamiento personalizado, y mediante la aplicación de tecnologías inmersivas, para recrear artificialmente un entorno que involucre plenamente al paciente en la rehabilitación. Esta personalización se gira en torno a la definición de un lenguaje especializado denominado *Personalised Exergame Language* (PEL), que se utiliza para definir ejercicios basados en la condición del paciente y como base para automatizar su generación en los entornos de rehabilitación donde se utilizan. La validación de estas propuestas se ha llevado a cabo a través de diversas evaluaciones realizadas con pacientes, lo que ha permitido mejorar y evolucionar las propuestas iniciales a lo largo de esta investigación. Para ello, se han analizado diferentes dimensiones relacionadas con el impacto de la motivación en la realización de los ejercicios, la utilidad, la facilidad de uso y la determinación de los pacientes a la hora de utilizar las diferentes propuestas.

Finalmente, se realiza un análisis de los resultados expuestos en las publicaciones científicas, con el objetivo de contrastar la hipótesis de trabajo inicial de esta tesis doctoral: el uso de técnicas artificiales e inmersivas mejora la motivación e impulsa la rehabilitación autónoma en el hogar.

To Alba
For always being by my side

To my parents
Thank you for everything

Declaration

I hereby declare that this doctoral dissertation entitled "***Artificial Intelligence and Immersive Systems Techniques for Precision Physical Rehabilitation***" is a presentation of original work and is my own personal effort. This work has not previously been submitted and / or evaluated by this or any other university.

The content presented here is based on my reading and understanding and has not been taken from other sources, except where otherwise indicated. All sources are properly recognised within the text as bibliographical references.

Furthermore, I declare myself to be one of the main authors of the work used in this Thesis. Therefore, the following works published in indexed scientific journals have been considered in the presentation of this doctoral dissertation by compendium of publications:

- Cristian Gmez-Portes, David Carneros-Prado, Javier Albusac, José J. Castro-Schez, C. Glez-Morcillo and David Vallejo, "PhyRe Up! A System Based on Mixed Reality and Gamification to Provide Home Rehabilitation for Stroke Patients". *IEEE Access*, 2021 [12]. IF: 3.376 (2020), Q2.
- Cristian Gmez-Portes, José Jesús Castro-Schez, Javier Albusac, Dorothy N. Monekosso and David Vallejo, "A Fuzzy Recommendation System for the Automatic Personalization of Physical Rehabilitation Exercises in Stroke Patients". *Mathematics*, 2021 [14]. IF: 2.258 (2020), Q1.
- David Vallejo, Cristian Gmez-Portes, Javier Albusac, Carlos Glez-Morcillo, and José Jesús Castro-Schez, "Personalized Exergame Language: A Novel Approach to the Automatic Generation of Personalized Exergames for Stroke Patients". *Applied Sciences*, 2020 [42]. IF: 2.679 (2020), Q2.

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1 Introduction

Neurological illnesses, specifically stroke or brain injuries, are becoming more and more frequent in our society [10]. These diseases involve an intensive treatment to reduce pain and improve quality of life. Although there is a significant number of studies to address the double challenge of motivating patients and ensuring an effective remote rehabilitation, the treatment is generally not adjusted to the patient condition. In this context, precision rehabilitation arises whose idea is to provide a technology which is flexible enough to deal with the patient needs.

This chapter presents an overview of the issues related to physical rehabilitation, the context of the work and the motivation that give rise to the research conducted in this doctoral thesis. Next, the research questions and objectives are formulated in order to define a set of actions to answer them. Finally, an analysis of the results reported in the main scientific publications is provided.

The rest of this document is organised as follows. In Chapter 2 is shown the list of scientific articles that have arisen as a consequence of the work developed during this doctoral dissertation. In Chapter 3 includes the conclusions drawn from the results of the scientific articles that support this work, giving answers to the research questions formulated in this chapter, as well as some lines of future work related to the subject of this doctoral thesis.

1.1 Overview and context

1.1.1 General overview

Patients suffering a neurological diseases, such as stroke or brain injury, need intensive physical rehabilitation and require recovery that is supervised by therapists in real time [43]. Actually, these kind of patients frequently need to be transferred to the nearest health centre, where their doctors check whether they are performing correctly their exercises. This also implies ever greater financial burdens on the current health system, which is difficult to sustain in the long term, and it is expected that this problem will only exacerbate as people's life expectancy increases [9]. For this reason, new solutions must be developed to face these challenges.

Recently, some technological breakthroughs have been incorporated to physical rehabilitation with the aims of improving the quality of life of patients [26] and increasing their degree of self-reliance. The most outstanding among these are those based on telemedicine, the aim of which is to make these activities more accessible and thereby enable patients to perform rehabilitation tasks at home [27, 21].

However, even though the previous approaches have been set out as promising solutions in physical rehabilitation, there are certain special challenges which have yet to be resolved. The most remarkable of these are (i) patients do not cease to perform rehabilitation exercises at home, which is related to motivation; (ii) ensuring that these exercises are performed both precisely and effectively, which is related to evaluation; and (iii) the exercises that are played at home are adequate and suitable for the patient, which is related to personalisation.

Nowadays, motivation and evaluation are addressed by the use of gamification techniques and serious games, whose purpose is not just for entertainment, but rather, focused on specific targets in order to imbue conventional tasks with fun, as well as making them motivating [7]. In the context of physical rehabilitation, there are some solutions [39, 11] in which an avatar guides a patient in performing physical activities and provides feedback in real time to help them to understand the degree of correctness of the performed exercise. This is particularly interesting in situations in which children or elderly patients with special needs are treated. Essentially, it encourages them to perform more tasks or to enjoy themselves whilst working on reducing the amount of physical rehabilitation they need [23].

Nevertheless, gamification techniques and serious games are not sufficient in themselves. In other words, it is not enough just to have a motivating design and gamification elements which encourage patients to perform rehabilitation exercises, as this is no guarantee that the desired therapeutic effect will be achieved. Ideally, the rehabilitation activities provided by technological systems should be customised by therapists for each patient based on his or her illness, following the precision rehabilitation principles [20], which would assure that therapy exergames are effective and safe [30].

1.1.2 Work context

This doctoral thesis arises as a project to help solve a current problem within the doctoral programme in Advanced Information Technologies at UCLM[1]. It is also framed within the AIR (Artificial Intelligence and Rendering) research group[2], where technology applied to health is one of the main research lines.

This project has been developed within the framework of the call corresponding to the year 2018 by means of anticipated processing for the awarding of grants of the Strategic Action in Health 2013-2016, of the State Program of Research Oriented to the Challenges of Society, within the framework of the State Plan for Scientific and Technical Research and Innovation 2013-2016. In particular, the project is framed within the health research projects (health technological development projects modality).

The funding obtained was associated with the project entitled "Development, validation and improvement of a telemedicine tool for the remote monitoring of stroke patients" (Ref. DTS18/00122). This project, executed between 2019 and 2021 and funded by the Instituto de Salud Carlos III (Ministry of Economy and Competitiveness) and co-funded with the European Regional Development Fund (ERDF), served as a catalyst to underpin this doctoral thesis.

1.2 Background and motivation

179 million Europeans are living with a brain disorder. In fact, it is estimated that one in three people suffers or will suffer from a neurological and psychiatric disorder. The overall cost to European national health budgets is estimated to be 800 billion euros per year (the same as 5 times the EU budget). According to the European Brain Council, this equates to 1.5 million euros per minute. Neurological disorders such as stroke, dementia or ABI (acquired brain injury) represent a major burden on European and global healthcare systems.

Specifically, in Spain, the cost of patients admitted to stroke units is estimated at 27.711€ per patient/year [2]. More than two thirds are social

[1] https://www.uclm.es/es/estudios/doctorados/Tecnologias-Informaticas-Avanzadas
[2] https://air.esi.uclm.es/

costs, mainly from informal care. Portugal also suffers similar problems in terms of economic and social consequences. The total cost of health and social care for patients with acute stroke each year in England, Wales and Northern Ireland was £3.6 billion [44], with an average cost per patient of £46,039, and is expected to rise to over £10 billion by 2025.

Stroke remains a major burden on healthcare systems and society, so additional efforts are needed for its prevention. There is a large treatment gap for mental health care in low- and middle-income countries, where the majority of people with mental, neurological and substance use disorders receive inadequate or no care [40].

In addition to meeting the needs of costs, there exists the problem of access to care which is not only limited to the access of the clinical centre. Unfortunately, it includes all the journey patient's home and the centre, such as the adaptations for wheelchairs, access for people with crutches, public transport adapted and accessible, or patients living out of the city. In this domain, lots of efforts still need to be taken.

For all the above reasons, there is a clear need to adopt solutions to face the aforementioned challenges that devise new treatments that facilitate the rehabilitation. In this sense, it would be advisable to include technology at the acute phase in which rehabilitation tools are adopted to the treatment. Thanks to the new advances, in particular the internet, a new branch of medicine has emerged: the tele-rehabilitation. This technology can be an alternative to face-to-face approaches to reduce costs, increase geographic accessibility, or act as a mechanism to extend limited resources. However, there are still some problems which concern the technology and affect the benefits and safety of the patients. In this regard, a calibration and customisation approaches seem to be mandatory to adopt in a treatment as each patient is unique with specific pathologies and limitations.

1.2.1 Gamification in Rehabilitation

Gamification is a well-known term in scientific research, and is used in a range of professional areas. It is based on the use of video game design elements in non-game contexts to make a product, service or application more fun, engaging and motivating [8].

In the context of health, there exists a taxonomy which relates different types of games used in a wide range of areas of this branch [34]. Within health and safety, one salient trend is the use of exergames (contraction of exercises and games) for simulating physical activities in order to help fulfil the patients' needs.

The use of video games has been partially based on the explosive expansion of the video gaming market which has had a positive impact on physical therapy interventions [22]. As motivation and engagement are crucial aspects of rehabilitation, this approach is being used to create an attractive and challenging settings to involve participants in the treatment [4].

The different potential and positive aspects of video games presented here above explain the success of integrating games in physical rehabilitation. Games can be used to increase the quality of rehabilitation for several patients. However, physical rehabilitation exercises should meet three criteria in order to be effective and have a positive effect within the treatment.

The first challenge is related to the motivation problem. It is obvious that rehabilitation performed at home is not exciting if there is no stimulus to become patients physically active. To do so, the literature [41] reveals that extrinsic and intrinsic motivation may be beneficial, but if introduced with care. Intrinsic motivation refers to motivation that comes from internal desires while extrinsic motivation is instead triggered by external rewards.

Another aspect, closely related to motivation, is the number of repetitions performed by the patient. It has been clearly demonstrated that the more the patient performs repetitions the more the gain will obtain [6]. As a consequence, the program will be more efficient. This fact is based on the games as patients are involved in the treatment because they are not getting bored when they play.

The last point is regarding guidance. It means that patients are somehow guided to perform the right motion while they play as games are considered goal oriented. In other words, video games are designed to meet targets which can only be accomplished by performing particular movements.

1.2.2 Calibration and Customisation

The idea of a personalised rehabilitation inherently entails a direct relationship with the use of technology for treating each patient's rehabilitation process in a customised manner. Generally, each patient is unique with specific condition inducing functional impairment and limitations.

Video games explicitly designed for entertainment introduce some problems to this respect as they do not support the possibility of modifying any relevant parameter [3]. Generally, they allow a simple difficulty selection between a few fixed options, while rehabilitation requires an in-depth control regarding range of motions and frequency of movements.

Such issues can be mitigated by the presence of the therapist who can ensure that the movements of the patient are correct at all times. However, specific commercial games probably cannot be played by certain patients whose condition does not allow to perform certain movements. Therefore, this approach is ineffective for remote rehabilitation where patients are at home and there is no supervision.

In this respect, autonomous systems are being developed alongside new games to address, partially, the needs of rehabilitation and the capacities of the patients. Based on this, several approaches are currently being used to adapt the games for individual patients [29, 19, 11, 38].

When the game is played under therapist supervision, the professional can manually change specific parameters relevant to the rehabilitation, such as speed, range of motions, joints, acceleration, complexity, etc. Furthermore, friendly-user interfaces have been developed to enable real-time modifications while the patient is playing [25]. On the other hand, if the session is performed at home, the system should infer the patient condition based on previous historical records, i.e., previous and current patient's performances, to update, in a more systematic way, the calibration and customisation of the game parameters [24, 28]. In this case, machine learning techniques are used where huge amount of data is analysed to get relevant and useful information for each particular patient.

1.3 Hypothesis and objectives

This chapter firstly presents the reasons that have motivated this doctoral thesis through a set of research questions which define the hypothesis of this work. They are stated and answered throughout the research articles available in chapter 2.

In order to achieve the hypothesis, the research questions are divided into smaller tasks as objectives that are lastly introduced. In essence, this approach allows to establish a relationship between all of the tasks in order to address the formulated problem from different points of view.

1.3.1 Research questions

Home rehabilitation seems to be a promising solution for physical rehabilitation, but patient motivation and autonomy need to be addressed. Therefore, the research question that we address in this work is thus:

- **RQ**. How can the development and application of Artificial Intelligence techniques and immersive technology be applied to efficiently design autonomous, personalised physical rehabilitation exercises?

In particular, our main research question can be separated into several smaller ones for ease of discussion:

- **RQ1**. How can we efficiently design and develop physical rehabilitation exercises through automatic approaches?
- **RQ2**. Does using immersive technology improve motivation towards autonomous rehabilitation?
- **RQ3**. How can we help physiotherapists and clinical staff personalise and adapt physical exercises with Artificial Intelligence?

As already mentioned, these research questions are addressed, either explicitly or implicitly, throughout the research articles included in this doctoral dissertation. Also, the results achieved in response to these research questions are discussed in the section 1.5.

1.3.2 Main objective and secondary objectives

The main objective of this doctoral dissertation is the "*development of a technological platform, together with methodological guidelines, based on Artificial Intelligence to provide precision rehabilitation, taking into account the psycho-social dimension and the need for natural interaction methods that increase the patient's autonomy. It proposes a co-creation and participation approach between patients and clinicians, in which the participants involved work together to personalise the patient's rehabilitation process.*".

From this objective, other more specific secondary objectives are defined, which allow the tasks to be carried out in a more restricted context. The following section details each of these objectives and the tasks to be carried out to achieve them.

[Obj01] Review of the state of the art

This objective consists in reviewing the current state of the art regarding the main lines of research of this thesis. The idea behind this review is to acquire the existing knowledge from other works and related tools that can potentially serve for the elaboration of the present proposal.

The specific tasks to be carried out to achieve this secondary objective are as follows:

- To perform a study of the state of the art by researching the literature on the following topics:

  - Remote tools for physical rehabilitation based on computer graphics and immersive technologies such as AR (Augmented Reality).
  - Gamification techniques and serious games that allow patients to be rehabilitated in a friendly and enjoyable way.
  - Existing autonomous rehabilitation systems which calibrate and customise the settings of the game based on the patient condition.
  - Up-to-date interaction mechanisms that help patients use easily the rehabilitation system.

- To identify potential improvements and innovation pathways in the topics researched.

[Obj02] Development of the software system

This specific objective is to develop a system for remote rehabilitation of patients suffering from neurological diseases, using appropriate technologies and entertaining approaches.

The particular tasks to be carried out towards achieving this secondary objective are as follows:

- To develop a remote system oriented to the physical rehabilitation through gamification techniques that can help patients at home.
- To develop serious games for patients that help them improve their autonomy.
- To develop a recommender system to propose automatically the most suitable exercises and routines to patients based on their current state.

[Obj03] Artificial Intelligence for precision rehabilitation

This specific objective is to develop advanced mechanisms using Artificial Intelligence techniques to enable personalised rehabilitation.

The specific tasks to be conducted in order to achieve this secondary objective are outlined below:

- To develop a module responsible for recognising the movements of a patient which are replicated by an avatar in a virtual environment.
- To define a language with the lexicon, syntax and semantic in order to specify the gamification and game elements of video games for physical rehabilitation.

- To develop a module capable of understanding specifications using the language defined to automatically create personalised video games.

[Obj04] Use of immersive technologies

This objective consists of integrating immersive and emerging technologies to develop software modules responsible for providing a natural communication interface to patients.

In order to achieve this secondary objective the following specific tasks are defined:

- To explore devices with an integrated in-depth camera that allows to track the movements of a patient during a rehabilitation session.
- To integrate natural interaction mechanisms (such as gestures or voice commands) into the developed software systems.

[Obj05] Rehabilitation environments

This objective addresses the introduction of a rehabilitation environment through use cases that allow to demonstrate the potential of the developed proposals. These use cases will prove its flexibility and scope.

The specific tasks to be conducted in order to achieve this secondary objective are as follows:

- To define a rehabilitation environment highly scalable that allows to integrate easily different use cases.
- To define a set of use cases aligned with the aforementioned rehabilitation environment.

[Obj06] Proposal evaluation and validation

This objective consists of evaluating the system presented according to various criteria.

The specific tasks to be conducted in order to achieve this secondary objective are listed below:

- To conduct an experiment that considers the intrinsic motivation of the patients and the subjective perception regarding the usefulness and ease of use of the proposals.

- To validate the proposal by analysing the results obtained from the evaluations conducted in order to answer the formulated research questions.

1.4 Work plan

As discussed previously, this doctoral dissertation has been developed since September 2019 in the context of the national research project entitled “Development, validation and improvement of a telemedicine tool for the remote monitoring of stroke patients” (Ref. DTS18/00122), funded by the Instituto de Salud Carlos III (Ministry of Economy and Competitiveness) and co-funded with the European Regional Development Fund (ERDF).

The development phase of the doctoral dissertation has been influenced by several factors that have had a great impact on the final result. First, the study and analysis of the existing literature to discover both potential lines of innovation and improvements. Second, the communication with professionals, such as therapists and professors, who have actively participated in different surveys conducted to validate the proposal. Third, the activities in which participated patients who suffered a stroke to validate directly the software prototype developed. Unfortunately, the COVID-19 pandemic reduced the number of experiments initially envisaged. The comments and suggestions provided by all participants have served to iterate on the initial proposal, improving and raising new use cases.

As a result, a set of publications indexed in relevant scientific journals and conferences, both national and international, have been obtained. The complete list of publications directly derived from this doctoral thesis is presented and detailed in chapter 2.

On the other hand, the rest of this chapter presents the work plan designed to complete this doctoral dissertation. It is divided into materials, the items to acquire the specific knowledge and the development the software prototype, as well as the phases followed in which this doctoral dissertation has been built.

1.4.1 Materials

The following are some of the materials used during the development of this doctoral dissertation:

- Books from the UCLM library.
- Digital libraries accessible from UCLM such as Scopus, ScienceDirect,

IEEE digital library and ACM digital library, among others.

- Hardware provided by the AIR (Artificial Intelligence and Rendering Research) group.
- Hardware provided by the WeCareLab (*Wellbeing and Healthcare Living Lab*).

1.4.2 Stages

This sections provides the different tasks of the research, which are shown graphically in Figure 1.1, and are structured in the phases described below.

Planning, analysis and organisation

In this phase, the context of the problem is defined. To this end, a systematic literature review is carried out of those scientific contributions and technological solutions that fully or partially address one or more of the stated objectives. In this way, it is possible to detect unresolved problems or unaddressed approaches and to identify information that can serve as a basis for the research.

- **T1**. Systematic review of the state of the art. This task is associated with the study of the state of the art.

The achievement of this phase allows us to reach the objective [Obj01].

Elaboration of the proposal

During this phase, the proposal that poses a solution to the general objective of this doctoral dissertation is established, thus defining the general framework in which the precision rehabilitation is applied.

- **T2.1**. Definition of the conceptual framework. This task is focused on the study of the general framework in the context of the definition of a methodology for precision rehabilitation. This methodology will guide the design, development and deployment of the precision rehabilitation platform.
- **T2.2**. Architecture design for precision rehabilitation. It's intended to design a scalable and maintainable system that allows the deployment of specific components depending on the physical rehabilitation to be

offered. The reference architecture for this task will be the Lambda architecture[3] for the design of highly scalable systems.

Development & Proposal validation

This phase comprises the core of the thesis in which the development of software prototypes that serve to validate both the proposed methodology and platform is carried out. The focus of the effort has been on the development of the main core, on the customised exergames part, and on the use of advanced.

- **T3.1**. Architecture development and implementation. This task is linked to the programming activities of the central core of the precision rehabilitation architecture.
- **T3.2**. Gamification techniques and customised exergames. This task is related to the implementation of a software module that allows the design and development of customised exergames.
- **T3.3**. Advanced human-computer interaction mechanisms. This task includes the development of prototypes based on computer vision systems, augmented reality and wearable devices to offer natural interaction interfaces. Special attention has be given to accessibility in the context of patients with cognitive and/or communication impairments communication.
- **T3.4**. Validation and application of the proposal to practical cases. This task is linked to the testing of the software prototypes generated, in the context of two specific applications: i) patients with neurological diseases, such as stroke, and ii) patients with spinal cord injury.

The achievement of this phase allows us to reach the objectives [Obj02], [Obj03], [Obj04] and [Obj05].

Result analysis

This phase is aimed at determining the degree of achievement of the initially proposed objectives, in order to evaluate and contrast the initial hypothesis.

- **T4.1**. Fulfillment of objectives and initial hypothesis. This task consists of evaluating the degree of fulfillment of the objectives and the initial hypothesis.

The achievement of this phase allows us to reach the objectives [Obj06].

[3] `https://en.wikipedia.org/wiki/Lambda_architecture`

Result dissemination

This phase includes the dissemination of the results of the thesis project and the preparation of the doctoral dissertation. This phase will take place between months 13 and 36, and consists of the following tasks:

- **T5.1**. Dissemination in international congresses and journals. This task refers to the communication of results in national/international congresses and their publication in prestigious international journals (indexed in the Journal Citation Reports).
- **T5.2**. Elaboration of the doctoral dissertation.

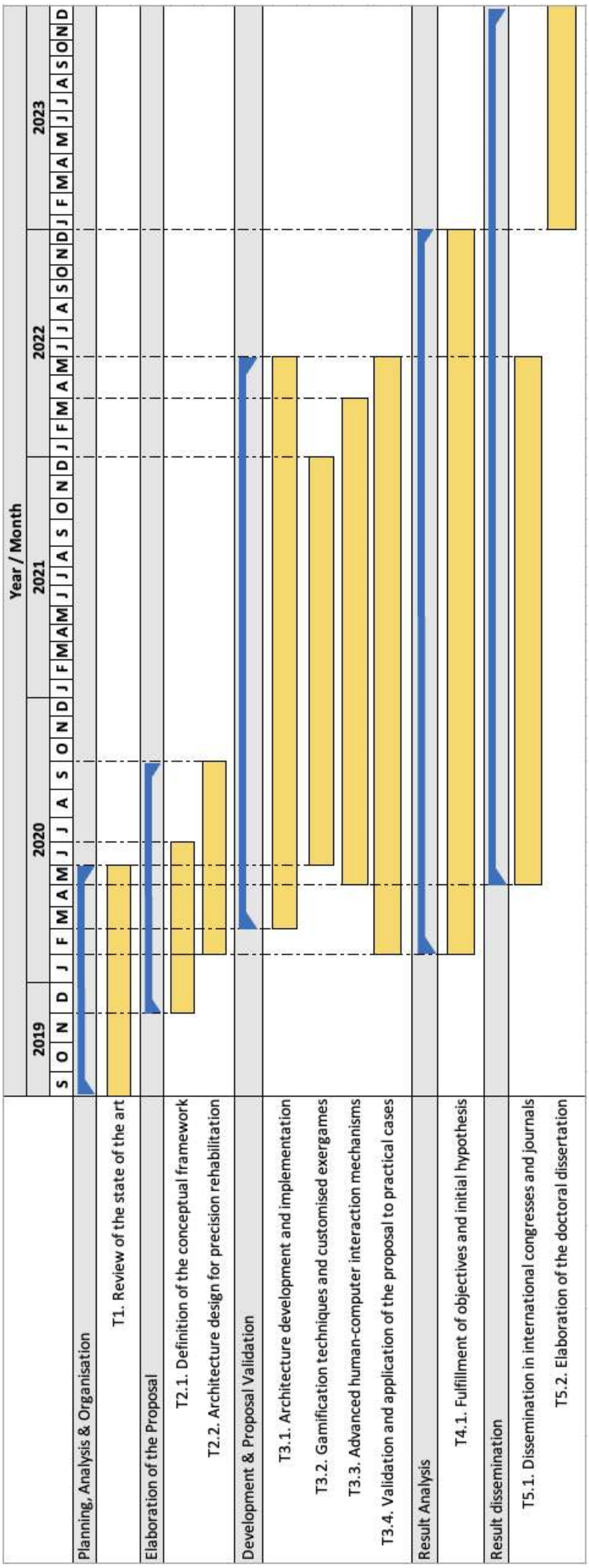

Figure 1.1: Gantt chart of the work plan.

1.4.3 Mobility plan

From 1th May 2022 to 1th August 20202 (3 months) a research stay[4] was carried out at Durham University, specifically at the Department of Computer Science, under the supervision of Professor Dr Dorothy N. Monekosso, with the aim of applying for the International Doctorate mention.

During the first month of the stay, special emphasis was dedicated to improve the prototype, taking into account Prof. Monekosso's ideas, which were focused on the usability of the system, interaction and increasing the number of games available within it. Professor Paolo Remagnino, who has extensive experience in integrating Artificial Intelligence techniques in different fields, also participated in this discussion.

The ideas previously discussed, along with the new development of the system, were demonstrated during the second month of the stay, in a meeting with researchers and staff from QE Hospital Gateshead[5] in Newcastle, UK. This meeting was attended by Prof. Monekosso, who introduced the demonstration of the system, highlighting the impact it would have in rehabilitation settings, as well as the economic savings for health systems, since the current number of stroke patients is increasing worldwide. After the demonstration, feedback was collected from the professionals to improve the prototype. In addition, many of them showed interest and have become involved in the project in order to use the system to help their patients in long term treatments.

During this period of the stay, a paper was written for a fuzzy logic conference in Toledo on the improvements made at QE Hospital Gateshead meeting. The paper was published in the proceedings of the 21st International Conference on Technology and Fuzzy Logic [13], and presented on September 6th. The chapter 2 includes more information on these articles and on the rest of the research articles published during the completion of this doctoral dissertation.

This collaboration has proven to be invaluable, laying the foundation for both current and future endeavours. The insights and feedback received during the research stay at Durham University, particularly from Professors Monekosso and Remagnino, have significantly informed the ongoing development and direction of our work. The promising demonstration of the system at QE Hospital Gateshead underscored the potential impact in rehabilitation settings, spurring further motivation and engagement from healthcare professionals. We are currently working on projects that build upon the ideas and advancements stemming from this collaboration, exploring new ways to optimise rehabilitation and patient care in various

[4]This research stay has been funded by Santander Research Grants for predoctoral stays abroad.

[5]`https://www.qegateshead.nhs.uk/hospitals/qe-gateshead/`

medical contexts. These promising advancements underscore the significance of international collaboration in research and the lasting impact it can have on advancing science and technology.

1.5 General discussion

This section discusses the results obtained from the main publications in scientific journals as well as other relevant articles that come from congress proceedings available in chapter 2.

Below is a brief analysis of the most outstanding results obtained in this doctoral dissertation.

1.5.1 Automatic generation of personalised exergames

Personalised **E**xergame **L**anguage (PEL) is a language designed to customise exergames in order to create adequate rehabilitation treatments while they capture the attention of patients and keep them motivated. Its design envisages certain sentences for designing different components which enable the rehabilitation exercises to be adapted according to the type of patient and illness dealt with. This language is supported by the *GL Transmission Format* (glTF) specification [33] which is based on the JSON standard [5], an open format designed for the efficient and interoperable distribution of 3D scenes and models. This was mainly chosen because it is open source and for the transmission and efficient loading of 3D content, apart from extending the bases of its format. Using this language entails employing a parsing process for analysing sentences and for generating the exergame desired. In this way, the exercises designed with PEL are exported to binary files and deployed on a computer connected to an Azure Kinect DK™.

Essentially, PEL is made up of a series of fundamental components which potentially enable tools to be set up and with which games-based exercises for physical rehabilitation can be developed. Below, the mission of each of them has been summarised:

- **Scenes**. This component contains the information of the different views which the game is split into. The language envisages the *Tutorial view* in which an animated avatar is shown, a scene in which a character displays the movement the patient must perform subsequently; the *participation view*, in which the patient performs the activity that has been seen previously, and his or her movements are replicated by the avatar; and the *result view*, which provides the results, for example, the patient performance or the score obtained.

- **Actors**. They represent the elements of the game which the avatar must interact with. Essentially, these objects are collision spheres that make up the trajectory of the activity the patient must perform. However, they can also be individual objects suspended over certain points in the 3D scene without maintaining a sequence or an order. Moreover, these elements provide visual feedback to indicate that the actors must be interacting or has interacted with the joint in question.

- **Gameplay**. It defines the game mechanics associated with the exergame. In other words, it specifies the set of actions that the patient must perform to complete a repetition of the exergame. The correct execution of these rules will trigger a sequence of actions, for example, updating a progress bar, the number of repetitions completed or the score obtained by the patient, among others.

At a practical level, this approach establishes a co-creation framework in which several roles (therapists, technicians and patients) are involved in the elaboration of physical rehabilitation exercises. Moreover, thanks to its extensibility, this approach is proposed as a foundation to be used in other rehabilitation contexts oriented to the physical rehabilitation, for example, back injuries, among others.

Relevant publications

The most significant scientific publications related to the automatic generation of personalised exergames are listed below:

- David Vallejo, Cristian Gmez-Portes, Javier Albusac, Carlos Glez-Morcillo, and José Jesús Castro-Schez, "Personalized Exergame Language: A Novel Approach to the Automatic Generation of Personalized Exergames for Stroke Patients". *Applied Sciences*, 2020 [42]. This publication covers two well differentiated results: PEL and an authoring tool for therapists. The work introduced the PEL language and how it is used to create easily and efficiently exergames.

- Cristian Gmez-Portes, David Vallejo, Ana-Isabel Corregidor-Sánchez, Marta Rodríguez-Hernández, José L. Martín-Conty, Santiago Schez-Sobrino and Begoña Polonio-López, "A Platform Based on Personalized Exergames and Natural User Interfaces to Promote Remote Physical Activity and Improve Healthy Aging in Elderly People", *Sustainability*, 2021 [18]. This publication arises as a result of an evaluation of physical rehabilitation exercises using PEL with 17 random users, aged between 62 and 89 years. The aim of the experiment was to evaluate the ease of use and usefulness of the built-in exercises using the PEL specification.

1.5.2 Serious games and gamification in rehabilitation

This doctoral dissertation has investigated the use of video games in rehabilitation focused on neurological diseases. Serious games designed with a primary purpose rather than pure entertainment have generally positive effects in therapies. Besides, the combination of gamification techniques enables patients to be involved in the treatment as well as motivated.

Several points can be extracted from this research about the use of serious games and gamification in rehabilitation:

- Variability of games. Although games are an excellent approach to motivate patients, they should frequently change to prevent them from getting bored. It is more empathised in children and teenagers.
- Competition. When video games are used in rehabilitation groups, patients are challenged to do their best and get the higher score. Thus, rehabilitation is performed in order to fulfil its task.
- Difficulty. It appears that if the game is not challenging enough, patients won't play, specially children and teenagers where motivation play an important role.
- Personalisation. Playing the same games can be usually bored. The game should be always attractive which can be achieved modifying parameters of the game, such as speed, number of balls, time, etc.
- Self-efficacy. Immersive technologies are capable of recreating activities to transfer performance from games to activities of daily living. This benefits patients as they are motivated and improve performance in real life.

Relevant publications

The most relevant research articles related to the serious games and gamification techniques are shown below:

- Cristian Gmez-Portes, Carmen Lacave, Ana I. Molina, David Vallejo, "Home Rehabilitation Based on Gamification and Serious Games for Young People: A Systematic Mapping Study", *Applied Sciences*, 2020 [15]. In this research article there is a systematic mapping study to identify how serious games are designed to enable an effective physical rehabilitation in children and teenagers. Based on the results obtained, it presents the improvements applied to the gamification-based software prototype.

- Cristian Gmez-Portes, David Carneros-Prado, Javier Albusac, José J. Castro-Schez, C. Glez-Morcillo and David Vallejo, "PhyRe Up! A System Based on Mixed Reality and Gamification to Provide Home Rehabilitation for Stroke Patients". *IEEE Access*, 2021 [12]. This publication proposes a gamification tool based on mixed reality for stroke patients. The proposal was evaluated with an small group of patients (25) with the objective of analysing the impact of applying immersive technologies in rehabilitation.

- Cristian Gmez-Portes, David Vallejo, Ana-Isabel Corregidor-Sánchez, Marta Rodríguez-Hernández, José L. Martín-Conty, Santiago Schez-Sobrino and Begoña Polonio-López, "A Platform Based on Personalized Exergames and Natural User Interfaces to Promote Remote Physical Activity and Improve Healthy Aging in Elderly People", *Sustainability*, 2021 [18]. This publication is based on the previous work [42] providing new improvements. They are based on new interaction mechanisms and games that support daily living activities to make them more attractive.

1.5.3 Recommender module for physical rehabilitation exercises

This module is an intelligent system that arises with the aim of proposing compelling physical rehabilitation exercises to enable an adequate remote therapy. When this kind of rehabilitation is taken place, the adjustment of the therapy turns into a complex process as the therapist does not know how the patient performs the exercises at home.

The proposal is based on the use of fuzzy logic to represent the therapist knowledge and handle the uncertainty when evaluating such exercises, taking into account the patient condition.

The module is capable of carrying out two different actions based on the patient's performance: (i) it can recommend a routine based on the available exercises in the system, (ii) and perform modifications in existing ones to alter the routine if the parameters are not consistent based on the patient condition.

Relevant publications

The most significant scientific publications related to the module capable of recommending physical rehabilitation exercises are shown below:

- Cristian Gmez-Portes, José Jesús Castro-Schez, Javier Albusac, Dorothy N. Monekosso and David Vallejo, "A Fuzzy Recommendation

System for the Automatic Personalization of Physical Rehabilitation Exercises in Stroke Patients". *Mathematics*, 2021 [14]. In this publication the theoretical definition of the architecture of the recommender module is presented. In order to analyse the capabilities, a case study is developed with the aim of demonstrating the utility and effectiveness.

- Cristian Gmez-Portes, David Carneros-Prado, Javier Albusac, José J. Castro-Schez, C. Glez-Morcillo and David Vallejo, "PhyRe Up! A System Based on Mixed Reality and Gamification to Provide Home Rehabilitation for Stroke Patients". *IEEE Access*, 2021 [12]. This research shows a system based on mixed reality for physical rehabilitation which uses the recommender module to propose compelling exercises to patients. It is clearly shown how the system is flexible enough to be used in different rehabilitation contexts.

2

Results

As previously mentioned, the doctoral dissertation presented herein is constituted as a compendium of three research articles. These are included in this chapter, alongside their main metadata. Moreover, other research articles have been included, which have been published in journals, as book or chapters, and in proceedings of international conferences, which are less related to the objectives of this doctoral dissertation, but which have emerged as a result of other work and collaborations.

2.1 Articles published in indexed scientific journals included in the compendium

In this section of the doctoral thesis, a comprehensive compilation of articles that constitute the core content of the research endeavour is presented. Within this compendium, detailed information about each article can be found. Through these meticulously curated selections, the aim is to showcase the depth and breadth of the scholarly work and its significance in advancing the understanding of the research topic.

Paper	Type	Journal	Publisher	Year	IF	Related?
[12]	Journal	IEEE Access	IEEE	2021	3,376	Yes
[12]	Journal	Mathematics	MDPI (Basel, Switzerland)	2020	2,258	Yes
[42]	Journal	Applied Science	MDPI (Basel, Switzerland)	2020	2,679	Yes

Table 2.1: Summary table with the relevant scientific articles of this doctoral dissertation

2.1.1 PhyRe Up! A System Based on Mixed Reality and Gamification to Provide Home Rehabilitation for Stroke Patients

- Title: PhyRe Up! A System Based on Mixde Reality and Gamification to Provide Home Rehabilitation for Stroke Patients [12]
- Authors: Cristian Gmez-Portes, David Carneros-Prado, Javier Albusac, José J. Castro-Schez, C. Glez-Morcillo and David Vallejo
- Type: Journal
- Journal: IEEE Access
- Publisher: IEEE
- E-ISSN: 2169-3536
- Year: 2021
- DOI: 10.1109/ACCESS.2021.3118842
- Category: Computer Science, Information Systems
- Impact Factor (2020): 3.376
- JCR Ranking: Q2
- Related to the current research topic: Yes

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PhyRe Up! A System Based on Mixed Reality and Gamification to Provide Home Rehabilitation for Stroke Patients

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ABSTRACT Stroke represents a global concern that currently affects a significant part of the world's population. Physical rehabilitation plays a fundamental role for stroke patients to recover mobility and improve quality of life. This process is costly, considering that patients must attend face-to-face rehabilitation sessions in hospitals or rehabilitation centers. Plus, there is a lack of specialized medical staff, who are usually insufficient to properly address the growing number of stroke patients that need physical rehabilitation. This situation has been exacerbated by the COVID-19 pandemic, as some of the human resources have been devoted to fight against the pandemic, and the physical presence of rehabilitation patients in hospitals has been severely limited. This paper proposes *PhyRe Up!*, a novel remote rehabilitation system that uses mixed reality and gamification techniques. *PhyRe Up!* has been devised for stroke patients to perform therapeutic exercises at home, with great precision, and with the potential supervision of clinicians. The system aims to increase the patient's motivation as well as maintaining the quality of performance for the exercises, similar to the obtained levels when attending face-to-face sessions with therapists. The underlying architecture combines declarative, procedural, and conditional knowledge to manage the rehabilitation process, which offers flexibility and scalability to enhance the capabilities of the proposed system. Experimental results highlight how the combination of mixed reality and gamification significantly influences the accuracy of rehabilitation exercises previously defined by therapists. Particularly, the conducted experiments in the first validation phase of *PhyRe Up!* shows that our proposal drastically reduces the intermediate steps required to complete an exercise thanks to the provided visual feedback. The accuracy with which the patient performs the assessed exercise for the first time is greater than when using traditional rehabilitation techniques.

INDEX TERMS Mixed reality, home rehabilitation, stroke, telehealth, telerehabilitation, gamification.

I. INTRODUCTION

Physical rehabilitation is essential in the recovery process of several diseases, such as neurological diseases, physical injuries or the recovery after a surgery [1]. In the context of neurological diseases, stroke rehabilitation represents a global challenge [2]. Stroke normally occurs when a part of the brain is suddenly deprived of blood supply. Patients affected by stroke are left with disabling effects, such as loss of strength, mobility or sensitivity in some parts of their body [1]. Therefore, long-term physical rehabilitation is necessary to improve their quality of life and regain mobility [3]. Also, time is a crucial factor, since the sooner they are treated, the greater the possibility that patients will recover some degree of mobility [4]. Stroke is a leading cause of mortality and disability in the world, not to mention the economic costs of treatment and post-stroke recovery [5] it involves. Only in the European Union, the number of people coping with stroke is estimated to rise by 27% between 2017 and 2047 [2]. Moreover, this issue is even expected to be exacerbated because of the increase of age in elderly people which will cause a negative impact in the coming years [6].

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In economic terms, however, there is a great cost regarding neurological diseases. According to the 2018 NHS Annual Report, and taking the United Kingdom as a reference, curative care and rehabilitation services assumed more than half of public healthcare spending in 2016, reaching 58.01 billion euros (57.0% of total healthcare expenditure). In Spain, as a particular example, the average cost of a patient affected by stroke was estimated at 27,711€ per year [7]. More than two thirds are due to social costs, mainly informal care. Moreover, on the report of the European Brain Council (https://www.braincouncil.eu/), more than 179 million people in Europe live with neurological disorders [8]. Indeed, it is estimated that 1 in 3 will suffer from some neurological or psychiatric disorder in their lifetime. Unfortunately, the socio-economic impact is even much more accentuated in low and middle-income countries.

Generally, stroke patients do not perform rehabilitation alone [1]. Instead, they are supported by therapists in face-to-face sessions on a regular basis. This poses a problem for patients whose health condition prevent them from attending sessions in the rehabilitation center, situation which is greatly affected by the current context of the SARS-CoV II pandemic to minimize exposure [9]. On the other hand, rehabilitation sessions provided in hospitals or rehabilitation centers are sometimes not sufficient for patients, as they are limited in duration. Furthermore, there is a barrier related to motivation and engagement. Traditional physical exercises consists in performing repetitive executions of correct movements which tend to be monotonous and boring. It can cause that patients loose motivation and, in consequence, their commitment to the therapy [10]. Unfortunately, this may affect the quality of the therapy. For these reasons, telerehabilitation arises. This branch of telemedicine allows for treatments of the acute phase of disease by replacing traditional face-to-face sessions with a rehabilitation at home [11]. There is a significant number of applications under this approach, but they are generally applied to physiotherapy where virtual reality (VR) techniques are used so that the patient mimic the movements of a virtual avatar. In essence, it is a relevant approach for home rehabilitation. However, it should be noted that when the responsibility of performing these exercises is delegated to the patient, at home and with no direct supervision by the therapist, the precision of the exercises that are executed may be low, potentially affecting the quality of the rehabilitation. In this sense, they may not be well performed at home, which can lead to undesirable situations in which the effects of rehabilitation may be negative [12].

One of the extensively used technologies for rehabilitation is immersive reality, which aims to recreate artificially rehabilitation environments. Among the different alternatives, mixed reality (MR) technology is highlighted, since it allows to merge both physical and virtual spaces in an environment where real objects coexist with virtual ones [13]. In essence, MR presents a great opportunity to make possible to modify easily the needs of a patient regarding his or her condition thanks to the amazing visualizations and advanced interaction it provides. Recently, some studies have explored the potential of MR within the context of medical applications [14]. However, its potential in supporting people for remote physical rehabilitation have not yet been exploited.

Thus, this article introduces *PhyRe Up!*, a telerehabilitation system based on MR and gamification techniques to assist in the physical rehabilitation of stroke patients at home. *PhyRe Up!* makes use of telerehabilitation as a proper framework to enable physical rehabilitation at home, along with MR to provide real-time, visual feedback, and guidance for patients when performing rehabilitation exercises. This system is intended to reduce the burden of stroke patients by enabling an alternative that would reduce the cost of stroke to health systems [7]. Special attention has been paid to the module that is responsible for recommending these exercises. The precision, with which the system assists patients, allows to improve the quality of the execution as well as enabling their autonomy. *PhyRe Up!* relies on two cutting-edge technology devices: Microsoft HoloLens 2™ and Azure Kinect DK™. The first provides MR capabilities and advanced interaction, while the second significantly facilitates the patient's body tracking. Thanks to these latter artifacts, a mixed reality scenario has been created, using the real-world context from the motion tracking device (i.e. real-time body tracking) so as to interact with the synthetic information (virtual elements) added to the physical space with the visualization device. Thus, both virtual and physical world are merged to fully immerse the patient in a real rehabilitation session.

The system aims at increasing the quality time therapists can spend on their patients, facilitating how rehabilitation exercises are defined, assigned and assessed. The architecture that underpins *PhyRe Up!* has been designed around a module that integrates the domain knowledge, which can be augmented to address how rehabilitation exercises are defined, assessed, and recommended.

The results obtained in this work after experimentation highlight that immersive techniques based on MR allow patients at home to faithfully recreate the therapies defined by experts without their presence, and without affecting the quality and success of recovery. The quality of execution of artificially guided exercises is similar by face-to-face therapy.

The rest of the article is structured as follows. Section II positions this research within the context of other relevant research works. Then, Section III discusses in depth the architecture of *PhyRe Up!* Subsequently, Section IV describes the conducted experiment and Section V explains the obtained results. Then, Section VI addressed the limitations of the system from the perspective of the study and the proposal. Finally, Section VII draws the conclusions of this research article and proposes future lines of research.

II. RELATED WORK AND BACKGROUND

Virtual rehabilitation has been a promising research field during the last few years, commonly associated to elderly care and rehabilitation of patients affected by neurological diseases [15]. In fact, virtual rehabilitation has been addressed

TABLE 1. Summary of the most relevant related works (NUI = Natural User Interface).

Article	Interaction paradigm	Upper limbs	Gamification?	HW device/s	Accurate tracking?	Scalable to other exercises?	Scalable to other limbs?
[24]	AR	Shoulder	No	Webcam	No	No	No
[29]	Desktop	Upper-arm	Yes	Graphics tablet	No	Yes	No
[30]	NUI	Palm, fingers	No	Leap motion controller	Yes	Yes	No
[27]	AR	Upper limbs	No	Webcam	No	No	No
[23]	MR	Upper limbs	Yes	Kinect, projector, tablet	No	Yes	No
[28]	AR	Shoulder	Yes	Kinect	No	No	No
[26]	AR	Lower limbs	No	Kinect, projector	No	No	No
[25]	AR	Head	No	HoloLens	No	No	No

from different points of view, and multiple disciplines have been involved. One of them is VR [16], where programs are defined as the use of computer-simulated environments that imitates physical real worlds. A systematic review and meta-analysis is presented by Domínguez-Téllez *et al.* [17] with a focus on game-based virtual reality interventions for stroke patients.

From a general point of view, a significant part of the research proposals have relied on Microsoft Kinect [18]. Initially conceived as a game device, the original Kinect has demonstrated to be a very flexible piece of hardware, clinically validated in a significant number of physical therapy and rehabilitation contexts [19]. Kinect was recently discontinued by Microsoft. The new version, named Microsoft Azure Kinect DK™, maintains stronger integration with the cloud and the use of artificial intelligence techniques.

Augmented Reality (AR), based on superimposing virtual objects over the real world, which are affected by the user's physical interaction [20], has been more recently used to assist in the physical rehabilitation process. A review presented by Gorman and Gustafsson [21] explores relevant works in which AR technology has been adopted when performing rehabilitation after stroke. The review concludes that further investigation is required in this field. Also, a recent study is also discussed by Viglialoro *et al.* [22], with a focus on analyzing to what extent AR-based systems have been used in upper-limb rehabilitation and on investigating the effectiveness of AR compared to other approaches.

MR, on the other hand, merges both physical and virtual spaces in an environment where real objects coexist with virtual objects [13]. Although MR is of increasing interest within the context of virtual rehabilitation, this approach is not as mature as VR or AR. Nevertheless, this situation is changing at a fast pace, and the application of MR technology to medical applications can be considered as an emerging research field [14].

Recently, a number of contributions have addressed physical rehabilitation of patients affected by neurological diseases, particularly stroke. For example, a portable low-cost MR-based tabletop prototype is presented by Colomer *et al.* [23] for upper-limb rehabilitation. This research include visual feedback and gamification techniques, and a clinical evaluation is conducted to assess effectiveness and acceptance.

Similarly, the research work discussed by Aung and Al-Jumaily [24] proposes *RehaBio*, a shoulder rehabilitation system that makes use of AR and provides basic visual feedback to retrain the plasticity of the brain for patients affected by traumatic brain injury, spinal cord injury or cerebrovascular accident. In terms of interaction, the system is able to capture the video scenes related to the user's movements, render the virtual object that the user must reach, track the marker, and detect the collision between the visual objects and the real marker. Range of motion and the effectiveness were assessed, while the system was proved to motivate users. Another research work in which the use of AR stands out was recently proposed by Liang *et al.* [25]. In this case, tests are carried out to evaluate the impact of use AR in teaching practitioners in a stroke assessment simulation designed for clinical training. A MR device is employed to project a human face that mimics facial drooping, an actual symptom of stroke, onto a simulated virtual avatar.

A related research work is presented by Sekhavat and Namani [26]. In this context, a system that relies on projection-based augmented reality to improve the understanding level between the body perception and the movement kinematics is presented. Experiments were conducted for both unimpaired and impaired users to modify gait depending on the visual feedback provided by the system. The results show that projection-based AR outperform monitor-based systems when it comes to synchronize foot-eye coordination. On the other hand, the research work discussed by Aparecida *et al.* [27] addresses the clinical feasibility of an AR system for upper-limb post-stroke motor rehabilitation. Two case studies are described: i) an evaluation of upper-limb motor function and ii) another one related to the gain of motion range of shoulder flexion and abduction. The authors concluded that enhancements are generated in the patients' shoulder range of motion and speed.

The work presented by Da Gama *et al.* [28] introduced a rehabilitation system aimed at recognizing and classifying biomedical movements, particularly the shoulder abduction exercise. The device Microsoft Kinect was used to track the patient's joints, while basic gamification mechanisms were integrated to engage the final users. The ultimate goal was to assess the efficacy of employing a clinically-related gesture recognition tool. The authors concluded that the achieved results indicated that the use of bio-mechanical standards to recognize movements may be valuable in guiding patients during the rehabilitation process.

Another contribution is presented by Hocine *et al.* [29]. In this research, the authors introduce *PRehab*, a serious game for upper-limb rehabilitation aimed at improving the training outcomes of patients affected by stroke. The proposal revolves around the idea of generating customized game levels, so that the game difficulty is dynamically adjusted depending on the patient's skill and performance. A graphics tablet was the chosen device for the patients to play *PRehab*. Patients and clinicians were involved in the conducted experiments to evaluate the immersion level and the motivation.

The work described by Vamsikrishna *et al.* [30] introduces a methodology to facilitate palm and finger rehabilitation, using computer-vision techniques. The leap motion controller is employed to track the patient's palm and fingers, while the system is able to analyze the steps involved in the rehabilitation process without the direct supervision of a physician. Experimental validation with healthy volunteers proved that linear discriminant analysis and support vector machines, both techniques used to classify the user's movements, perform in a similar way when recognizing isolated gestures.

PhyRe Up!, the system proposed in this work, has been designed so that therapists can remotely supervise stroke patients' evolution when they complete the rehabilitation routines at home. Therapists can assign the exercises that best fit the patients' progression depending on their skills and degree of the injury. Plus, motivation plays a key role to avoid stroke patients quitting rehabilitation. In order to face this challenge, the system uses gamification techniques to turn the exercises into playful "games". In this way, patients make rehabilitation while they play and enjoy [31], maintaining their resolve and engagement level.

III. ARCHITECTURE

A. GENERAL OVERVIEW

PhyRe Up! is a telerehabilitation system based on MR and gamification techniques for stroke patients. The system can be used by both therapists and patients. In the first case, therapists can define a set of exercises and routines, which can be used as a reference to supervise how patients do rehabilitation from home. The system displays virtual 3D information in real time on a real environment, which serves as a guide for the patient to perform the exercises previously defined by the therapist. At the same time, the system automatically tracks the patient's joints and checks the correct execution of the exercises at all times. A continuous feedback exists between two of the major software modules that compose *PhyRe Up!*: the tracking module and the MR module. This is essential to establish proper synchronization with the execution of exercises by the patient.

Figure 1 shows a graphical overview of how the data flow through the different entities involved in *PhyRe Up!* and their interactions. The device Azure Kinect DK^{TM} is used to collect raw tracking data, which are then processed and sent to the MR device Microsoft HoloLens 2^{TM}. Patients wear the goggles on their head, which allows the system to augment the real-world information with holograms. Tracking data are used as a reference to render the virtual information (please see the upper right window where the user's point of view is represented and virtual spheres are drawn to guide the patient's physical movement). On the other hand, Figure 2 shows how the architecture of *PhyRe Up!* has been designed and how the different hardware and software components are related to each other. The MR device can be used by the patient when performing the rehabilitation exercises, but also by the therapist in order to define, in a visual way, the reference/gold standards. In other words, the ideal execution of the rehabilitation exercises. Thus, the therapist has the capability to test, in advance, the very same exercises that the patients will perform later on by using the same MR device. The MR therapist's module provides detailed information on this matter.

The architecture is composed of 4 main modules, which are briefly introduced next:

- **Domain Knowledge module**. This module contains and handles the knowledge of the system. It possesses declarative, procedural and conditional knowledge needed to enable the achievement of the developed system's objectives. Moreover, all the information generated during its use will be stored and managed to properly assess and monitor the patient's evolution. A back-end architecture is deployed on the cloud Microsoft Azure to guarantee the extensibility of the system and facilitate its use.
- **MR therapist's module**. This module allows the therapist to define the rehabilitation exercises and routines that will be performed by the patient throughout the rehabilitation process. This module relies on the device Microsoft HoloLens 2^{TM} (https://www.microsoft.com/es-es/hololens), which facilitates the exercise definition thanks to the use of an approach based on natural user interfaces.
- **MR patient's module**. This module integrates the software required to manage a series of rehabilitation exercises in the form of exergames. They must be done by the patient to perform the rehabilitation routine. The exercises must have been previously defined by the therapist. Again, this module relies on the device Microsoft HoloLens 2^{TM}. Gamification techniques are also integrated to engage the patient during a rehabilitation session.

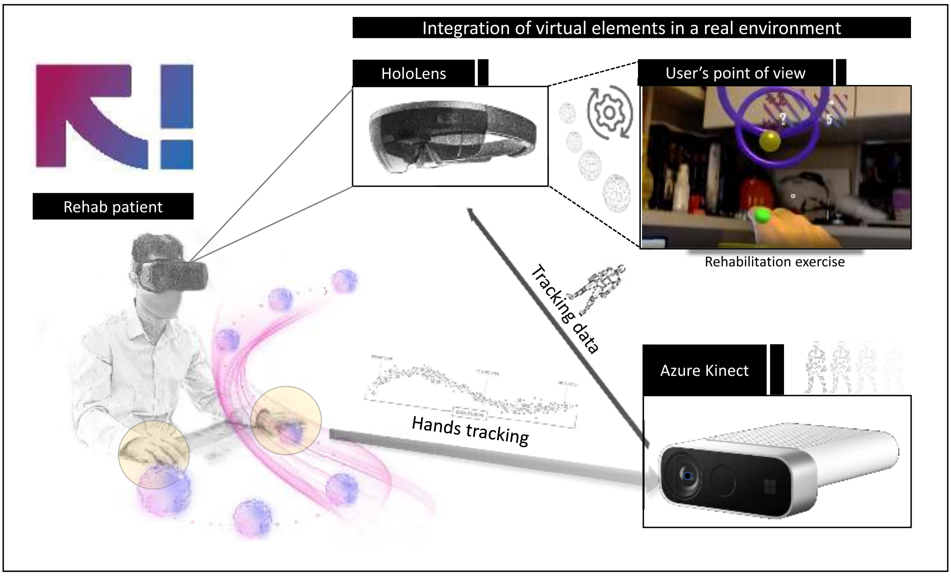

FIGURE 1. High-level visual representation of the data flow and interactions within *PhyRe Up!* The user wears a MR device, Microsoft HoloLens 2^{TM}. A different tracking device, Azure Kinect DK^{TM}, tracks the user's hands in real-time. Tracking data are processed and sent to the MR helmet, which renders the visual information shown in the upper right part of the image. In this latter view, the light green sphere represents the current position of the user's right hand, while the yellow sphere represents the starting position of the rehabilitation exercise. Purple spheres and rings represent the exercise trajectory.

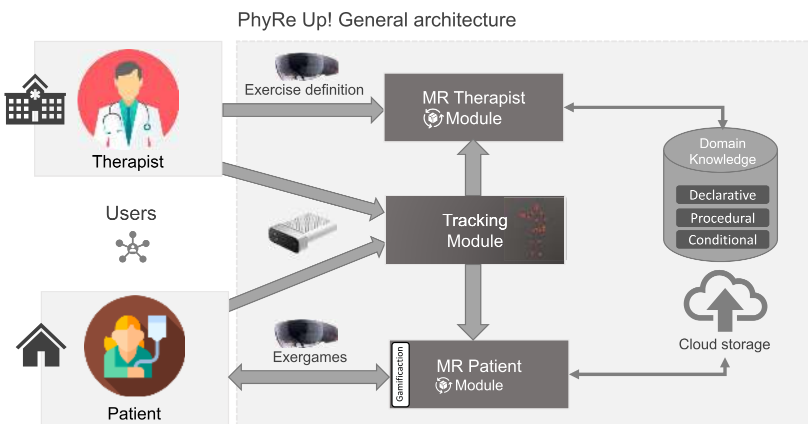

FIGURE 2. General overview and key components of the *PhyRe Up!* architecture.

- **Tracking module**. This module tracks the patient's skeleton to obtain the 3D position and orientation of the joints involved in the rehabilitation exercise. The tracking data are sent to the MR modules. The current version of *PhyRe Up!* relies on the device Azure Kinect DK^{TM} (https://azure.microsoft.com/es-es/services/kinect-dk/), a cutting-edge technology in terms of body tracking.

B. SPECIFICATION OF THE ARCHITECTURE MODULES

Next, each one of the modules that compose the devised architecture is discussed in detail, including how the interactions are carried out.

1) DOMAIN KNOWLEDGE MODULE

This module constitutes the core of the system, since it contains the specific knowledge to achieve the objective of proposed system: the rehabilitation of patients affected by stroke.

In this module the knowledge is totally structured and organized to designate the articulation of knowledge to the rest of the subsystems. This structure is clearly differentiated in three types of knowledge, which are distinguished as follows:

- *Declarative knowledge*. It is the factual knowledge ("knowing what"). It includes organized bodies of knowledge about the problem and context. In this way, such knowledge elements are attributed to the set of articulations that exist (i.e. $J = \{j_1, j_2, \ldots, j_{31}\}$; https://docs.microsoft.com/bs-latn-ba/azure/kinect-dk/body-joints), the constraints associated with them (i.e. $C(J) = \{C(j_1), C(j_2), \ldots, C(j_{31})\}$), and the variables associated to monitor the rehabilitation exercise of patients (i.e. $V = \{v_1, v_2, \ldots, v_k\}$).
- *Procedural knowledge*. It refers to the execution of procedures, strategies, techniques or methods to achieve an end, that is "knowing how". In our context, this knowledge defines the rehabilitation exercises and the game dynamics associated with them (i.e. $E = \{e_1, e_2, \ldots, e_n\}$), where each rehabilitation exercise (i.e. $e_y \in E$) works a specific injury or joint (i.e. $j_x \in J$) with a different degree of complexity. It is even possible to divide the set E according to the injury or joint worked. Also, the algorithms needed to track a rehabilitation exercise with the aim to check how well they are being performed are included here.
- *Conditional knowledge*. This kind of knowledge implies knowing when and why to do something. In the context of this research, this knowledge is used for recommending the next exercise the patient should take ($e_i \in E$). To do that, it takes into account the progress and results obtained in the last exercises carried out by the patient ($v_1 \times v_2 \times \ldots v_k \times E$). That is, it approximates the function: $V^k \times E \longrightarrow E$, that contains the therapist's knowledge about the exercises that a patient should do depending on his or her condition. To model this function we use a set of rules (i.e. $R = \{r_1, r_2, \ldots, r_m\}$), being each conditional rule $r_i \in R$ will generally have the following form: IF X is DDX THEN Y is e_i, where X is a subset of input variables ($X \subseteq V$), DDX is a set that represents the values that must take these variables (X), and Y is the exercise to be recommended.

Moreover, this module contains a memory element, which is responsible for saving a snapshot of the performance and the evolution of a patient. That is, a history that contains the key elements, such as number of repetitions, score, time employed in finishing the exercise, and even the failure steps, among others. A record of the exercises already performed will also be kept.

The domain knowledge module has been deployed on the cloud Microsoft Azure (https://azure.microsoft.com/es-es/) to store the rehabilitation exercises, analyze the data obtained from their execution and, above all, guarantee the security of sensitive data.

2) MR THERAPIST'S MODULE

PhyRe Up! has been developed to facilitate a therapist the definition of rehabilitation exercises and the game dynamics associated with them. It will constitute the declarative and procedural knowledge of the system. In this sense, the interface has been designed on the promise of providing therapists the utmost freedom. Therefore, communicating between the tool and therapist is carried out through natural interaction, which means that therapists can create exercises using voice and gestures.

An exercise is designed as a game, which consist of a path composed mainly of virtual elements, such as points, rings or any other element, i.e. targets representing the trajectory of the rehabilitation exercise. The patient's joint involved in the exercise needs to pass through these virtual elements to achieve the goal. Figure 3 shows an exergame example defined by a therapist, which is framed in the box (1); (2) is the starting point which is marked in yellow to be differentiated than the others; (3) are the points which compose the exercise, i.e. the path, and (4) the control rings. The difference between (3) and (4) is that (3) represents parts of the path that the patient must follow, and (4) represents key or strategic points in the performance of the exercise. The rings guide the exercise, and the spheres or intermediate points appear progressively as the patient reaches the control points (rings). Due to the importance of the strategic points (rings), the achievement of these means a higher score for the patient. It should be noted that the scheme of the exergame has been defined by a therapist using the MR device through multi-modal interaction.

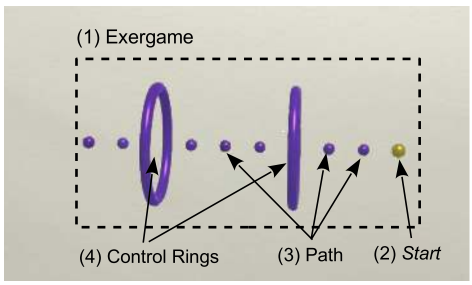

FIGURE 3. Example of an exercise defined by a therapist. The yellow sphere represents the starting position of the exercise. The purple spheres represent the path that defines the movement associated to the exercise. The purple rings act as intermediate control points.

This research work makes use of the exergame concept, which implies adding virtual elements to turn a traditional rehabilitation exercise into a gamified one.

Theoretically, the exergame (i.e. rehabilitation exercise and dynamic game) $e_i \in E$ defined with the system proposed herein consists of eight-tuple, $e_i = (D_i, JI_i, SET_i, VE_i, T_i, RG_i, C_i(JI_i), KPI_i)$. Next, we define each one of these elements:

D_i is a descriptive information of the exergame e_i.

JI_i is the set related to joints involved in the rehabilitation exercise e_i, that is, $JI_i \subseteq J$.

SET_i is the setup of the exercise and it is defined by means of the tuple: (sc, rp, t, c), where sc is a quantitative indicator of success in the performing of a step of the rehabilitation exercise e_i ($sc \in \mathbb{N}$); rp are the repetitions required to perform the exercise e_i ($rp \in \mathbb{N}$); t is the time needed to finish the exercise e_i ($t \in \mathbb{R}$); and c is the degree of complexity of the exercise ($c \in \mathbb{N}$).

VE_i defines the virtual elements fixed in the 3D space, such as points, rings, hoops or other elements used in the exergame e_i ($VE_i = \{ve_{i1}, ve_{i2}, \ldots, ve_{ik}\}$, with each ve_{ij} being a virtual element). A virtual element ve_{ij} denoted as three-tuple $(ve_{ij}(x), ve_{ij}(y), ve_{ij}(z))$, where $ve_{ij}(k) \in \mathbb{R}$ and it represents the position of the element $ve_{ij}(k)$ in the 3D space $(X(ve_{ij}(x)), Y(ve_{ij}(y))$ or $Z(ve_{ij}(z)))$.

T_i refers to trajectories associated with the movements that a patient will do when performing the exergame e_i. T_i is defined as a set of virtual points that establish the movements the patient must perform ($T_i = \{ve_{ij}, ve_{ij+1}, \ldots, ve_{in}\}$). It should be noted that a T_i is a set that may have repeated elements.

RG_i is a set of rules that contains the game mechanics of the exercise e_i, which are based on the interaction between JI_i and T_i in the 3D space to achieve an objective. Formally, $RG_i = (rg_{i1}, rg_{i2}, \ldots, rg_{in})$, where each particular rule of the game rg_{ij} is used to define the function $JI_i \times VE_i \times O \longrightarrow GM$ where:

- JI_i establishes the joints that interact with the game rule.
- VE_i establishes the virtual nodes that interact with the game rule.
- O is a set of objectives defined to satisfy the game rules ($O = \{o_1, o_2, \ldots, o_m\}$).
- GM is a set of game mechanics to be triggered when a joint involved JI_i interacts with a virtual node VE_i meeting a certain objective o_j.

$C_i(JI_i)$ is a set of constraints that are associated with joints that the patient should not ideally move to compensate for the lack of mobility or strength in the exercise e_i (i.e. $(C_i(JI_i) \subseteq C(J))$.

KPI_i is a set of key performance indicators that are used to monitor patient's evolution according to the performance of the exercise e_i (i.e. $KPI_i = \{k_{i1}, k_{i2}, \ldots, k_{im}\}$). These KPIs depend on what information therapist wants to obtain after the patient finishes the exercise e_i. Each k_{ij} is defined as a pair $(Vk_{ij}, DDVK_{ij})$, where:

- Vk_{ij} is a set of input variables used to define a KPI concept ($Vk_{ij} = \{v1_{ij}, v2_{ij}, \ldots, vn_{ij}\}$).
- $DDVK_{ij}$ is a set of definition domains of the KPI's variables Vk_{ij}, that is, $DDVK_{ij} = \{DDV1_{ij}, \ldots, DDVn_{ij}\}$, where $DDVx_{ij}$ is the definition domain of the variable vx_{ij}.

As can be observed, the definition of an exergame involves defining both declarative and procedural knowledge.

The exergames will be defined by therapists thorough an interface in such a way that the information established herein is easier for them to be introduced. This is added into the Domain Knowledge module as procedural one. Moreover, the exergames can be represented by means of strings designed in a language for physical rehabilitation, called Personalized Exergame Language (PEL). The intention to use this kind of knowledge representation is to be comparably to other rehabilitation contexts. However, the underlying details of the language, such as vocabulary, syntax, and semantics, are not provided because it is beyond the scope of this paper. This information is deeply described and explained in [32].

3) MR PATIENT'S MODULE

This is the module that will allow the patient to perform the rehabilitation exercises. It is responsible for encouraging the patient's performance of the rehabilitation exercise during a rehabilitation session as well as evaluating how well the patient performs it. Declarative, procedural and conditional knowledge available in the domain module will be used herein.

The module presents an exergame e_i to be performed by patients as a step of their rehabilitation plan ($e_i \in E$). This exergame may be assigned to the patient directly by the therapist or automatically by the module using the conditional knowledge.

An example will be used to show how the module works. Let's suppose the therapist assigns to the patient the exercise shown in Figure 3. We refer it as e_5 (such that $e_5 \in E$).

As it can be seen, e_5 it is composed of ten virtual nodes (8 points and 2 rings) defined as $VE_5 = \{ve_{51}, ve_{52}, \ldots, ve_{510}\}$, and a linear trajectory defined as T_5 $(ve_{51}, ve_{52}, \ldots, ve_{510})$, with ve_{51} being the starting point (marked in yellow in Figure 3).

It is a drag-and-drop exercise. From a straight position, the exercise consists of taking the yellow ball with the indicated hand and dragging it through each of the virtual nodes, which are part of the trajectory, following a linear movement. Essentially, the objective of the game is to rehabilitate the right shoulder (j_{12}). For this purpose, the patient has to pass the right hand (j_{15}) through each of the virtual nodes that are part of the trajectory T_5 (in this way, $JI_5 = \{j_{12}, j_{15}\}$).

Since the example proposed e_5 tends to rehabilitate the right shoulder (j_{12}), the patient's joints that should not ideally move to compensate the lack of movement or strength may be left upper limb (j_5, j_6 and j_7) and spine (j_1), i.e. $C_5(JI_5) = \{C(j_{12})\}$, with $C(j_{12}) = \{not\ move(j_1, j_5, j_6, j_7)\}$. This warns the patient that some joints are being used to complete the exergame. It should be noted that it is also useful to prevent patient from provoking an injury.

Part of the dynamic of the game is established in the exercise setup, i.e. $SET_5 = (sc = 40, rp = 4, time = 180s, c = 5)$. It means that the patient has to perform four repetitions in less than three minutes ($180s$) reaching to 40 score in an exercise with complexity grade 5. In essence, this configuration allows the module to assess how successful or unsuccessful has been the performance according to the grade of complexity.

Another aspect of game dynamic is established in the rules of the game associated with the exercise, RG_5. At this point it is important to remark that a rule may be triggered when a joint involved JI_i interacts with a virtual node VE_i meeting a certain objective o_j. In this particular case, $RG_5 = (rg_{51}, rg_{52}, rg_{53}, rg_{54})$, where:

rg_{51}: IF $distance(position(j_{15}), ve_{51}) \leq \alpha$
AND $isGrabbed(ve_{51})$
THEN $score(+5\ ptos)$ ELSE $feedback(ve_{51})$

rg_{52}: IF $distance(position(j_{15}), ve_{5j}) \leq \alpha$
with $j \in \{2, 3, 5, 6, 7, 9\}$ AND
$isVisited(ve_{5(j-1)})$ AND
$isTouched(ve_{5j})$
THEN $score(+1\ ptos)$ ELSE $feedback(ve_{5j})$

rg_{53}: IF $isInRing(position(j_{15}), ve_{5j})$
with $j \in \{4, 8\}$ AND
$isVisited(ve_{5(j-1)})$ AND
$isCrossed(ve_{5j})$
THEN $score(+12\ ptos)$ ELSE $feedback(ve_{5j})$

rg_{54}: IF $distance(position(j_{15}), ve_{510}) \leq \alpha$
AND $isVisited(ve_{59})$
AND $isDropped(ve_{510})$
THEN $score(+5\ ptos)$ ELSE $feedback(ve_{510})$

$position(j_i)$ is a function that returns the position of the joint j_i in the 3d space. $distance(x, y)$ is a function that returns the distance between two points x and y in a 3D space. $isGrabbed(x)$ is a function that returns true if the ball has been grabbed in x. $isVisited(x)$ is a function that returns true if x has been previously visited according to the order of the virtual points established in the trajectory T_i. $isTouched(x)$ is a function that returns true if x has been touched. $isCrossed(x)$ is a function that returns true if x has been crossed. $isDropped(x)$ is a function that returns true if the ball has been dropped in x. And $isInRing(x, y)$ is a function that returns true if x has passed through the rings y. The parameter α is used to establish the precision of the system; its value has been defined as 0.05.

The rule rg_{51} is used to check whether the patient grabs the ball that must be dragged until the final position in the starting one (i.e. ve_{51}); rg_{52} is a rule to check whether the patient passes the ball through the intermediate points (i.e. $ve_{52}, ve_{53}, ve_{55}, ve_{56}, ve_{57}, ve_{59}$); rg_{53} is the rule that checks whether the patient passes the ball through the rings (i.e. ve_{54}, ve_{58}); lastly, rg_{54} checks whether the patient drops the ball in the final position (i.e. ve_{510}).

The set of objectives O defined to satisfy the game rules are $O = \{o_1, o_2, o_3, o_4\}$, where: $o_1 = isGrabbed(ve_{51})$; $o_2 = isVisited(ve_{5x})$, being $x \in \{2, 3, 4, 5, 6, 7, 8, 9\}$; $o_3 = isTouched(ve_{5x})$, being $x \in \{2, 3, 5, 6, 7, 9\}$; $o_4 = isCrossed(ve_{5x})$, being $x \in \{4, 8\}$; and $o_5 = isDropped(ve_{510})$. The set of game mechanics GM are related to increase the score achieved when an objective is reached (i.e. $score(+y ptos)$), or providing feedback when it is not (i.e. $feedback(ve_{5x})$). Visual feedback provides useful information to the patient for the achievement of the objectives, in case they have not been achieved. It provides a helpful orientation and guidance in the performance of exercises.

The game rules are defined to motivate the patient during a rehabilitation session, since feedback is presented to the patient when each game rule is triggered. Figure 4 shows an example when rg_{52} is fired as a consequence of being satisfied the objectives o_2 and o_3.

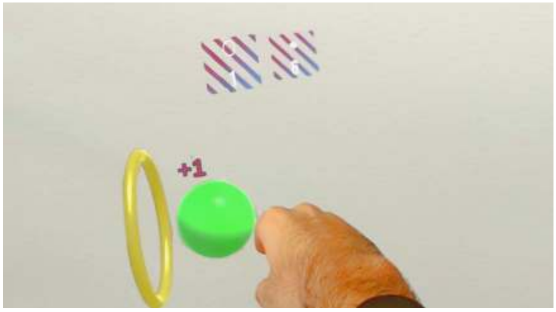

FIGURE 4. Patient's view. The widgets on top of the image shows the points (left) and rings (right) obtained. The "+1" particle is fired when the right hand passes through a virtual element, as well as the animation of the joint pointer.

The tasks for detecting these joints, checking associated constraints satisfaction $C_5(JI_5)$, tracking motion and evaluating functions (i.e. *distance*, *position*, *isInRing*, *isGrabbed*, *isVisited*, *isTouched*, *isCrossed*, *isDropped*), will be delegated to the tracking module due to the high computational cost. The tracking module is explained in detail in the next Subsection.

Finally, the exergames may contain metrics or KPIs to measure or monitor certain aspects in a rehabilitation exercise, for example, performance, mobility or displacement, among others. Consider that the therapist has defined in the example detailed herein a metric $k_{51} \in KPI_5$ to monitor the performance of the patient. Imagine that k_{51} consists of two input variables $Vk_{51} = \{score(v1_{51}), labels(v2_{51})\}$. Their domains are $DDV1_{51} = \{10, 20, 30, 40\}$ and $DDV2_{51} = \{bad, normal, good, perfect\}$. The patient's module is responsible for understanding this information and evaluating the exercise with respect to this definition. Specifically, the module associates a label with a score. In other words, the label *bad* would be matched to a score lower or equal to 10 points, the label *normal* a score higher than 10 and lower or equal to 20, the label *good* a score higher than 20 and lower or equal to 30, and label *perfect* a score between 31 and 40.

Once the exergame has finished, the results of the exergame are saved into the memory of the Domain Knowledge module.

As mentioned above, there is the possibility for this module to automatically assign exercises to the patient based on his or her previous results. To this end, conditional knowledge is used. Then, a brief explanation about what conditional knowledge consists in is presented.

The conditional knowledge has been codified by means of a set of fuzzy rules (i.e. $R = \{r_1, r_2, \ldots, r_m\}$) that model the function $V^k \longrightarrow E$. In the current state of the work, the variables used to make the recommendation are: $V = \{difference\_number\_steps,\ accumulated\_deviation,\ difference\_time\}$. Their meaning is explained below:

- *difference_number_steps* (v_1) is the difference between the number of steps that the patients and the therapists performed to carried out the last rehabilitation exercise (i.e. the patient fails to pass through all the virtual points that establish the trajectory associated with the exercise).
- *accumulated_deviation* (v_2) is the cumulative spatial deviation between the patient and the therapist (i.e. this calculation is based on the distance accumulated in the completion of the trajectory associated to the last exercise).
- *difference_time* (v_3) is the difference in time invested regarding the execution of the last routine between the patient and the therapist.

These variables has the following domain of definition: $DDV_x = \{VL$ (very low), L (low), M (medium), H (high), VH (very high)$\}$. The definition of these fuzzy values are not shown, as the authors of this paper do not deem this to be important in order to understand the system presented herein.

In addition, the last rehabilitation exercise performed by the patient, *last_exg*, will be used in the rules to determine the next exercise to be performed. In this respect, a function will be applied, *propose_exercise*, that selects from the set of available exergames E one whose lesion and joint JI_i are similar to the last exercise *last_exg*. This is combined with another one to return the exergames based on the complexity of *last_exg*, that is, those whose complexity can be higher, lower or equal.

Full details of all the rules used by the module are out of the scope of this research work, but, by way of example, some of them will be shown:

r_1: IF *difference_number_steps* is $\{VL\}$
AND *accumulated_deviation* is $\{VL\}$
THEN
propose_exercise(*more_complex*(*last_exg*))

r_5: IF *difference_number_steps* is $\{M\}$
AND *difference_time* is $\{M\}$
THEN
propose_exercise(*same_complex*(*last_exg*))

r_9: IF *accumulated_deviation* is $\{VH\}$
AND *difference_time* is $\{VH, H\}$
THEN
propose_exercise(*less_complex*(*last_exg*))

r_{11}: IF *difference_number_steps* is $\{M\}$
AND *accumulated_deviation* is $\{M\}$
AND *difference_time* is $\{M\}$
THEN
repeat_last_exg()

Particularly, the rule r_{11} makes use of three previously mentioned parameters, that is, *difference_number_steps*, *accumulated_deviation* and *difference_time*, which are relevant for recommending an exergame that might be added in the next rehabilitation session. This rule means that if i) the patient has performed a number of steps moderately different to the therapist, ii) the spatial deviation between them is considerable, iii) and the time invested varies reasonably, it would be ideal that the patient repeats the last exergame.

On the other hand, we do think that justifying the use of fuzzy logic when designing this module would be beneficial. At this stage, there is no attempt to provide an accurate assessment of how much patients have progressed, but rather to provide them with guidance that they can understand. In this respect, using linguistic variables makes it easier for them to interpret this information.

As a consequence of the work done by this module, the patients will receive detailed feedback on the work they have done, with an explanation about the areas in which they have performed well, and others which may still require more attention. In addition, on a broader level, patients will be informed whether they have truly done well the routine.

Interestingly, the approach presented herein shows the potential to define aspects related to physical rehabilitation. The underlying idea of this method is to be extensible and customizable enough to be used in other rehabilitation contexts.

As a result of the example detailed in this section, the complete execution of the exercise is shown in Figure 5, where multiple key frames have been selected. This figure is the composite of frames following the order from left to right and from top to bottom.

4) TRACKING MODULE

This module is responsible for running real-time body tracking recognition of the users' movements when they perform rehabilitation exercises. Essentially, it obtains 3D spatial coordinates of the human body joints, that is, the position given as a three-tuple (x, y and z) $\in \mathbb{R}^3$ and the rotation given as a four-tuple (w, a, b and c) $\in \mathbb{R}^4$. The rotation is expressed as a normalized quaternion. Principally, the process to perform body tracking is used through Azure Kinect DK™ device. Fundamentally, this hardware device has been utilized along with Microsoft HoloLens 2™. In essence, the MR device cannot track the subject's body. Therefore, an additional system has been required to obtain the information of the users' joints JI_i involved in the rehabilitation exercise e_i, in real-time without wearing markers or sensors, among others.

Specifically, the human movement recognition, in an exergame of this approach, is mainly composed of skeleton acquisition and distance measurement. Firstly, the human skeleton is obtained and the spatial coordinates of the skeleton joints JI_i are calculated (*position* function). Then, it calculates the distance between the particular joint involved j_i and the virtual node ve_{ij} (*distance* function). Also, this module determines whether or not the subject has touched or crossed the virtual node target (*isTouched* and *isCrossed* functions) or

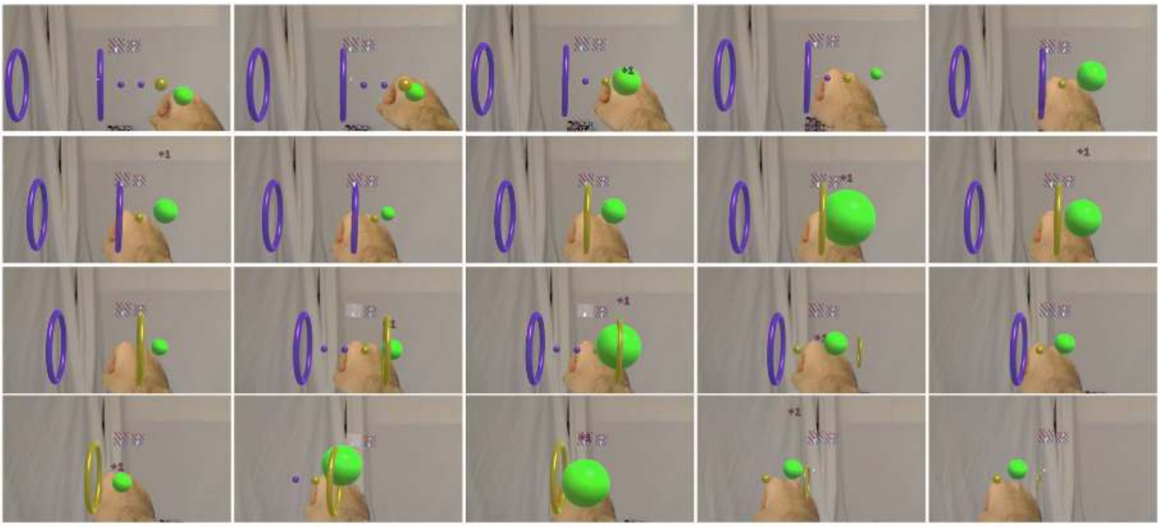

FIGURE 5. Frames of the execution of an exercise performed by a patient.

other functions has been triggered on it (i.e. using *isGrabbed*, *isVisited*, *isDropped* and *isInRing* functions).

A coordinate system has been created to share the position and rotation of the joints. It is due to the fact that HoloLens 2 device cannot obtain, at least accurately, the information of the human joints. In this respect, the tracking device obtains the spatial coordinates of the human body joints and they are shared to be used by the MR device. This can be graphically observed in Figure 6.

Fundamentally, an AR marker is placed on the Azure Kinect device to obtain, through Vuforia computer-vision library (https://developer.vuforia.com/), the information required. By using the position of the head $p_h = (x_h, y_h, z_h)$ and the position of the marker $p_k = (x_k, y_k, z_k)$, the vector between the head and the device Azure Kinect DK^{TM} is computed:

$$\overrightarrow{v_k} = p_k - p_h \tag{1}$$

It should be noted that MR device is the origin coordinate, while the Azure Kinect DK^{TM} device has its own one, created in the AR marker location, to have the adequate position of the tracked joint. The x and y axes of the tracking coordinate system is inverse to the ones managed by HoloLens 2^{TM}. Therefore, once a joint position is obtained by the tracking device, the aforementioned components need to be multiplied by -1 to be them aligned with the HoloLens coordinate system.

Particularly, the actual distance between the person and the camera is calculated using the module $|\overrightarrow{v_k}|$. It is mainly performed to ensure that the confidence level of the key points is optimal, since high or low distances may influence the quality of body tracking recognition; it is recommended a range between 0.5 - 3.86 m

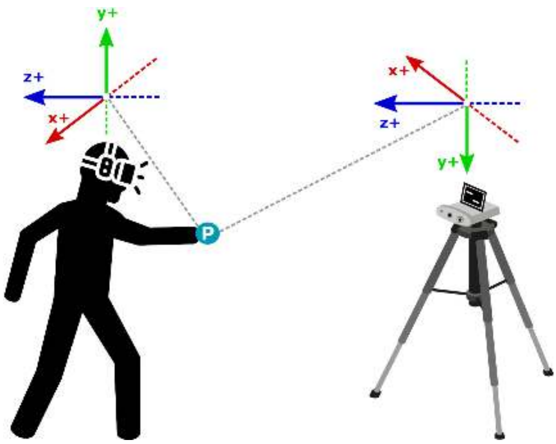

FIGURE 6. Overview of the coordinate system.

distance (please, refer to https://docs.microsoft.com/es-es/azure/kinect-dk/hardware-specification).

At this point, combining the vector between the head and the tracking device $\overrightarrow{v_k}$, and the position of the particular joint involved j_i, the point from the head is:

$$position\ (j_i) = \left(j_{ix}, j_{iy}, j_{iz}\right) + \left(v_{kx}, v_{ky}, v_{kz}\right) \tag{2}$$

Then, the Euclidean distance is used to get the distance between the joint and virtual node, being $X(x_1, x_2, x_3)$ the joint and $Y(y_1, y_2, y_3)$ the virtual node in the spatial coordinate system:

$$distance\ (x, y) = \sqrt{(x_1 - y_1)^2 + (x_2 - y_2)^2 + (x_3 - y_3)^2} \tag{3}$$

By using the above information, the MR device is capable of determining whether the joint involved j_i has touched or crossed a virtual node ve_{ij}. It is carried out using a value internally defined as a threshold.

However, it should be noted that this process should show low latency, since a high latency may significantly affect the feedback that patients/therapists receive on behalf of the MR module. To achieve the best performance, a combination of i) an approach based on the asynchronous processing of the frames, by means of queues, and ii) a multi-threaded architecture, is proposed. The main thread of the tracking application obtains the depth frames through Azure Kinect DK™ and queues them. Additional application threads are waiting in the queue to retrieve the raw images. These threads will then process the frames in the depth camera to obtain the depth map and, in this way, the patient's joints JI_i. After obtaining the frame, and calculating the depth map and the position of the joints, the data are sent to the MR device via the UDP protocol, as it is faster than TCP. In this context of interactive graphics, speed is considered to be especially relevant.

IV. RESULTS

This section describes the experiments conducted to empirically highlight the benefits of the proposal, which mainly influence the accuracy with what the subject recreates the physical exercises defined by the therapist. The accuracy of the executed exercises, along with perseverance, is key to achieve effective recovery, reducing therapy times and maximizing mobility [4].

A representative group of 25 anonymous volunteers of different sexes (12 men and 13 women) of different ages ranges [18-25] (6) [25-45] (8) [45-75] (11) with distinct technological skills. They were healthy, but some of them required physical rehabilitation treatment in some point of their life. The sample only involved upper limbs exercises. The subjects who took part in the experiment used adjustable weights from 1 to 3 kg to limit their movements with the aim of simulating injuries in the upper extremities.

Volunteers signed an informed consent agreement which stated that the data collected would be anonymized and treated only for research purposes.

The experiments were composed of several steps. First of all, a therapist defines, with the MR device, one or several rehabilitation exercises of different levels of difficulty. The difficulty varies depending on the range of the movement, the existence of changes of the direction in the movement, and the number of involved dimensions in 3D space. Secondly, the subjects visualize a video of the exercise to be performed (without considering the use of the MR device). This is related to a traditional rehabilitation, that is, patients that perform exercises in a clinic trying to recreate the exercises with no visual reference by not using any kind of technology. Finally, the MR device Microsoft HoloLens 2™ is used afterwards by the subjects through which they receive visual feedback about the exercise to be performed.

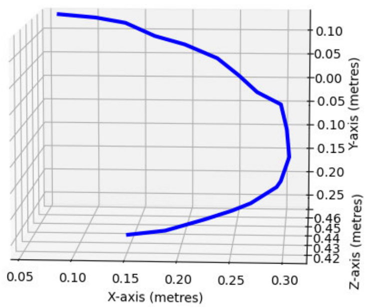

FIGURE 7. Simple rehabilitation exercise defined by a therapist.

FIGURE 8. Exercise defined in Figure 7 considering how it is rendered by *PhyRe Up!*.

Figure 7 graphically shows a simple example of an exercise defined by the therapist. It is defined as a semi-circular movement that must be performed with the right hand. Figure 8 depicts the movement as it is constantly appreciated by the user thanks to *PhyRe Up!* The rings represent control points that the user must physically reach, while the spheres represent the path to be followed. The yellow sphere represents the current point where the subject is located.

On the other hand, Figure 9 shows, by means of a blue line, the previous exercise defined by the therapist. In red, all the attempts made by different subjects without having a constant visual feedback are represented. As can be appreciated, the trajectories made by the subjects greatly differ from the trajectory defined by the therapist, despite being a relatively simple exercise. The greatest differences occur in the Z axis because the subjects lose the sensation of depth when watching the video in two dimensions.

Once the exercises were performed without the visual guidance provided by *PhyRe Up!*, the very same exercises were performed again, but this time with the assistance of *PhyRe Up!*, thus receiving continuous visual feedback. Figure 10 shows a comparison between the trajectory defined by the

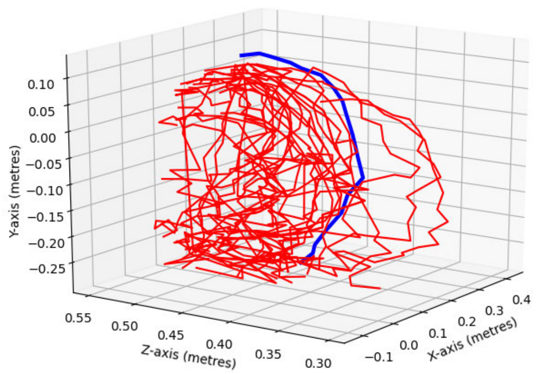

FIGURE 9. **Result of the rehabilitation exercise without feedback. In blue, the exercise defined by the therapist; in red, the trajectories traced by the test subjects. Each red line represents a single execution of an exercise performed by a subject without visual feedback.**

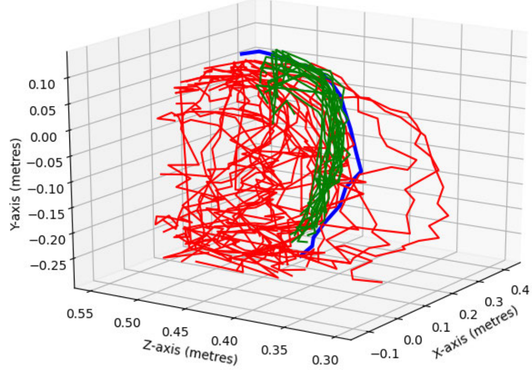

FIGURE 11. **Comparison of the result with and without the feedback offered by *PhyRe Up!*. In blue, the exercise defined by the therapist. In red, the trajectories followed by the test subjects without feedback. In green, the exercises performed with feedback.**

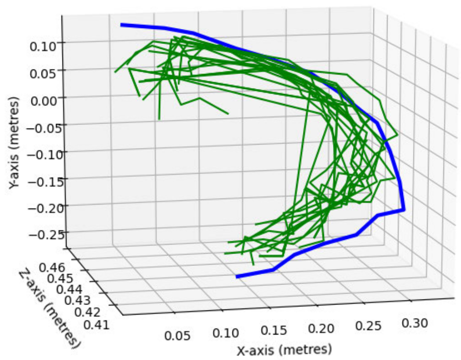

FIGURE 10. **Paths followed by the subjects of the experiment when using *PhyRe Up!* In blue, the exercise defined by the therapist; in green, the trajectories followed by the test subjects. Each green line represents a single execution of an exercise performed by a subject with visual feedback.**

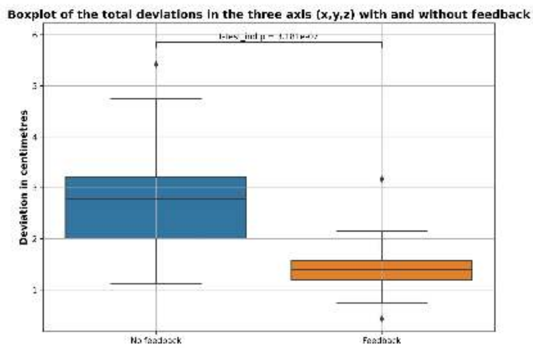

FIGURE 12. **Graphic representation of the total deviation in the three axis with and without the feedback offered by *PhyRe Up!*. The y-axis represents the cumulative deviation measured in centimeters. The greater the deviation, the greater the difference between the movement defined by the therapist and the one made by the subject.**

therapist (blue line) and the trajectories made by the subjects when using *PhyRe Up!* (green ones). In this occasion, it can be clearly seen how the subjects' joint makes a much more faithful trajectory regarding the one defined by the therapist.

In addition, Figure 11 includes both modes, i.e. paths made with and without visual feedback, along the path defined by the therapist. In this comparison the differences between one mode and the other can be seen at first sight. A simple path has been chosen in the previous graphs to demonstrate that the differences between one mode and another are already apparent from a simple exercise. In the case of complex exercises the differences are even more magnified.

Finally, the visual information included above is complemented by the data shown in Table 2, which summarizes the results obtained in the 25 conducted tests and compares the performance of exercises with, and without visual feedback with respect to the exercises defined by a therapist. The reference exercise was, again, a semi-circular movement with the right hand. The columns in the table, from left to right, represent the following items: test identifier, number of intermediate points or steps followed by the subject to perform an exercise without visual feedback, deviation on the x-axis, deviation on the y-axis, deviation on the z-axis and accumulated deviation on the three axes. These measurements are computed by adding up the current position of the joint and the next control point. On the other hand, the last five columns have the same meaning, but regarding the execution of the exercise when *PhyRe Up!* was used. This information reflects that the visual feedback provided by our proposal reduces the number of intermediate steps to complete an exercise and decreases, to a great extent, the accumulated deviation. The latter implies that the accuracy of the performed exercises is much higher.

As a result, it can be noted that the MR-based visual feedback mode dramatically reduces the total number of steps the subjects need to complete an exercise, as well as the total deviations from the therapist-defined points, which can be also observed in Figure 12. However, it should be highlighted

TABLE 2. Deviation produced in each axis regarding the reference exercise with no feedback and when using *PhyRe Up!*, respectively.

	No Feedback from *PhyRe Up!*					Using *PhyRe Up!*				
Test_id	Steps	dev. X	dev. Y	dev. Z	dev. TOTAL	Steps	dev. X	dev. Y	dev. Z	dev. TOTAL
1	34	0.66	0.77	1.46	2.89	26	0.48	0.86	0.36	1.70
2	31	0.70	0.45	0.85	2.00	33	0.67	0.86	0.34	1.87
3	34	0.78	0.46	1.05	2.29	25	0.47	0.52	0.33	1.32
4	35	1.15	1.10	1.03	3.28	27	0.30	0.51	0.24	1.05
5	24	0.35	0.73	1.70	2.78	23	0.49	0.33	0.31	1.13
6	27	0.70	0.68	1.80	3.18	35	0.53	1.89	0.75	3.17
7	26	1.28	1.34	0.73	3.35	15	0.16	0.20	0.39	0.75
8	35	1.00	1.40	0.55	2.95	26	0.56	0.43	0.40	1.39
9	37	0.99	1.64	0.58	3.21	22	0.25	0.31	0.32	0.88
10	31	1.06	1.66	0.69	3.41	27	0.39	0.40	0.35	1.14
11	24	0.52	0.42	0.80	1.74	28	0.44	0.41	0.35	1.20
12	20	0.55	0.54	0.70	1.79	39	0.70	0.74	0.71	2.15
13	19	0.55	0.64	0.77	1.96	29	0.42	0.57	0.30	1.29
14	17	1.89	0.5	0.49	2.88	24	0.53	0.45	0.24	1.22
15	31	1.28	1.35	2.11	4.74	22	0.59	0.59	0.32	1.50
16	27	0.96	1.13	0.38	2.47	23	0.63	0.58	0.35	1.56
17	33	0.94	0.63	0.43	2.00	33	0.34	0.69	0.49	1.52
18	33	1.35	1.23	0.54	3.12	29	0.56	1.16	0.37	2.09
19	32	1.61	2.51	1.30	5.42	12	0.10	0.10	0.23	0.43
20	26	0.47	0.69	0.85	2.01	27	0.49	0.40	0.35	1.24
21	26	0.59	1.05	0.60	2.24	24	0.59	0.37	0.35	1.31
22	27	0.55	0.73	0.97	2.25	26	0.57	0.60	0.35	1.52
23	16	0.14	0.35	0.63	1.12	22	0.59	0.58	0.31	1.48
24	16	1.86	0.71	0.85	3.42	24	0.72	0.68	0.31	1.71
25	22	0.38	0.61	0.91	1.90	23	0.62	0.67	0.29	1.58
				TOTAL:	**68.4**				**TOTAL:**	**36.2**

TABLE 3. Total deviation in each of the three axes individually, total accumulation in 3D space and differences between using *PhyRe Up!* or not.

	Steps	X dev.	Y dev.	Z dev.	Accumulated dev.
No Feedback	683	22.31	23.32	22.77	68.4
PhyRe Up!	644	12.19	14.9	9.11	36.2
Difference	-39	-10.12	-8.42	-13.66	-32.2

that this result cannot be generalized for all population. Concretely, the last three subjects had more steps and deviations after using the new technique compared no feedback, which are different to other subjects. The reason for this consideration may be attributed to the subjects' age, since they are found in the third age range. It seems to be logical because it is unfortunately usual that people who are older find themselves inexperienced using technology.

Table 3 shows the number of total intermediate steps that were needed to perform the 25 tests, the deviations accumulated individually on each of the axes and the total deviation in the 3D space. The last row shows the difference between not using *PhyRe Up!* and using the proposed system. Despite having taken an exercise whose path is simple, the differences are remarkable, especially in the Z-axis (see Figure 13). This could be when the subjects do not use *PhyRe Up!* since they watch an exercise by means of a traditional 2D video and lose the depth reference. However, the AR lenses and the 3D feedback offered by *PhyRe Up!* allow the subjects to have an accurate representation of the whole exercise.

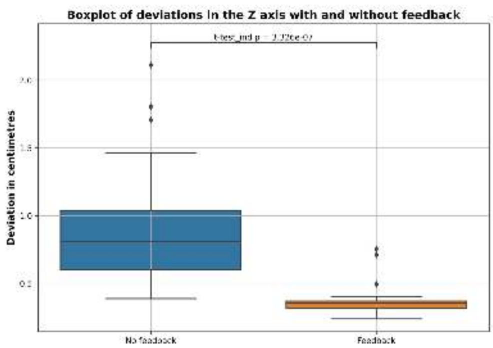

FIGURE 13. Graphic representation of the deviation in the z-axis with and without the feedback offered by *PhyRe Up!*. The y-axis represents the cumulative deviation in centimeters on the z-axis between the movement defined by the therapist and the one performed by the subject.

V. DISCUSSION

Stroke represents a global challenge that affects significantly a part of the society, particularly elderly people. Plus, it is expected that population aging will have a negative impact on the coming years. In this context, physical rehabilitation is essential for stroke patients to recover mobility and improve quality of life. However, the face-to-face supervision of these therapies implies that the patients, and commonly their relatives, have travel related time and costs. In other words, a high cost both for patients/families and health services. Visual representation systems, supported by immersive technology, allow to recreate virtual rehabilitation environments at home. These solutions combined with accurate skeleton tracking methods have been proposed in the last few years for patients for home rehabilitation without the need for a continuous and face-to-face supervision.

The proposed system *PhyRe Up!* aims to help stroke patients perform rehabilitation exercises by evaluating how accurately they adjust to the physician's requests. The experiment presented herein aims to assess the evaluation of accuracy, as this is a key aspect when performing rehabilitation exercises. Validation of the system for accuracy is the first step before applying for a clinical trial with patients, who have suffered moderate or severe stroke, according to the levels measured by the National Institutes of Health Stroke Scale (NIHSS) scoring system. The need for future randomized control trials is required in order to assess feasibility and effectiveness of proposed system on the recovery of stroke patients.

Interestingly, the data obtained from the conducted experiment shows that our proposal drastically reduces the intermediate steps required to complete an exercise thanks to the visual feedback that *PhyRe Up!* provides (see Section IV). Furthermore, the accuracy of the performed exercise is higher compared to traditional rehabilitation techniques. The employed gamification-based approach complements the visual and auditory feedback by rewarding the patients when they achieve a goal. It is important to highlight that previous research has shown to be effective and motivating [23], [24], [27], but they do not mention an improvement on the accuracy of the exercises. Only one research [26] showed a better performance in terms of a decrease in steps to complete an exercise. However, this presents a limitation regarding the usability of the system. These aspects should highlight the benefits of our proposal which could help physical rehabilitation exercises be well performed and motivated, while being also user friendly and more portable than those shown in last research. However, new approaches, methods, and techniques need to be devised in order to maintain the quality of therapeutic exercises performance and patient motivation. The objective is to reduce the risk of patients dropping out the treatment.

VI. LIMITATIONS OF THE STUDY

The experiment conducted has been oriented towards the evaluation of accuracy and data acquisition, as this is a key aspect when proposing a system that allows autonomous but guided rehabilitation. This first step is essential before evaluating its usefulness with real patients who have suffered a moderate or severe stroke, according to the levels measured by the National Institutes of Health Stroke Scale (NIHSS) scoring system.

Once the proposal presented herein has been accepted by the scientific community, a series of clinical trials, according to the guidelines provided by physicians, will be carried out in a second phase. These are intended to be performed in rehabilitation center rooms where the system will be deployed. The technological requirements of the proposed system are not excessive (MR headset, hand-tracking system and standard laptop). In fact, it should not be considered as high-cost since it aims at reducing the burden of stroke treatment by facilitating treatment and by fighting the lack of specialized staff [7], whose cost is significantly higher. The main objective of the research, in this phase, is to show the usefulness, and even the acceptance, of the system in patient rehabilitation, studying and analyzing the influence of motivation on the patient's commitment.

Lastly, in a third phase, a clinical trial will be conducted to analyze the feasibility and effectiveness of the system for its intended use, which is to allow effective rehabilitation at home. In this phase, the system should be prescribed by the physician and approved by the administration, being left on loan for the duration of the treatment in those special cases that require it.

Apart from this, we hope that two aspects will be improved in the long term: 1) the cost of the technology applied in the proposed system herein is expected to be reduced, and 2) people are progressively acquiring digital skills. These expectations are intended to make the system available for everyone in a short period of time.

VII. CONCLUSION

In this work we have introduced *PhyRe Up!*, a non-intrusive system based on MR and gamification techniques designed to rehabilitate stroke patients at home. The adopted interaction mechanism and the knowledge from the therapist make it possible to adjust the rehabilitation routine to the patient's needs. The use of gamification components aims at maintaining motivation while the patients recover their lack of mobility. The feedback provided through our approach is also intended to provide guidance to ensure that rehabilitation exercises are correctly performed, that is, they are accurately executed, similar as when the therapist supervises them in person. Temporal and movement accuracy aspects have been especially considered when designing *PhyRe Up!*, since these positively affect the recovery success rate. An experiment has been conducted to validate these aspects with a group of 25 subjects performing rehabilitation exercises with traditional methods and using the approach proposed herein (rehab with MR device). The results seem to be promising because the MR-based visual feedback mode appears to improve the rehabilitation. The total number of steps that needs to be completed by a subject seem to be reduced, as well as the total deviations from the therapist-defined points. However, it should be highlighted that this conclusion cannot be generalized for all population considering the limitation of the sample size, blinding and methods used to define the experiment.

As future lines of research, and once the system has been validated in terms of its efficacy with attention to its accuracy, we want to launch two clinical trials. One to assess its efficiency and other one to analyze its influence on the patient rehabilitation. Furthermore, other aspects will be measured with the aim of exploring the efficacy of the system on patient recovery. The objective will be to evaluate the degree of improvement of a patient when the system is used continuously in a treatment.

Therefore, the data collected in these clinical trials will be of interest for the further improvement of the system, *PhyRe Up!*. Moreover, we are confident that these data could be used by machine learning algorithms to obtain a set of rules to guide the rehabilitation of each patient, offering personalized recommendations in a dynamic way, thus adapting their rehabilitation plan according to their level of progress. This will also be a line of work in the future.

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2.1.2 A Fuzzy Recommendation System for the Automatic Personalization of Physical Rehabilitation Exercises in Stroke Patients

- Title: A Fuzzy Recommendation System for the Automatic Personalization of Physical Rehabilitation Exercises in Stroke Patients [14]
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Article

A Fuzzy Recommendation System for the Automatic Personalization of Physical Rehabilitation Exercises in Stroke Patients

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Abstract: Stroke is among the top 10 leading causes of death and disability around the world. Patients who suffer from this disease usually perform physical exercises at home to improve their condition. These exercises are recommended by therapists based on the patient's progress level, and may be remotely supervised by them if technology is an option for both. At this point, two major challenges must be faced. The first one is the lack of specialized medical staff to remotely handle the growing number of stroke patients. The second one is the difficulty of dynamically adapt the patient's therapy plan in real time whilst they rehabilitate at home, since their evolution varies as the rehabilitation process progresses. In this context, we present a fuzzy system that is able to automatically adapt the rehabilitation plan of stroke patients. The use of fuzzy logic greatly facilitates the monitoring and guidance of stroke patients. Moreover, the system is capable of automatically generating modifications of existent exercises whilst considering their particularities at any given time. A preliminary experiment was conducted to show the advantages of the proposal, and the results suggest that the application of fuzzy logic may help make correct decisions based on the patient's progress level.

Keywords: remote rehabilitation; recommender system; stroke; fuzzy logic; telemedicine

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1. Introduction

One in six people will suffer a stroke during their lifetime. Globally, stroke causes more than 6 million deaths each year, according to statistics provided by the World Health Organization [1]. Approximately two-thirds of stroke survivors leave hospital with some form of disability. Current predictions for the coming years are, unfortunately, negative, due to factors such as the incidence of stroke in middle-income countries [2]. In fact, 70% of strokes globally occur in low- and middle-income countries. This figure has doubled in recent decades, while in high-income countries, it has fallen by 42% [1]. The impact of this unresolved clinical challenge on health systems is enormous, due to issues such as the continuous need for physical rehabilitation and face-to-face supervision by qualified medical staff. In addition, stroke often affects people who are at the productive peak of their working careers, which can also have an impact on a country's socioeconomic development [3].

Much of the post-stroke rehabilitation process focuses on the physical rehabilitation of patients. In this process, both physiotherapists and occupational therapists guide the patient to regain day-to-day autonomy by addressing the movement and mobility difficulties resulting from stroke. In this sense, rehabilitation plans are usually designed around the concept of *self-care*, i.e., based on activities and exercises that the patient can progressively perform at home and in an independent way, whenever possible. The intensity of rehabilitation will depend on the condition of each patient, although it is quite common to carry out daily sessions of 45 min for periods of between 2 and 6 weeks. In more severe cases of stroke, rehabilitation may last several months.

In recent years, a significant number of applied research studies have appeared in which technology has been used to deploy virtual home rehabilitation systems [4,5]. These pursue the dual goal of facilitating patient monitoring and motivating patients to carry out rehabilitation exercises at home. These systems generally provide natural interaction mechanisms in a 3D virtual environment, guiding and helping patients to perform rehabilitation exercises in a playful and enjoyable way. Typically, a system offering such features will consist of (i) a device that can detect the patient's movements by means of a tracking system that calculates the positions and orientations of the joints in 3D space; (ii) a laptop running the system's software; and (iii) a monitor that provides visual feedback. It should be noted that technological solutions based on the low-cost Microsoft Kinect™ device have underpinned much of the research work conducted in recent years [6], with numerous studies giving credit to the clinical validity of the generated tools [7,8]. However, this device has already been replaced by more modern and scalable alternatives.

In order for a remote rehabilitation system to be used effectively from home, different aspects need to be considered. Firstly, usability is essential. If the underlying technology involves an entry barrier for the patient, then the system will be discontinued. Such a system can be considered usable when technology becomes transparent and natural for the patient. In this sense, natural interfaces based on gesture and movement detection are particularly relevant. At the same time, the system must be able to offer continuous assistance to the patient, making it as easy as possible to use the system, especially when approaching the system for the first time. Secondly, the ability to motivate the patient is another fundamental element to guarantee the continuous use of the system, since rehabilitation routines are usually based on the systematic repetition of a limited set of exercises. The integration of gamification techniques has been used in recent years to increase patient motivation [9]. Thirdly, the system must be able to recognize, with a certain precision and in an automatic way, the movements or exercises performed by the patient, which are usually previously assigned by the therapist. Home rehabilitation systems are often designed to encourage the patient to complete the entire routine, even if the execution is not perfect. In this regard, it is often desirable to strike a balance between the economic cost of the tracking system and the accuracy of the system.

A system that integrates these three fundamental characteristics will maximize the chances of successful use, guiding the patient through the rehabilitation process at home, facilitating the therapist's work, and ultimately, improving the quality and effectiveness of remote rehabilitation. However, the therapist would still be responsible for the individualized supervision of each patient according to their inherent condition (considering aspects such as their age, physical condition, or severity of the stroke) and their level of progress according to the assigned rehabilitation routine. Ideally, a remote rehabilitation system may incorporate an intelligent module that would automatically and dynamically adapt this routine for each patient, thus incorporating the notion of personalization. This adaptation would serve, among other things, to recommend more difficult exercises or to suggest variations of exercises based on the patient's performance.

In the previously introduced research context, our work has been essentially focused on the creation of a comprehensive remote rehabilitation system capable of automatically evaluating and classifying rehabilitation exercises [10]. On these foundations, we also designed a language whose sentences are processed by a software that can automatically generate personalized exergames that motivate the patient to perform rehabilitation exercises. In this article, we focus on the automated and intelligent personalization of the rehabilitation process adapted to each patient [11]. Thus, this paper proposes a fuzzy system for the recommendation of rehabilitation exercises for stroke patients. This system integrates an expert knowledge base defined by means of fuzzy rules and variables that reflects aspects such as the performance of a patient when performing rehabilitation exercises. The system is capable of adapting the rehabilitation plan initially assigned by the therapist. This adaptation takes the form of recommendations for new exercises, or exercises already performed by the patient, depending on the variation in the patient's level of progress as the rehabilitation process progresses.

The remainder of this article is structured as follows. Section 2 positions our work in the context of recommender systems, and particularly, those that operate automatically in remote rehabilitation systems. Subsequently, Section 3 presents our contribution, discussing the fundamental aspects and addressing the integration in a remote rehabilitation system. Section 4 presents the results obtained after conducting an experiment that illustrates with examples of how the fuzzy recommender system adapts a patient's rehabilitation routine. These results are discussed in Section 5, and the article ends with a series of conclusions in Section 6.

2. Related Work

When designing remote rehabilitation systems, it is essential to take into account the personalization of the patient's rehabilitation process. A symbiosis must be sought between the patient, the system, and the clinician, which seeks to adapt to the patient's progress according to the state of their injury. Achieving this involves the design of recommendation systems that are adaptive to the patient.

The design of a recommender system depends to a large extent on the used information and the available knowledge. Recommender systems can be classified into different groups [12]: (i) user profile recommendation systems; (ii) content recommendation systems; (iii) hybrid recommendation systems; (iv) filter-based recommendation systems; and (v) feature-based recommendation systems.

In the field of remote rehabilitation, recommendation systems based on the user's profile are commonly used. These systems analyze the patient's profile, considering their condition and evolution, and based on this, recommend a rehabilitation routine from the established plan for the recovery of their injury.

One of the main problems to be faced when studying a patient's profile is the uncertainty and vagueness with which the patient's condition is usually assessed. Furthermore, determining how well they are performing a certain exercise or even establishing how they are progressing represent similar challenges. In this sense, fuzzy logic and linguistic variables [13,14] are well-validated tools to be taken into account when dealing with uncertainty and vagueness.

In the context of remote rehabilitation systems, González-González et al. [15] presented a proposal in which the general objective is the design of an intelligent rehabilitation system based on exergames, consisting of an exercise player and a tool for designing them. The system includes a recommendation module that analyses the user's interactions, physical history, and preferences to assign the exergames to be performed. In turn, this module handles the concepts of difficulty levels and user skills. The recommendation algorithm revolves around three simple assumptions based on the patient's most recent performance (last exergame performed): (i) if the performance was low, the algorithm chooses an easier exergame; (ii) if the performance was good, the algorithm assigns a more difficult exercise; (iii) otherwise, the algorithm chooses an exercise of medium difficulty. The system was evaluated with domain experts, users and therapists, with positive results in terms of gesture-based interaction and medical applications.

Esfahlani et al. [16] discussed a serious game designed for the user to perform a series of tasks based on a dynamic of reaching virtual goals with a therapeutic objective. The difficulty levels of these tasks are adjusted based on a fuzzy controller, which has the user's skeleton tracking data (position and orientation of joints in 3D space) as input and the difficulty level of the game that the patient will perform later as output. In this sense, the proposed system allows to guide, in an automatic way, the patient's rehabilitation routine through continuous and personalized learning. The fuzzy rules are derived from consultancy and collaboration with physiotherapists, along with the various tests carried out. On the other hand, the authors of [17] describe related work in which a grammar is used to enable therapists to specify rehabilitation exercises. The system includes a fuzzy logic-based component that evaluates, in real time, whether the patient performs the exercises according to the exercise definition. In a related context, the prototype of the patient rehabilitation station that integrates video games for rehabilitation based on computational intelligence techniques is presented in [18], both for the online monitoring of the execution of movements during the games and for the adaptation of the game to the patient's condition. The prototype integrates a fuzzy system to monitor the execution of the exercises, in real time, according to the clinical constraints defined by the therapist at the time of configuration, and to provide direct feedback to the patients. At the same time, the system adapts to modify the game according to the patient's current performance and progress and to the exercise plan specified by the therapist. This latter work represents one of the pillars of the methodology for the design of safe, therapeutic exergames introduced by these same authors [19].

In a line of research more linked to the management of expert knowledge, a tele-rehabilitation system for the remote selection, evaluation and management of physical therapies is proposed in [20]. The main contribution of this work is the creation of an integral system for tele-rehabilitation, although the authors place special emphasis on the extraction and use of knowledge through the definition of an ontology composed of 2300 classes and 100 properties, to appropriately select the exercises assigned to each patient. To do this, a knowledge base is used that contains information about the patient's medical history and the previously assigned treatment.

On the other hand, Karime et al. [21] proposed a web-based framework for wrist rehabilitation that makes use of fuzzy logic to offer adaptive tasks to the patient, in parallel with the supervision performed by the therapist. In this work, an evaluation of the effectiveness of the framework is carried out, considering the adjustment of various parameters used in the rehabilitation process in a framework that combines the level of personalization of the rehabilitation based on the patient's performance and the feedback offered by the therapist. The use of fuzzy logic is also present in articles focusing on patient rehabilitation using robots or exoskeletons, such as the work discussed in [22], where a system based on deterministic adaptive robust control is introduced whose control parameters are optimized thanks to a novel approach based upon cooperative game theory. External disturbances (possibly time-varying) are managed through fuzzy logic and its ability to work with uncertainty.

Our proposal, which is described in detail in Section 3, which falls within the scope of several lines of research that are currently considered popular research topics. Particularly noteworthy is the line that contemplates the definition of artificial intelligence models and the use of expert knowledge to guide or orientate the patient's evolution, based on their clinical data and the context of their illness. This line is closely related to the impact that precision medicine has had on the medical domain, and whose ideas can be borrowed with the ultimate aim of adapting or personalizing the rehabilitation process to each patient. Furthermore, this work is also framed in the field of telemedicine tools in the context of physical rehabilitation, thus trying to respond to an unresolved clinical challenge as a consequence of the lack of specialized clinical staff to supervise patients affected by stroke or, from a more general point of view, by neurological diseases requiring physical rehabilitation.

Thus, the main contributions of this research article are as follows:

- Firstly, a recommendation module which can automatically modify rehabilitation plans previously devised by physicians is proposed. Conditional knowledge is defined to select the most suitable exercise for the patients, depending on their current condition and how they progress in terms of rehabilitation;

- Secondly, the gap between the rehabilitation system in which the recommendation module is integrated and the patients/physicians is reduced, thanks to the use of fuzzy logic to both represent and infer knowledge. This approach facilitates the understanding of the artificial system, and particularly, how the recommendation module operates. We think that this contribution is especially relevant when it comes to explain how artificial systems make decisions. Furthermore, the feedback provided to the patients can be used to guide the rehabilitation process in a dynamic way;
- Thirdly, the proposal sets the foundations for providing physicians with a tool that reduces the time spent supervising stroke patients. Currently, there is a lack of specialized personnel to supervise, face-to-face and on a regular basis, patients affected by neurological diseases that require physical rehabilitation. Our work may eventually help improve the quality and effectiveness of remote rehabilitation by addressing the automatic adaptation of rehabilitation routines.

3. Material and Methods

3.1. Remote Rehabilitation System Overview

In this section, a fuzzy system for automatically recommending rehabilitation exercises for stroke patients is proposed. Particularly, the exercises recommended by this system are therapeutic exergames, which involve physical effort guided by gamification techniques. Fundamentally, this system was mainly designed to enable patients to perform home rehabilitation exercises, according to their condition and situation at a given moment of their therapy. The proposed approach employs the therapist's knowledge to evaluate the patient mobility and recommend, in consequence, a rehabilitation exercise according to such information. However, it should be pointed out that the recommendation of an exercise when patients perform rehabilitation at home is exacerbated, since the adjustment of the therapy turns into a more complex process by having a fuzzy idea of their current situation. This system bears this in mind, and is able to automatically generate personalized modifications of existent exercises by considering the particularities of the patients. Despite this, it should be noted that the system does not pretend to remove the therapist's role. On the contrary, it aims to complement it in order to reduce their workload by delegating tasks to the proposed intelligent system.

The system introduced herein consists of several components that interact between them. Figure 1 depicts the overall architecture, whose interrelated components are the domain knowledge module (i); the interface module (ii); the tracking module (iii); the evaluation module (iv); and the recommender module (v). Each component is briefly described below.

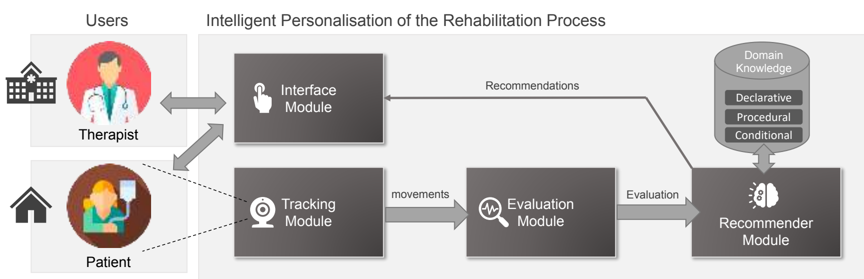

Figure 1. Architectural overview of the proposed system.

The **domain knowledge module** integrates the knowledge necessary for the system to correctly work. This module considers the following aspects: knowledge about the physical rehabilitation of stroke patients, knowledge about the performance of rehabilitation exercises, knowledge about managing their rehabilitation plan, knowledge about the patient's body, their injury, their condition, and the evolution in their rehabilitation. This module is referred to as the knowledge of domain experts from a higher perspective. Specifically, this is structured and organized in three specific classes of knowledge, which are clearly differentiated: declarative knowledge, procedural knowledge, and conditional knowledge:

- *Declarative knowledge*. It refers to the facts or static knowledge. In this regard, it defines the set of existent body joints that can be exercised during the rehabilitation, which will be recognized by the system (i.e., $J = \{j_1, j_2, \ldots, j_{31}\}$ https://docs.microsoft.com/bs-latn-ba/azure/kinect-dk/body-joints, accessed on 11 June 2021), the constraints associated with them (i.e., $C(J) = \{C(j_1), C(j_2), \ldots, C(j_{31})\}$), the associated variables to monitor the rehabilitation exercise of patients (i.e., $V = \{v_1, v_2, \ldots, v_k\}$);
- *Procedural knowledge*. This knowledge defines the rehabilitation exercises and the game dynamics associated with them (i.e., $E = \{e_1, e_2, \ldots, e_n\}$. In each $e_i \in E$, the patient works out a concrete joint (i.e., $j_x \in J$) with a different degree of complexity, trying to rehabilitate a body member with low mobility. The procedural knowledge also includes the knowledge required to check how well the patient performs an exercise and to determine how the patient is progressing in the rehabilitation process;
- *Conditional knowledge*. This knowledge will be used to recommend the next exercise to be performed in the patients' rehabilitation plan (i.e., $e_i \in E$), based on their degree of injury and their progress towards recovery. Fundamentally, it makes use of a set of fuzzy (if–then) rules (i.e., $R = \{r_1, r_2, \ldots, r_m\}$) to achieve the aforementioned goal. This will be deepened in the following section.

The **interface module** enables the communication between the patient/therapist and the system. On the one hand, it includes the adequate interaction mechanisms so that patients perform rehabilitation exercises as if they played games. On the other hand, it provides the software components to the therapists in order to define rehabilitation exercises and game dynamics associated with them.

The **tracking module** is responsible for recognizing in real time the users' movements to perform rehabilitation exercises. In essence, it captures the body tracking results from a sensor device, in this case Microsoft Azure Kinect DK https://azure.microsoft.com/es-es/services/kinect-dk/, accessed on 11 June 2021. These results represent the 3D spatial coordinates of the human body joints, i.e., positions (x, y and z) $\in \mathbb{R}^3$, and rotations (w, a, b and c) $\in \mathbb{R}^4$. The latter is expressed as a normalized quaternion.

The **evaluation module** assesses the performance of a rehabilitation exercise according to the level of complexity that it entails for the patient. This information is necessary to know the patient's status within the context of the rehabilitation plan and to recommend new rehabilitation exercises.

The **recommendation module** is responsible for modifying the patient's rehabilitation plan according to the patient's current condition. This module will make use of conditional knowledge to determine the most appropriate exercise for the patient based on their injury and their current level of progress within their rehabilitation plan. This module, which is the core of the paper, is fully detailed in the next section.

As described above, procedural knowledge contains the exercises used in this system. These are physical activities to be executed by patients within the rehabilitation plan with a motivational approach that is based on play, i.e., exergames. The exergame constitutes the core of the system and it is defined as a 8-tuple, consisting of the following elements:

$$e_i =< D_i, JI_i, SET_i, VE_i, T_i, RG_i, C_i(JI_i), KPI_i > \tag{1}$$

where each element represents the following:

- D_i is a description of the exercise e_i;
- JI_i is the set associated with the joints involved in the rehabilitation exercise e_i, i.e., $JI_i \subseteq J$;
- SET_i is the setup of the exercise which is defined as a 4-tuple (sc, rp, t, c). sc indicates the degree of success by achieving a step in the rehabilitation exercise e_i ($sc \in \mathbb{N}$); rp are the repetitions required to perform the exercise e_i ($rp \in \mathbb{N}$); t is the time needed to finish the exercise e_i ($t \in \mathbb{R}$); and c is the degree of complexity of the exercise ($c \in \mathbb{N}$);

- VE_i represents the virtual objects positioned in a playable scene in the 3D space. Examples of this objects may be rings, spheres and hoops, among others;
- T_i refers to the trajectories associated with the movements that a patient will make when performing the exergame e_i. T_i is defined as a set of virtual points that establish the movements the patient must perform;
- RG_i is a set of rules that contains the game mechanics of the exercise e_i, which are based on the interaction between JI_i and T_i in the 3D space to achieve an objective. Formally, $RG_i = (rg_{i1}, rg_{i2}, \ldots, rg_{in})$, where each particular rule of the game rg_{ij} is used to define the function $JI_i \times VE_i \times O \longrightarrow GM$ where:
  - JI_i establishes the joints that interact with the game rule;
  - VE_i establishes the virtual nodes that interact with the game rule;
  - O is a set of objectives defined to satisfy the game rules ($O = \{o_1, o_2, \ldots, o_m\}$);
  - GM is a set of game mechanics to be triggered when a joint involved JI_i interacts with a virtual node VE_i meeting a certain objective o_j. Example of game mechanics may be visual feedback provided to the patient to correct a bad movement.
- $C_i(JI_i)$ is a set of constraints that are associated with joints that the patient should not ideally move to compensate for the lack of mobility or strength in the exercise e_i (i.e., $(C_i(JI_i) \subseteq C(J))$;
- KPI_i is a set of key performance indicators that are used to monitor the patient's evolution according to the performance of the exercise e_i.

3.2. Proposed Recommendation Module

This module aims to help therapists recommend new exercises to patients who perform home rehabilitation. Generally, therapists ask patients to carry out a series of exercises at home, when the therapy has not yet been completed in the rehabilitation center. Once the patients return to the clinic, therapists interview them about how they have performed the exercises and evaluate their progress in order to be able to recommend new exercises. Without the use of technology, the therapists' knowledge may be inaccurate regarding the patients' progress as they do not know their commitment at home.

The developed system will collect data on how the patients have performed exercises at home within their rehabilitation plan. In addition, the system, using an intelligent recommender, is able to adapt the rehabilitation plan to the patients' needs. This section presents the architecture devised for the intelligent rehabilitation module which will be used by the general system to autonomously modify the patients' rehabilitation plan according to their evolution.

However, entering before fully into detail of the formal model, the next subsection shows the fundamental ideas of the proposed system.

3.2.1. Fundamental Ideas

This system allows therapists to define a rehabilitation therapy based on the patients' injury and the their initial assessment regarding the patients' condition (their injury state, their physical condition, and their age).

Particularly, the overall rehabilitation system makes use of the gym metaphor to define a rehabilitation therapy. This means that our approach is based on the global concept of patient's rehabilitation plan, which can be considered as a succession of exercises taken from E and ordered by their complexity, which must be carried out by the patient in a sequential way. However, the plan should be able to be altered according to the patient's progress. Thus, provided that the system detects that the patient is finding difficulties to perform an exercise in the plan, the system should be capable of recommending an exercise with lower complexity. It even may modify an existent exercise, reducing the number of repetitions or increasing the time to be spent on it. On the other hand, the system should behave in a similar way when in a situation in which complex exercises are easily performed.

Thus, a rehabilitation plan for a patient p_i, denoted as $P(p_i)$, is defined as follows: $P(p_i) = \{e_x, e_y, \ldots, e_k\}$ where each $e_j \in P(p_i)$ is also an element of E (i.e., $e_j \in E$) and it is satisfied that $Complexity(e_x) \leq Complexity(e_y) \leq \ldots \leq Complexity(e_k)$ with $Complexity(e_j)$ being a function that returns the complexity of the exergame e_j (taken from $c \in SET\_j$).

As mentioned above, the exercises that form part of a patient's plan are initially selected and organized by the therapists according to the patient's injury and condition. The recommendation module will automatically adjust the plan according to the patient's performance, acting on the set of exercises included, their order or even their configuration (values of parameters rp (number of repetitions) and t (time needed to finish the exercise) taken from SET_x).

3.2.2. Recommender Module Definition

The recommendation system presented herein has been proposed as a function that will determine an action on the patient's rehabilitation plan to be adjusted, as much as possible, to the patient's state of recovery. Therefore, this function models the existing relationship between the domain, i.e., the patient's condition in the recovery of the injured limb, and the codomain, i.e., an action to be performed in the rehabilitation plan.

The challenge to be faced is the domain of definition of such a function. This should provide information on how the patients are progressing in their recovery. It will be determined by how they have performed the last exercise of the plan as well as the state in which they are found regarding their recovery.

The variables, which can be recorded by the system, and can provide information on how the patient performed the last exercise of the plan, are defined below:

- *difference_number_steps* (V_1) is the difference between the number of steps that the patients and the therapists performed to carry out the last rehabilitation exercise $last\_exg$ (i.e., the patient fails to pass through all the virtual points that establish the exercise trajectory);
- *accumulated_deviation* (V_2) is the cumulative spatial deviation between the patient's exercise and that gold standard or the therapist's exercise (i.e., this calculation is based on the distance accumulated when traversing the trajectory associated to the last exercise $last\_exg$);
- *difference_time* (V_3) is the temporal difference regarding the execution of the last exercise $last\_exg$ between the patient and the therapist.

These variables collect information about the patients' status, i.e., how they have performed the last exercise of the allocated plan. However, they do not take into account their evolution, that is, how they have progressed. Significantly, it becomes essential to add this information to the domain to know the actual state of the patient in detail. Thus, the variable *progress_level* (PPL) was included in order to track the state in which a patient is found before performing the last exercise. Its value belongs to the range $[0, 10]$, and the initial one is determined by the therapists when they assess the patient for the first time. It should be noted that the value of the previous variable is considered to choose the exercises for the patient's rehabilitation plan. Furthermore, this variable is modified depending on the patient's evolution towards the last recovery session.

On the other hand, the codomain should reflect the next exercise to be performed by the patients according to their condition. In this research work, the initial rehabilitation plan established by the therapist is modified by proposing a new exercise based on a desirable difficulty recommended to the patient. Thus, the output will consist of a new exercise, which will be established depending on the difficulty given by one of the following functions:

- $propose\_exercise$. It chooses an exercise from E whose lesion and joint JI_i are similar to the last exercise $last\_exg$. This function takes into account an exercise that has not yet been performed, since the system internally stores information about the patients and the exercises they performed, i.e., their level of success regarding the exercise, their points, as well as the time spent by the patient to complete it. To do this, this function takes two parameters: (1) a label indicating the complexity of the exercise to be searched for (MC, more complexity; SC, same complexity; LC, less complexity) based on the (2) last performed exercise ($last\_exg$);

- $repeat\_last\_exg$. It recommends the repetition of the last exercise performed by the patient $last\_exg$ based on modifying its configuration. This function takes as parameters rp (number of repetitions) and t (time needed to finish the exercise) from SET_{last_exg}.

It is important to highlight that the execution of the last exercise influences the patient's progress level, i.e., the results from the execution of the $last\_exg$ affects the value of the variable *progress_level* (PPL). This is why any action on this variable will also be included as an output of the recommender system. This variable, denoted as $EPPL$, is named *Effect_on_PPL*.

When modeling the function that relates the domain or inputs to the codomain or outputs, a mechanism is used to understand why the recommendation was made. At the same time, this mechanism also deals with the imprecision and uncertainty that exists when evaluating the performance of the last exercise performed by the patient. Even when evaluating the level of progress of the patient within the context of their rehabilitation plan. For this reason, a set of IF-THEN fuzzy rules (R), which model the function $V_1 \times V_2 \times V_3 \times PPL \longrightarrow E \times EPPL$, are defined.

The linguistic variable V (i.e., $V = \{V_1, V_2, V_3\}$) considers the following domain of definition: $DDV_x = \{$ very low (VL), low (L), medium (M), high (H), very high (VH)$\}$ being x defined from 1 to 3. Each linguistic value in DDV_x is defined by means of a trapezoidal function (Π), enclosed by a lower limit a, an upper limit d, a lower support limit b, and an upper support limit c, where $a < b < c < d$ (see Equation (2)). If the values of b and c are equal, a triangular function is obtained:

$$\Pi(x; a, b, c, d) = \begin{cases} 0 & iff \quad x < a \\ (x-a)/(b-a) & iff \quad a \le x < b \\ 1 & iff \quad b \le x \le c \\ (d-x)/(d-c) & iff \quad c < x \le d \\ 0 & iff \quad x > d \end{cases} \tag{2}$$

The choice of the trapezoidal function to construct the membership function, for each of the values that the variables used in the system can take, is justified because it is the only one that gives us the necessary freedom to represent any type of value (i.e., ordered-discrete or ordinal, unordered-discrete or nominal, boolean, numerical, ranking or the most frequent continuous) [23].

The domain of the definition of each variable $V_x \in V$, i.e., DDV_x, is matched to the normalized measurements $\{0, 0.25, 0.5, 0.75, 1.0\}$. The membership value was confined to the closed range $[0, 1]$. The corresponding fuzzy membership set is depicted in Figure 2.

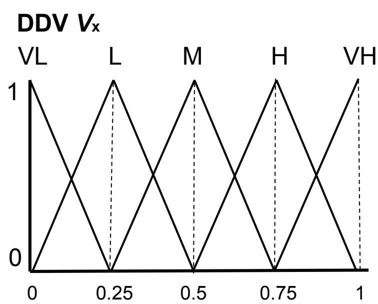

Figure 2. Domain of definition of the variable V_x, i.e., $V1$, $V2$, $V3$.

On the other hand, the linguistic input variable PPL may take the following values: "excellent achievement" (EA, equivalent to 9 or 10); "outstanding achievement" (OA, equivalent to 7 or 8); "satisfactory achievement" (SA, equivalent to 5 or 6); and "not achieved" (NA, smaller than 5). Each linguistic value that this variable can take is defined by means of a trapezoidal function—as can be seen Figure 3.

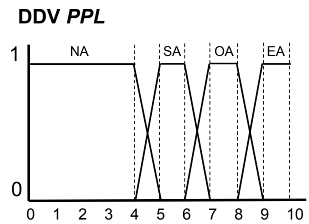

Figure 3. Domain of definition of the variable PPL.

The linguistic output variable $EPPL$ takes the following values: "substantial decrease" (SD, equivalent to decrease 1 point); "moderate decrease" (MD, equivalent to decrease 0.5 point); "no change" (NC); "moderate increase" (MI, equivalent to increase 0.5 point); and "substantial increase" (SI, equivalent to increase 1 point). Each one of these linguistic values will also be defined by means of a trapezoidal function—as can be seen in Figure 4. It is purely used to modify the patient's level of progress as the patient recovery level potentially suffers a change after a physical activity. The operations to be considered are three: increasing the patient's progress, decreasing it or maintaining it.

Knowledge engineering techniques have been used during the design of the system, mainly based on interviews with physicians, using designs and executions which have been fine-tuned in different stages as a basis. Thanks to this process, the rules and the variables and values they take have been determined, seeking a compromise between understandability and efficiency.

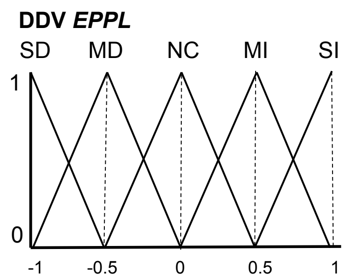

Figure 4. Domain of definition of the variable $EPPL$.

As for the other output of the system, it will be a recommended exercise for the patient by invoking the function *propose_exercise*, as mentioned above. This function will recommend an exercise from the set $P(p_i)$ with higher, lower or same complexity as the last exercise performed by the patient. Otherwise, if the exercise to be recommended is not found, E will be used. The function is shown in Algorithm 1. It should be pointed out that we assume an exercise will certainly be taken from E.

Invoking the function $repeat\_last\_exg(rp, t)$ involves recommending to the patient the repetition of the last performed exercise e_y, however, altering some of its configuration parameters from SET_y, namely rp by setting a different number of repetitions, or t by giving a different time to finish the exercise e_y. The modification of the values may be an increase (+) or reduction (-) in the parameters rp and t.

Algorithm 1: Behavior of proposed exergame function.

Input: degree of complexity DC, i.e., HC (higher complexity), SC (same complexity), LC (lower complexity); and the last exergame $last\_exg$ performed
Output: recommended exergame, e_{out}

if $last\_exg \notin P(p_i)$ **then**
  switch DC **do**
    case HC **do**
      Select e_i from $P(p_i)$ such that $SET_i(c) > SET_{last\_exg}(c)$
    end
    case SC **do**
      Select e_i from $P(p_i)$ such that $SET_i(c) = SET_{last\_exg}(c)$
    end
    case LC **do**
      Select e_i from E such that $SET_i(c) = SET_{last\_exg}(c)$
    end
  end
else
  switch DC **do**
    case HC **do**
      Select e_i from $P(p_i)$ such that $SET_i(c) > SET_{last\_exg}(c)$
    end
    case SC **do**
      Select e_i from E such that $SET_i(c) = SET_{last\_exg}(c)$
    end
    case LC **do**
      Select e_i from E such that $SET_i(c) = SET_{last\_exg}(c)$
    end
  end
end
return e_i

Each rule $r_i \in R$ has the following form: IF V_1 is $DDV_1(i)$ AND V_2 is $DDV_2(i)$ AND V_3 is $DDV_3(i)$ AND PPL is $DDV_{PPL}(i)$ THEN e_y and $EPPL$ is $DDV_{EPPL}(i)$. On the one hand, e_y represents the exercise to be recommended. On the other hand, $DDV_x(i)$ represents the values that the variable V_x takes in the rule i, that is, $DDV_x(i) \subseteq DDV_x$. Similarly, $DDV_{PPL}(i)$ and $DDV_{EPPL}(i)$ represent the values that the variables PPL and $EPPL$ take in the rule i, respectively, where $DDV_{PPL}(i) \subseteq DDV_{PPL}$ and $DDV_{EPPL}(i) \subseteq DDV_{EPPL}$. The set DDV_x is a global set that represents the values that must take the variable V. Furthermore, the set DDV_{PPL} and DDV_{EPPL} are the global sets that represent the values that must take the variables PPL and $EPPL$.

Lastly, some of the rules defined in this system to model the behavior of the recommender system, which will constitute the conditional knowledge of the remote rehabilitation system, are shown below:

r_1: IF $difference\_number\_steps$ is $\{VL\}$
AND $accumulated\_deviation$ is $\{VL\}$
AND PPL is $\{EA, OA\}$
THEN $propose\_exercise(HC, last\_exg)$ AND $EPPL$ is $\{SI\}$

r_5: IF $difference\_number\_steps$ is $\{M\}$
AND $difference\_time$ is $\{M\}$
AND PPL is $\{SA\}$
THEN $propose\_exercise(SC, last\_exg)$ AND $EPPL$ is $\{NC\}$

r_9: IF $accumulated\_deviation$ is $\{VH\}$
AND $difference\_time$ is $\{VH,H\}$
AND PPL is $\{SA\}$
THEN $propose\_exercise(LC, last\_exg)$ AND $EPPL$ is $\{SD\}$

r_{11}: IF $difference\_number\_steps$ is $\{M\}$
AND $accumulated\_deviation$ is $\{M\}$
AND $difference\_time$ is $\{M\}$
AND PPL is $\{NA\}$
THEN $repeat\_last\_exg(-rp, +t)$ AND $EPPL$ is $\{NC\}$

At this point, we must clarify that a variable not appearing in a rule means that all the values of its definition domain may be taken. For example, in the rule r_1, the variable $difference\_time$ (V_3) takes the following values: $\{VL, L, M, H, VH\}$. As can be seen, the rules are highly explainable, which will help understand why the system makes a new recommendation.

3.2.3. Functions Of The Proposed Recommender System

In this section, we present how the proposed system uses the fuzzy rules presented above to recommend a new rehabilitation exercise and to alter a patient's progress level.

Given that the output of the rules consists of two elements, that is, the recommended exercise and an alteration in the value of the patient's progress level, two outputs need to be obtained for each occurrence of the inputs ($V_1 \times V_2 \times V_3 \times PPL$). Therefore, the system infers two situations for each input, which are enumerated below:

1. The next rehabilitation exercise that the patient should perform;
2. How to alter the value of the patient's progress level.

For this purpose, we will consider that the rules inform of the following two relations, since the consequent is related to a logical AND: $V_1 \times V_2 \times V_3 \times PPL \longrightarrow E$ and $V_1 \times V_2 \times V_3 \times PPL \longrightarrow EPPL$.

To infer within the first relationship, we will check the activation degree of each rule. This will be done by evaluating the antecedent of each one. This evaluation is performed as discussed subsequently.

A function φ_{ji} will be associated with each variable V_i in the rule j, whose definition depends on the values taken by the variable V_i in it. Therefore, if the variable takes a single linguistic label L_x (i.e., $L_x \in DDV_i$), the definition of the function φ_{ji} will be the same as the one defining the linguistic value (i.e., $\varphi_{ji} = \Pi_{L_x}$). However, when the variable takes more than one linguistic value, this function will be built based on whether or not the values are close to the domain of definition of the variable V_i, i.e., DDV_i. For consecutive linguistic values, we will refer to this set as C. The function φ_{ji} will be defined as a trapezoidal one with the following parameters:

$$a = \min_a \{\Pi_{L_x}(x; a, b, c, d) | L_x \in C\} \tag{3}$$

$$b = \min_b \{\Pi_{L_x}(x; a, b, c, d) | L_x \in C\} \tag{4}$$

$$c = \max_c \{\Pi_{L_x}(x; a, b, c, d) | L_x \in C\} \tag{5}$$

$$d = \max_d \{\Pi_{L_x}(x; a, b, c, d) | L_x \in C\} \tag{6}$$

If the variable V_i in a rule takes non-consecutive values, or there are two non-consecutive groups of values, the function φ_{ji} will be defined with as many trapezoidal functions as there are non-consecutive values or non-consecutive groups (Figure 5).

Example 1. *For the rule r_1 shown above, which is: IF V_1 is {VL} AND V_2 is {VL} AND V_3 is {VL,L,M,H,VH} AND PPL(V_4) is {OA,EA} THEN $propose\_exercise(MC, last\_exg)$ AND EPPL is {SI}, the φ_{1i} functions will be defined as follows:*

$$\begin{aligned}
\varphi_{11}(x) &= \Pi_{VL}(x; 0, 0, 0, 0.25) \\
\varphi_{12}(x) &= \Pi_{VL}(x; 0, 0, 0, 0.25) \\
\varphi_{13}(x) &= \Pi_{\{VL,L,M,H,VH\}}(x; 0, 0, 1, 1) \\
\varphi_{14}(x) &= \Pi_{\{OA,EA\}}(x; 6, 7, 10, 10)
\end{aligned}$$

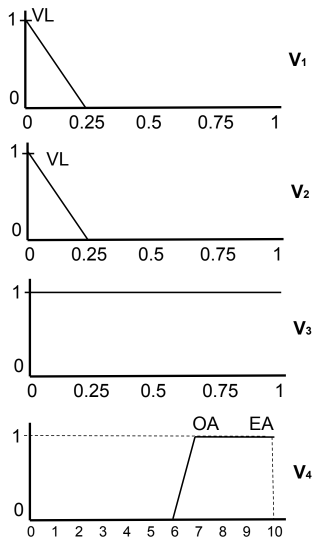

Figure 5. φ_{1i} functions for each variable V_i in the rule r_1.

The *activation degree* of a rule r_j for an input (x_1, x_2, x_3, x_4), where x_i is the input value (crisp value) taken by the variable V_i, will be calculated by determining the membership value of each input x_i to the function that defines the input variable V_i, i.e., $\varphi_{ji}(x_i)$. Given that the antecedent of our rules has more than one part related with a logical AND operator, the t-norm [24] of the minimum has been applied to obtain a single membership value. The definition of this calculus is as follows:

$$\text{activation degree}(r_j) = \underset{i=1,\ldots,4}{min}\{\varphi_{ji}(x_i)\} \quad (7)$$

To obtain the output of this first inference process, the t-conorm [24] of the maximum will be used (i.e., the t-conorm corresponding to the minimum t-norm). As a result, the system will recommend the exercise that proposes the rule with the highest activation degree:

$$\text{output\_exercise}(r_j) = \underset{j=1,\ldots,n}{max}\{\text{activation degree}(r_j)\} \quad (8)$$

On the other hand, the inference of the second relationship has been carried out by using the Mamdani's fuzzy inference method [25], whose output is a fuzzy set. This fuzzy inference process is composed of the following steps:

1. Evaluate the antecedent for each rule $r_j \in R$ to obtain a single membership value, i.e., *activation degree* (r_j). We will do this as in the previous case;
2. Obtain the conclusion of each rule in $EPPL$. To do this, we truncate the fuzzy value taken by the consequent of the rule in the variable $EEPL$ using the minimum with the *activation degree*(r_j) on its membership function. The output will be a new fuzzy set defined by means of a membership function μ_j where:

$$\mu_j : [-1, 1] \longrightarrow [0, \text{activation degree}(r_j)]$$

and it is defined as

$$\mu_j(x) = min\{\Pi_{L_x}(x), \text{activation degree}(r_j)\} \tag{9}$$

with L_x being the value that the variable $EPPL$ takes in the rule r_j ($L_x \in DDV_{EPPL}$).
3. Aggregate rule's conclusions into a single fuzzy set defined by means of the function μ, using a fuzzy aggregation operator. The t-conorm of the maximum has been used to aggregate the truncated output functions returned by the previous step:

$$\mu(x) = \max_{j=1,\ldots,|R|} \{\mu_j(x)\} \tag{10}$$

4. Defuzzification. Since we want to obtain a crisp value that affects to the PPL value, which we recall is confined to the range $[0, 10]$, so we need to transform the fuzzy set obtained in step 3 into a single numerical value. To do this, we used the defuzzification method of the centroid, which returns the center of the area under the fuzzy set obtained in step 3. It should be pointed out that the total area of the membership function distribution used to represent the combined control action is divided into a number of sub-areas. We denote the centroid as $EPPL_{co}$ and it is calculated as

$$EPPL_{co} = \frac{\sum_{i=1}^{N} x_i \mu(x_i)}{\sum_{i=1}^{N} \mu(x_i)} \tag{11}$$

where N indicates the number of sub-areas, $\mu(x_i)$ and x_i represent the area and the centroid of the area, respectively, of the i^{th} sub-area.

The value $EPPL_{co}$ ($EPPL_{co} \in [-1, 1]$) is used to modify the patient's progress level (PPL) with the aim of updating their progress:

$$PPL = \begin{cases} 0 & iff \quad PPL + EPPL_{co} \leq 0 \\ PPL + EPPL_{co} & iff \quad 0 < PPL + EPPL_{co} < 10 \\ 10 & iff \quad PPL + EPPL_{co} \geq 10 \end{cases} \tag{12}$$

We would like to conclude by stressing that Zadeh's conventional t-operators of Min and Max, which have been used in this system, perform significantly well within the context of our problem [26].

4. Proposed System In Operation

This section describes an experimental case study conducted to show the benefits of the proposal discussed in this research work. Then, an example that describes how the fuzzy system that underpins our proposal would work in a real-world situation is presented.

However, before fully entering the description of the experimental case study, let us take a look at the holistic view of the whole recommender system presented in Figure 6 in order to understand how it works with all the modules involved.

1. The system proposes an exercises ($e_x \in E$) to the patient through the **interface module**;
2. The patient performs an exercise whose movements are captured by the **tracking module**;
3. The system evaluates, through the **evaluation module**, the performance of the patient. Particularly, it obtains the value of the variables (V_1, V_2, V_3);
4. The system, based upon the values of the variables (V_1, V_2, V_3, and PPL), triggers the rules following the next criteria:
   (a) It computes the activation degree of the rules belonging to the knowledge base (i.e., *conditional knowledge*);
   (b) It selects, employing the first inference system, the rule whose activation degree is greater among the set of rules. Its consequent contains the exercise to be recommended, which may be a new one or a modification of the last exercise performed;
   (c) It modifies, employing the second inference system, the patient's progress level ($EEPL$). It should be noted that this modification takes into account the last exercise performed.

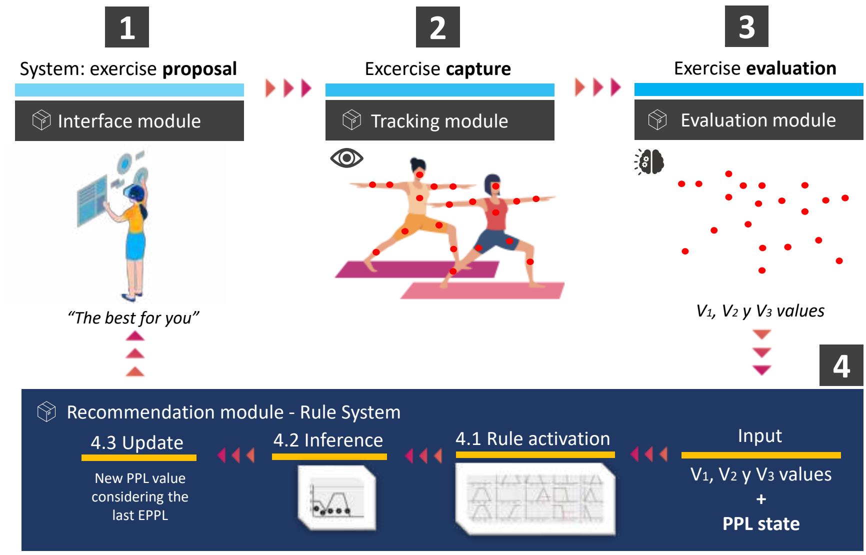

Figure 6. Holistic view of the recommender system.

Consider a stroke patient whose mobility on the left side of the body has been substantially reduced. Fortunately, the patient's progress has relatively improved over the past few sessions. Imagine that the last exercises performed consisted in, from an upright bipedal posture, raising the left arm from the hip to the shoulder, passing the hand in red color through the spheres placed in the 3D world that draw a trajectory. Fundamentally, the hand must pass first through the sphere close to the hip and with the largest size, ending the repetition when the colored joint reaches the sphere close to the shoulder and with the smallest size. This exercise comprises three repetitions and it must be completed under two minutes. Figure 7 graphically shows the left shoulder abduction by means of a virtual system in which the patient simulates the movement, so that their left hand touches the colored spheres.

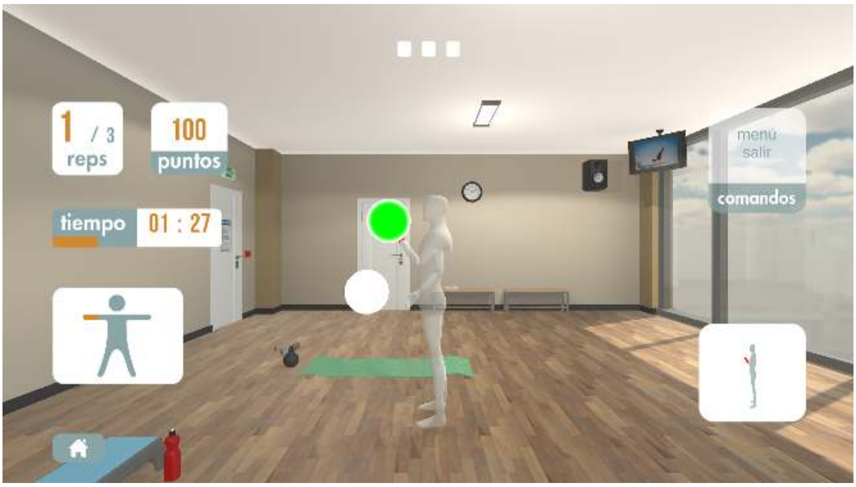

Figure 7. Left elbow flexion representation.

Example 2. *Assume that the value of the variable PPL is assigned to* 4.5 *based on the last session. After performing the last exercise, the values of the variables V_1, V_2 and V_3 were obtained. They are* 0.75*,* 0.80 *and* 0.55*, respectively. The process to obtain the $EPPL$ value is described below.*

The previous description means that the patient took more steps than the therapist. The trajectory between them differed considerable. However, the patient did not spend much more time on completing the exercise than the therapist. It should be reminded that the values of these variables are the result of the mean after the patient performing all repetitions.

It should be highlighted that the previous values of the input scores are computed taking into account the configuration SET_i and the performance of the therapist. However, the underlying details of this process are not provided as it is beyond the scope of this paper.

Considering this situation as an starting point, the inference process that this system carries out is discussed subsequently. At this point, it is important to point out that the system infers two situations for each input, i.e., $V_1 \times V_2 \times V_3 \times PPL \longrightarrow E$ and $V_1 \times V_2 \times V_3 \times PPL \longrightarrow EPPL$.

The first inference process consists of proposing a physical rehabilitation exercise that is best suited according to the patient's situation. Initially, the values associated with each input v_i are applied to each rule r_j to obtain its activation degree. We show below only the rules from R whose activation degree is greater than 0 (i.e., $\{r_i \mid r_i \in R \wedge \text{activation degree}(r_i) > 0\}$):

r_3: IF $accumulated\_deviation$ is $\{M, H\}$
AND $difference\_time$ is $\{L, M\}$
AND PPL is $\{NA, SA\}$
THEN $repeat\_last\_exg(-rp, +t)$ AND $EPPL$ is $\{NC\}$

r_8: IF $difference\_number\_steps$ is $\{M, H\}$
AND $difference\_time$ is $\{H\}$
AND PPL is $\{NA, SA\}$
THEN $propose\_exercise(LC, last\_exg)$ AND $EPPL$ is $\{MD\}$

r_{12}: IF $difference\_number\_steps$ is $\{M, H\}$
AND $accumulated\_deviation$ is $\{H, VH\}$
AND PPL is $\{NA\}$
THEN $propose\_exercise(LC, last\_exg)$ AND $EPPL$ is $\{SD\}$

Their activation degrees are as follows:

$$\text{activation degree}(r_3) = 0.80$$
$$\text{activation degree}(r_8) = 0.20$$
$$\text{activation degree}(r_{12}) = 0.50$$

Therefore, the best compelling exercise to be recommended is obtained from the rule whose activation degree is greater among the set from the previous step. In other words:

$$max\{\text{activation degree}(r_3), \text{activation degree}(r_8), \text{activation degree}(r_{12})\}$$

As a result, the recommended exercise is the one related to the rule r_3 which proposes the repetition of the last performed exercise, but reducing the repetitions and increasing the time. Given that the system infers that the exercise was not well performed because of time, the algorithm responsible for this update proposes two repetitions in 3 min. That is, the system subtracts one repetition and adds one minute. The underlying details of this algorithm are not provided as it is beyond the scope of this paper. This new configuration for the proposed exercise will be used later so as to see the reliability level of the system in terms of decisions making.

On the other hand, the inference of the second relationship was also performed in order to update the patient's progress level. Clearly, the completion of the last rehabilitation exercise must have had some effect on their progress. Let us see how that effect is computed.

As from the activation degrees previously obtained, the output fuzzy set is truncated with the aforementioned values by using the minimum method. That is, the output fuzzy set is reshaped for each rule r_j, whose output is represented by the following new sets defined as membership functions:

$$\mu_3(x) = min\{\Pi_{NC}(x), 0.80\}$$
$$\mu_8(x) = min\{\Pi_{MD}(x), 0.20\}$$
$$\mu_{12}(x) = min\{\Pi_{SD}(x), 0.50\}$$

From the outputs calculated in the previous step, an aggregation process is employed to unify these values in a single fuzzy set. The outputs of each rule (i.e., activation degree) are combined into a single fuzzy set as follows:

$$\mu(x) = max\{\mu_3(x), \mu_8(x), \mu_{12}(x)\}$$

In Figure 8, all three rules, which are activated, are displayed to show how their outputs are aggregated into a single fuzzy set ($\mu(x)$). The membership function of this fuzzy set assigns a weight for every output $EPPL$ value.

Finally, a representative value is obtained after performing the defuzzification step that uses the $EPPL_{co}$ defined in Equation (11). In the aggregated fuzzy set, as shown in Figure 8, the total area is divided into five sub-areas. This value and with the centroid of each sub-area are calculated in Table 1.

Table 1. Result of each sub-area and centroid related to example 2.

Sub-Area Number	Area ($\mu(x_i)$)	Centroid of Area (x_i)	Area * x_i
1	0.375	−0.625	−0.234375
2	0.0875	−0.7084	−0.061985
3	0.2	−0.534	−0.1068
4	0.16	0	0
5	0.16	0.234	0.03744
	$\sum$ Area = 0.9825		$\sum$ Area * x_i = −0.36572

The defuzzified value $EPPL_{co}$ is: $\sum Area * x_i / \sum Area$; $-0.36572/0.9825 \simeq -0.38$. Therefore, the new PPL value is updated through Equation (12), that is, $4.5 - 0.38 = 4.12$. This result indicates that the patient's progress level should be reduced.

The system now proposes performing the last exercise with reduced repetitions but increased time (output of the rule r_3). The repetitions to be taken are 2 and the time is 3 min.

Example 3. *After performing the last proposed exercise, the values of the variables V_1, V_2 and V_3 are* 0.2, 0.45 *and* 0.15*, respectively. The PPL value is* 4.12*, whose result was obtained in the previous example. The process to obtain the new EPPL value is described below, omitting unnecessary steps.*

It is remarkable that the patient correctly performed the exercise. They took almost the same number of steps as the therapist. The trajectory was relatively low. Furthermore, the time spent completing the exercise was also similar to that of the therapist.

As in the previous example, we show below only the rules from R whose activation degrees are greater than 0:

r_2: IF $difference\_number\_steps$ is $\{L\}$
AND $accumulated\_deviation$ is $\{L\}$
AND PPL is $\{NA, SA\}$
THEN $propose\_exercise(HC, last\_exg)$ AND $EPPL$ is $\{MI\}$

r_7: IF $accumulated\_deviation$ is $\{L, M\}$
AND $difference\_time$ is $\{L, M\}$
AND PPL is $\{NA, SA\}$
THEN $propose\_exercise(SC, last\_exg)$ AND $EPPL$ is $\{NC\}$

r_{13}: IF $difference\_number\_steps$ is $\{L\}$
AND $accumulated\_deviation$ is $\{M\}$
AND PPL is $\{NA, SA\}$
THEN $propose\_exercise(SC, last\_exg)$ AND $EPPL$ is $\{MI\}$

Furthermore, their activation degrees are as follows:

$$\begin{aligned}
\text{activation degree}(r_2) &= 0.20 \\
\text{activation degree}(r_7) &= 0.60 \\
\text{activation degree}(r_{13}) &= 0.80
\end{aligned}$$

As a result of applying the output exercise function 8, the rule r_{13} is triggered as its activation degrees is greater among the others. Therefore, the best compelling exercise to be proposed by the system is one whose complexity is the same as the last exercise performed. This exercise consists of a left arm abduction, that is, a movement which implies raising the left arm around the shoulder, moving it laterally away from the body. This exercise comprises two repetitions and it must be completed under three minutes. Figure 9 graphically shows the left shoulder abduction by means of a virtual system in which the patient simulates the movement, so that their left hand touches the colored spheres.

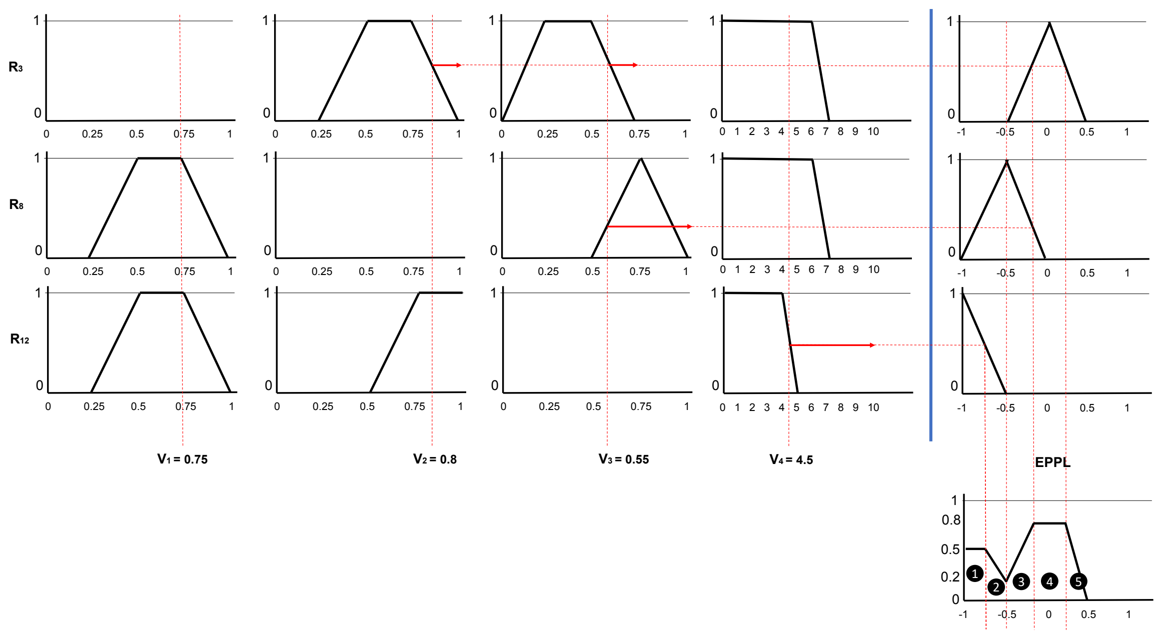

Figure 8. Visual representation and results when applying the aggregation method (max) related to example 2.

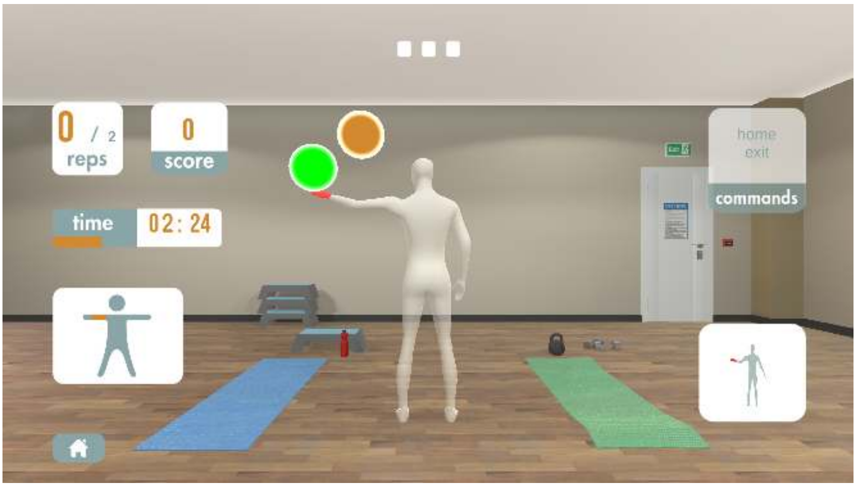

Figure 9. Left shoulder abduction representation.

Then, the new membership functions are computed as a consequence of truncating the output fuzzy sets with the values previously obtained. In other words:

$$\mu_2(x) = min\{\Pi_{MI}(x), 0.20\}$$
$$\mu_7(x) = min\{\Pi_{NC}(x), 0.60\}$$
$$\mu_{13}(x) = min\{\Pi_{SD}(x), 0.80\}$$

After that, a single fuzzy set is obtained by combining the previous outputs using the function 10. The result is as follows:

$$\mu(x) = max\{\mu_2(x), \mu_7(x), \mu_{13}(x)\}$$

Finally, the output, i.e., $EPPL_{co}$, is computed using the centroid function defined in (11). Similar to the previous example, the total area is divided into six sub-areas. Table 2 shows the area and centroid of each sub-area. Furthermore, Figure 10 depicts the new aggregated fuzzy set.

Table 2. Result of each sub-area and centroid related to example 3.

Sub-Area Number	Area ($\mu(x_i)$)	Centroid of Area (x_i)	Area * x_i
1	0.09	−0.3	−0.234375
2	0.24	0	0
3	0.0275	0.2167	0.005995925
4	0.0975	0.35	0.034125
5	0.16	0.5	0.08
6	0.16	0.74	0.1184
	$\sum$ Area = 0.775		$\sum$ Area * x_i = 0.21148425

The defuzzified value $EPPL_{co}$ is: $\sum Area * x_i / \sum Area$; $0.21148425/0.775 \simeq 0.27$. Therefore, the new PPL value is updated through Equation (12), that is, $4.12 + 0.27 = 4.39$. This result indicates that the patient's progress level has relatively improved.

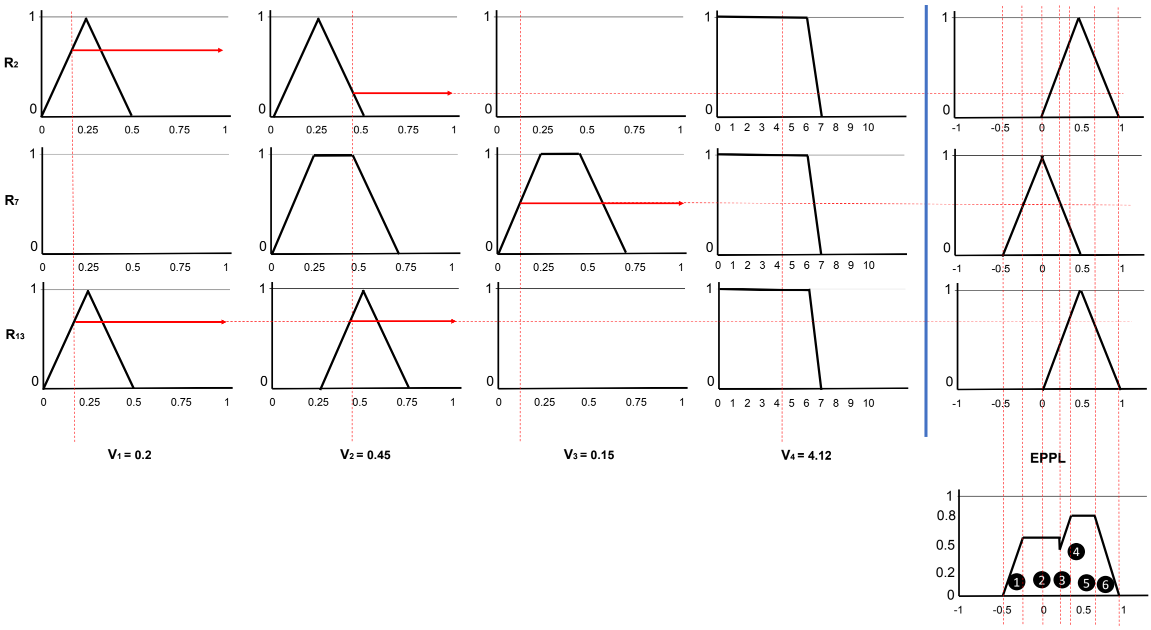

Figure 10. Visual representation and results when applying the aggregation method (max) related to example 3.

5. Discussion

A preliminary evaluation was carried out and the results obtained appear to be quite interesting. The discussed case study showed that the system proposed in this research work is capable of inferring the next rehabilitation exercise and appropriately updating the patient's progress level. Both tasks are based on the performance of the last exercise made by the patient.

The main goal of the experiment conducted was oriented towards demonstrating the utility of the proposed system. This is the first step before using the system for a clinical trial with patients, who have a suffered moderate or severe stroke, according to the levels measured by the National Institutes of Health Stroke Scale (NIHSS) scoring system. These clinical trials will test the efficacy of the system in the recovery of stroke patients.

Interestingly, the results of the evaluation are in accordance with the values of the input variables v_i. The patient's progress level was relatively low ($PPL = 4.5$). The time invested was not too bad with respect to the time spent by the therapist ($V_1 = 0.55$), but the number of steps between the patient and the therapist was significantly different ($V_2 = 0.75$). In addition, the trajectory greatly differed from the one charted by therapist ($V_3 = 0.8$). In other words, the exercise was not accurately performed by the patient. This means that the patient preferred to sacrifice accuracy over time. In this regard, the system automatically concluded that the patient needs to keep working out to positively upgrade their progress. Additionally, the system suggested that the patient repeats the last performed exergame, considering that the number of repetitions should be reduced but the time spent in performing the exercise should be increased. Remarkably, the result of this system's suggestion is coherent taking into account the progress level of the patient ($PPL = 4.12$) and also the performance of the last exercise proposed ($V_1 = 0.2$, $V_2 = 0.45$, $V_3 = 015$). As a result, the patient's progress level was moderately upgraded, highlighting that this increase is reasonable based on two previous performances. In view of these facts, the reliability of the system is noteworthy. The system adequately performs recommendations and updates the progress of the patient accordingly.

However, one limitation of our research work is the difficulty to test the proposed system with a representative sample of stroke patients due to the current COVID-19 pandemic. To date, we focused our work on evaluating the system from an internal point of view, that is, according to case studies such as the one described in Section 4. Therefore, the results presented in this paper need to be interpreted with caution.

Despite the limitations of this evaluation, our findings suggest that the use of Fuzzy Logic for physical rehabilitation seems to make sense as it enables making decisions in an automatic and understandable way. What this approach offers is to dynamically monitor and guide the home rehabilitation process, whose supervision is difficult to be made by a therapist because of their lack of time and the need for a face-to-face supervision. However, the developed system does not aim at replacing the therapist. On the contrary, it is intended to relieve the therapists' workload and help them interpret, through an inference process similar to the human one, how the patient progresses as the rehabilitation plan is being completed.

This research aims to be complemented, in a second phase, with a clinical trial to evaluate the impact of using our system on the recovery process of real stroke patients. In a third phase, another clinical trial will be conducted to analyze the efficacy of the system for its intended use, which is to improve physical rehabilitation at home.

6. Conclusions

In order for a remote rehabilitation system to be used continuously and effectively by stroke patients, three essential characteristics must be provided: (i) usability, to remove the barrier that the use of technology may represent, and adequately guide the user in the process of autonomous rehabilitation; (ii) motivation, to encourage the continued use of the system and reduce the possibility of abandonment by the patient; and (iii) autonomy, to be able to automatically recognize and evaluate the rehabilitation exercises performed by the patient without the need for continuous supervision and presence of the therapist. A significant part of the existing research work focuses on one or more of these features, with the therapist being responsible for adjusting the rehabilitation routine according to the level of progress of their patients. Ideally, a remote rehabilitation system that offers an integral solution should be able to offer suggestions or recommendations that enable the ability to customize the rehabilitation routine automatically or semi-automatically.

In this paper, we proposed a new recommender system to determine the next action that should be performed by the patient in their rehabilitation plan. The system is based on a set of fuzzy rules and a double inference process on them. The use of fuzzy logic is justified because it provides patients and physicians with guidance that they can understand. In this sense, the use of linguistic variables makes it easier for them to interpret this information. On the other hand, the recommender system provides the patients with detailed feedback on the work they have done, with an explanation about the areas in which they have performed well, and others which may still need improvement. In addition, on a broader level, patients will be informed whether they have truly performed the rehabilitation routine well.

The approach presented herein shows the potential of automating the work of monitoring and guiding the steps in a patient's rehabilitation. The idea of this method is not to replace the role of the physician, but to support them with tools that enable them to conduct an efficient rehabilitation process, dedicating their time to higher level tasks. The proposed system is intended to speed up the assignment of exercises to patients and to obtain data that can be provided to physicians. All these data allow them to evaluate and determine the patient's state of evolution in their injury.

The discussed case study shows the potential of our approach in terms of adapting the rehabilitation process to the patient's progress level. Particularly, the adoption of fuzzy logic to guide the processes of knowledge representation and inference of recommendations greatly facilitates the automatic customization of rehabilitation routines, since the way such processes are described is inherently close to the way therapists adjust rehabilitation routines. Thus, this research work contributes to increase the level of autonomy for remote rehabilitation systems thanks to the capacity of dynamically adjusting the rehabilitation process.

As future lines of research, we can stress the need to work on a main objective: evaluating the degree of improvement on stroke patients using the proposed system in a real treatment. For doing so, once the system has been validated by the research community, two clinical trials will be conducted. The first will study the impact of using the recommender system on real stroke patients over a significant period of time. The second will study the efficacy of the system on patient recovery. The data collected in these clinical trials will be used for improving the system and exploring other solutions that may be of interest to be included in it.

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2.1.3 Personalized Exergame Language: A Novel Approach to the Automatic Generation of Personalized Exergames for Stroke Patients

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Personalized Exergames Language: A Novel Approach to the Automatic Generation of Personalized Exergames for Stroke Patients

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Abstract: Physical rehabilitation of stroke patients is based on the daily execution of exercises with face-to-face supervision by therapists. This model cannot be sustained in the long term, due to the involved economic costs, the growing number of patients, and the aging population. Remote rehabilitation tools have emerged to address this unmet clinical need, but they face the double challenge of motivating patients and ensuring an effective remote rehabilitation. In this context, exergames allow patients to play while performing repetitive therapeutic tasks in a safe and ecological environment. This work proposes the design of Personalized Exergames Language (PEL), a language whose sentences can be processed via software in order to automatically generate exergames. The definition of exergames through PEL, guided by an effective methodology of the design and generation of personalized exergames, will include both game mechanics and the necessary metrics to monitor, guide, and adapt the rehabilitation of each patient. The integration of authoring tools are considered to visually guide the therapist when designing exergames. A study has been carried out with stroke patients and therapists from a hospital and two community centers, in order to evaluate several exergames, automatically generated using PEL, in terms of usability, understanding, and suitability.

Keywords: exergames; rehabilitation; tertiary digital prevention; stroke

1. Introduction

Therapeutic exergames enable patients to exercise by playing, thereby relieving the burden of repetitive tasks through the use of motivating and engaging game dynamics [1]. In this context, an exergame can be understood as a game that tries to mimic, within a virtual or augmented world, a physical exercise that is associated to a therapeutic treatment.

When it comes to using technological tools, based on exergames, either for remote or face-to-face rehabilitation, the therapists assign routines, which are composed of rehabilitation exercises, to patients. These exergames, previously created, do not usually allow the therapists to customize or adapt them directly. This can be due to a number of factors, including the dependency that is introduced by the used rehabilitation systems, the complexity of the process, or the issues raised should therapists have to deal with the technical aspects of exergame development.

In this context, this work addresses the automatic generation of personalized exergames for the physical rehabilitation of patients that are affected by stroke [2]. Although the proposal discussed in this work can be generalized to other neurological diseases, the focus is on stroke, which remains an unmet clinical need nowadays [3]. The incidence of this disease is increasing worldwide, especially in low- and middle-income countries [4]. Additionally, the ideas of personalized and universal access to telerehabilitation [5] are part of the core of the proposal, which aims at contributing to personalized healthcare technologies and improving the flexibility that is provided in terms of physical location, used hardware devices, interaction mechanisms, and multimedia content [6].

A formal language, named Personalized Exergames Language (PEL), has been designed and developed along with a software system thta is able to process PEL sentences. PEL allows for the specification of exergames, while the software system is capable of analyzing PEL sentences and generating exergames automatically. The use of PEL is based on a methodology that is also devised in this work. Such methodology is aligned to the idea of adapting the physical rehabilitation process for each patient. This methodology, which guides the workflow when using PEL to define exergames, consists in the following steps: (i) definition of an exercise from the therapist's point of view, (ii) definition of an interaction scheme on behalf of patients, (iii) definition of feedback mechanisms for guiding and keeping patients motivated when they make rehabilitation, and (iv) the definition of the metrics that the therapists use to monitor the patients' progress. All these definitions can be specified by means of PEL. Thus, the whole proposal aims at laying the foundations to build software systems that are able to automatically generate exergames and dynamically customize the patient's rehabilitation routine as they improve their performance.

In order to implement PEL, the GL Transmission Format (glTF) specification [7] has been adopted. glFT is an open standard, which is based on the JSON format, conceived to store and transmit 3D model information. glTF was chosen to its maturity level as an interoperable and extensible format when handling and integrating 3D contents. Its capacity to describe scenes with the JSON format and easily extend it were strong reasons for this decision. glTF syntax not only allows to define exergames, but it also enables interactions between the virtual nodes of an exergame that has been customized for rehabilitation. Additionally, the glTF extensions let properties, semantics, and even additional formats be added. On the other hand, the use of JSON messages allows for minimizing the size of 3D assets and the impact on the efficient transmission and loading of 3D models and scenes into applications.

The use of PEL as the core component to define exergames is proposed in order to provide a resource that therapists can use to create exergames. It must be noted that, even though the current version of PEL is simple enough to understand how to specify exergames, its direct use on behalf of therapists is not currently recommended without the support of developers. Nevertheless, PEL has been designed to be integrated with high-level authoring tools that facilitate the generation of personalized exergames. These tools will integrate a software module to generate the PEL sentences that represent the graphic definition of the exergame made by the therapist. This work also addresses the initial design of a high-level graphical tool to provide this support for therapists.

The research work carried out in this article is focused on the benefits that the definition of a language to personalize exergames, which can be automatically generated, may have in the physical rehabilitation process of stroke patients. Particularly, the generated exergames must engage and motivate them. At the same time, these exergames must be useful, easy to use, and increase the intention of use of the developed rehabilitation system. From the therapist's point of view, a benefit should be also achieved thanks to the customization and monitoring capabilities that are offered by PEL. To validate the proposal, and with the aim of evaluating the current capabilities of PEL as a basis for the generation of personalized exergames, a study has been conducted with 17 patients and six therapists. Thus, the main contributions of this article are as follows:

- Firstly, a methodology is proposed for the design and generation of customized exergames. This methodology addresses the therapeutic goals of the rehabilitation process, the enabled interaction schemes for the patients to interact with the exergames, the feedback and motivation mechanisms to engage patients by means of gamification techniques, and the definition of metrics to keep track of the patients' progress.

- Secondly, a language, named PEL, is designed and developed for the creation of personalized exergames, whose sentences can be processed to automatically generate exergames. The lexical, syntactical, and semantic aspects of PEL are presented.
- Thirdly, the foundations for building computing systems that are able to process PEL sentences are established. This base can be used not only to automate the generation of exergames, but also to facilitate the automatic adjustments of rehabilitation exercises that are defined by means of PEL. A design proposal of a graphical tool to support the definition of exergames by therapists is also addressed.

The rest of the paper is structured, as follows. Section 2 provides a description of relevant related work within the scope of the proposal. Subsequently, Section 3 introduces the proposed methodology and describes in depth PEL, the devised language for personalizing exergames. Section 4 deals with a case study in which PEL is used to define a number exergames for stroke patients. These exergames are evaluated by stroke patients and therapists from one hospital and two community centers. Section 5 validates the proposal and discusses the major conclusions that were obtained after evaluating the use of PEL as a core component to define exergames and the rehabilitation system that runs the generated exergames. Finally, Section 6 presents the final conclusions and outlines future research lines.

2. Background and Significance

At present, stroke remains a global challenge that must be tackled from a prevention perspective [8]. For patients, physical rehabilitation is essential to regain mobility and improve their quality of life. Within this framework, tertiary digital prevention, by means of technology, attempts to mitigate the effects of neurological diseases, such as stroke. By way of example, in Europe alone, there are several million stroke survivors who need rehabilitation and, unfortunately, this number is only expected to rise in the coming years.

Traditionally in health care, rehabilitation consists pf daily sessions of exercises, in which therapists supervise patients in real time. Accordingly, in financial terms and in accordance with the European Brain Council (https://www.braincouncil.eu/wp-content/uploads/2018/04/Brain-Mission-Final-v2.pdf), the estimated cost to European healthcare systems has risen to 800 billion euros per year. In countries, like Spain, the average cost of treating a patient with ictus by specialist units is estimated at 27,711 euros per year [9]. This problem can be extrapolated to a worldwide scale and it is especially relevant in low- and middle-income countries [4]. Thus, this situation has led to medical needs that have yet to be covered [3].

That is why telemedicine tools, especially those that are designed for remote rehabilitation, have attempted to meet this challenge. In this context, the exercises performed by patients can be analyzed by a machine [10], using physical sensors for tracking joints [11,12] or computer vision techniques [13]. The latter have been traditionally based on using Kinect [14,15], a low-cost hardware solution whose effectiveness has been proved in the field of physical rehabilitation [16–18]. Using entertainment and fitness-orientated commercial games has also been tried out in order to provide home rehabilitation [19,20], although some studies indicate that there are a few adversary effects of this as the games may lack customization in terms of physical rehabilitation [21]. Some approaches are even focused on specific brain disorders, such as Parkinson's disease [22].

The aim of a study into the psychological effects of playing exergames is to measure how committed players feel [23]. Because the patient motivation is essential for rehabilitation at home, some authors have put forward gamification and serious games as a way of motivating them [24]. In this respect, the design phase is crucial, not just because they can be supervised appropriately that way, but also to guarantee their efficiency and safety [25].

Regarding the specification of methodologies for creating and designing therapeutic exergames, in [26] a four-stage approach is discussed: (i) choosing an appropriate set of exercises for therapy, (ii) implementing the primary goals in virtual exercises, (iii) transforming virtual exercises into exergames, and (iv) including secondary objectives that are characterized by the game mechanics.

This methodology is based on a game engine that has been specifically designed for supporting and integrating computer intelligence methods when monitoring patients [27].

Additionally, the state of the art covers more general-purpose solutions aimed at making it easier to generate or automatize customized exergames, such as the framework that is shown in [28]. In this research, the authors envisaged designing tools to support experts in the field, such as doctors or therapists, so that they can adapt and customize games-based training programs for elderly and disabled people. One of the strong points of the research discussed in [29], in which a platform with a range of functions for motor and social cognitive rehabilitation for hospitalized children is discussed, is that these contents can be edited by means of high-level graphic tools. Likewise, controlling emotions appropriately and feedback provided to patients is also dealt with in research that focuses on designing rehabilitation frameworks [30]. Plus, the process for creating contents within the exergames themselves (such as, for example, the dynamic appearance of game elements according to how patients are performing [31]) has also been addressed in the literature, mainly for the dynamic adaptation of the level of difficulty in the game to patient performance [32].

Ontologies have also been devised for describing exergames. The work discussed in [33] is a recent example, in which OWL Web Ontology Language is used for such a description and for defining the key components of exergames. Within this context, the authors also developed a framework in order to apply the created ontology to online exergames. On the other hand, grammars may also play an essential role to simplify the process of creating rehabilitation exercises. Thus, it is possible to define specific languages for specifying body postures and movements [34], which can be augmented thanks to editors that facilitate therapists' work. In this contribution, an exercise-specification grammar is employed to guide the virtual avatar and provide quality feedback by comparing the user's gestures against those performed by the coaching avatar. Related to these works, there are more general approaches, such as those discussed in [35,36], where the models may be used for guiding game designers to specify game design elements.

The work proposed in this article aims at providing the therapists with tools that can be used to personalize how patients employ rehabilitation systems and how therapists run the rehabilitation process. However, instead of designing and developing ad-hoc tools, we have devised a language that can work as the core component in multiple rehabilitation tools. This language provides sentences that can be used to design personalized exergames, and these sentences can be processed in order to automatically generate exergames for specific platforms and game engines. This is the major contribution of this work, which opens the door to deepening the idea of precision physical rehabilitation. On this basis, high-level authoring tools can be built that allow therapists to visually create exergames. Assuming that these tools export such a creation to a set of PEL sentences, then it is possible to cover the whole cycle of design and automatic generation of exergames. On the other hand, the definition of a language, and the capacity to process its sentences by a computer program, would facilitate the automatic adaptation of the rehabilitation routines that are defined by therapists.

3. Personalized Exergame Language

Before presenting the proposed language, named PEL, the devised methodology that guides the design and generation of customized exergames is introduced. An exergame, as previously defined in Section 1, can be understood as a game that mimics a physical exercise that is part of a physical rehabilitation routine. The exergame includes game dynamics to motivate and engage patients when making rehabilitation. PEL will be presented after discussing the adopted methodology, paying special attention to the lexical, syntactical, and semantic aspects of the language.

3.1. Proposed Methodology for Designing and Generating Exergames

Figure 1 graphically shows the steps that are required to effectively apply the proposed methodology for the design and generation of customized exergames. The major reference for our proposal is discussed in [26]; however, the one proposed in this work is particularly tailored when considering PEL, the designed language for defining exergames.

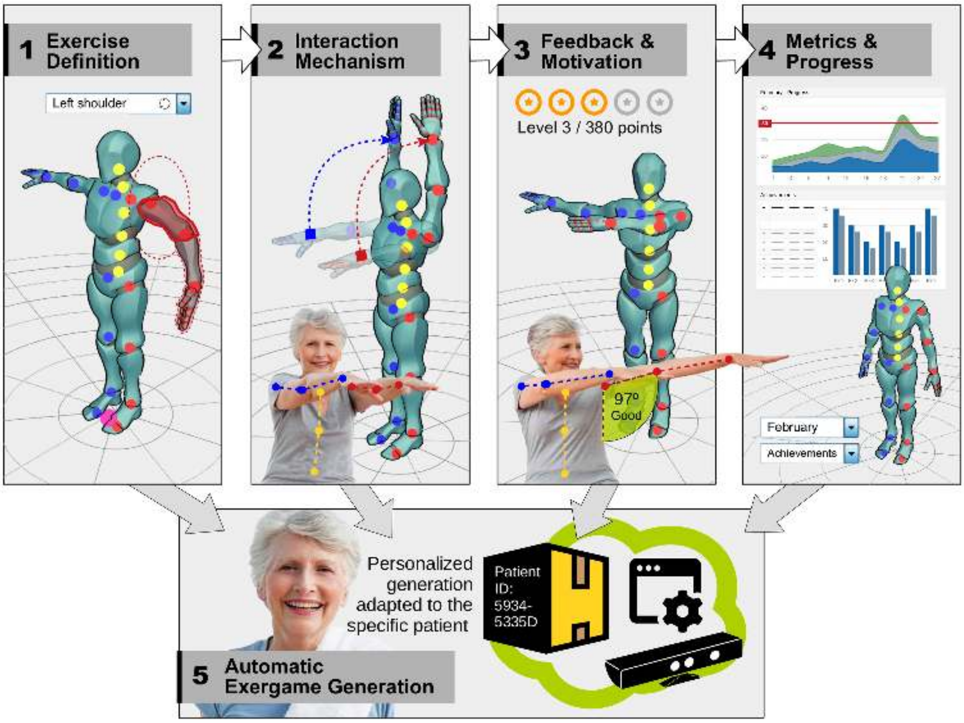

Figure 1. Visual representation of the proposed methodology for the definition and generation of customized exergames.

1. **Definition of exercises**. The therapist establishes the therapeutic objectives of the rehabilitation process, considering the parts of the patient's body involved in this process and the skill to be trained (muscle strength, balance or mobility, among others). At this point, the therapist establishes, at a high level, the temporal sequence of actions or steps that make up the rehabilitation exercise. Each element of the temporal sequence of actions can be evaluated independently and globally (when considering the exercise as a whole). This allows for the patient to obtain feedback on the exercise progress from both points of view. At the same time, and for each exercise, the therapist outlines the metrics that will be used to measure the patient's performance when executing an exercise. Finally, the definition of the exercise is completed with the specification of constraints. This element allows the therapist to represent very common situations in physical rehabilitation processes, where patients try to compensate for the limitations of the body part to be rehabilitated with other fully functional parts of their body.
2. **Definition of the interaction scheme** between the patient and the rehabilitation system regarding the exergame definition. The therapist establishes aspects, such as the position of the virtual avatar, the position of the virtual camera, the set of virtual nodes that make up the trajectory, or the specific actions of the rehabilitation movement. All of these elements are associated with the type of rehabilitation exercise and the affected parts of the body. Currently, a finite set of positions of the virtual avatar representing the patient (standing, seated, and lying-down) is assumed. On the other hand, the virtual path of the movement to be executed by the patient in the exergame consists of a set of ordered lists of virtual nodes or points in the three-dimensional (3D) space. The interaction in each exergame is defined by associating a node or a path with one

or several joints. It is also possible to specify whether the interaction between a joint and a node is simple (simple virtual collision) or the patient must hold the position for a certain amount of time. In this work, the use of Azure Kinect DK (https://www.microsoft.com/en-us/p/azure-kinect-dk as a body tracking device is used in the experimental tests in Section 4.

3. **Definition of feedback and motivation mechanisms**. The definition of every exergame has associated gamification techniques that maintain the level of commitment of the patient when making the exergame. Thus, this step aims at relieving the burden of traditional rehabilitation, in which the same exercise is made over and over again. On the contrary, fun and entertainment become more important. This is related to defining the game objectives. These objectives may be directly aligned with the patient's specific movements or may be reached as a result of the evolution of the game state in the exergame. Feedback, from a general point of view, must be provided to both guide the patient when doing the exercise and offer a feeling of immersion in the game. The therapist will be able to assign scores that are based on the patient's performance. The current version of this work only considers visual feedback, while using a color code, so that the patient can easily know, in real time, if they are performing the exercise correctly or not.
4. **Definition of metrics or key performance indicators** (KPIs) to measure the progress of the patient. The therapist defines what aspects he/she needs to measure when the patient does the exercise. The ultimate pursued goal consists in monitoring the progress of the patient. One of the reference metric considered in the current version is the similarity between the execution of the exercise performed by the patient and the gold standard (specified by the therapist). If the similarity is high, then the value of this metric, which is called performance, will be positive. This metric can be complemented with more specific metrics or KPIs, which depend on the exercise to be performed. In contexts where mobility is the skill to be trained, a different metric can be defined, which serves to study the achieved degree of amplitude in a joint. This value can be easily calculated from the information that was obtained by the device that tracks the bones of the patient's skeleton. Another set of metrics that can be integrated into the rehabilitation system and whose information can be obtained relatively easily are temporal metrics.

These definitions can be specified by means of a language. The existence of this language will allow the automatic exergame customization by means of computing systems. These systems could additionally make slight variations and gene rate adapted exergames according to the patient's behavior and evolution during the rehabilitation process. However, this would require the inclusion of a processor that would generate the exergame, in the rehabilitation system, from its specification using the language.

3.2. Design and Development of PEL

This section discusses in depth how the language has been designed, so that it can be understood by expert personnel and, most importantly, automatically handled by computing systems. It should be noted that the syntactic structure of PEL is strongly linked to JSON, since this is the format used in the GL Transmission Format (glTF) specification [7]. This specification has been adopted in order to implement PEL.

In the following subsections a detailed specification of the components that form PEL is given.

3.2.1. Basic Exergame Structure

From a general point of view, an exergame defined with PEL integrates three major components:

- *Scene*. This component comprises the different views or parts of the exergame, understood from the point of view of the patient who performs it. Three basic views are considered: (i) tutorial view, which will usually reproduce an animation of the virtual avatar recreating the exergame that the patient must execute, (ii) participation view, which is associated to the real-time execution of the exergame, where the patient must reach a specific objective (for example, performing a certain number of repetitions), and (iii) results view, which will offer visual feedback to the patient, depending on what the therapist has specified when designing the exergame (for example, the obtained score by the patient).

- *Actors*. This component groups those elements of the exergame that maintain some type of behavior, such as those associated with the 3D animations or three-dimensional (3D) transforms. Every exergame has at least one actor: the virtual avatar that recreates the movements of the patient.
- *Gameplay*. This component defines the set of actions that the patient must perform to make a repetition of the exergame. The correct execution of the game mechanics associated to the exergame will trigger a sequence of actions, such as updating the score obtained by the patient.

The current version of PEL is particularly focused on the participation view, where the actual exergame definition is involved.

At content structure level, an exergame that is defined in PEL makes use of several content exchange files that are referenced to each other. However, all of them are governed by a single specification file containing the exergame meta-information. PEL relies on glTF, so it is possible to encapsulate, in self-contained files, all of the graphic resources of the exergame and, at the same time, to use the glTF extensions as a basis for the definition of PEL itself. As a practical example, all of the resources and statements specified in PEL are encoded (i) internally using base-64 data URIs (in a single .gltf file) or (ii) externally through references (using a .gltf file and another .bin file).

3.2.2. PEL Specification

The design of a language involves the definition of the three following aspects:

- The lexicon, which establishes the vocabulary of the language.
- The syntactic rules, which describe the form of the language sentences.
- The semantic rules, which define the meaning of the syntactically correct sentences of the language.

Because glTF uses the JSON format and PEL will be integrated into it by means of extensions, PEL lexical and syntactic aspects are conditioned by the use of data objects structured in attribute-value pairs and arrays. In this sense, the use of special symbols to delimit values and the use of list and dictionary structures are noteworthy. The reader is referred to review the JSON formal grammar [37].

The lexical component of PEL establishes the low-level language constructions (tokens), such as keywords, strings, punctuators, numbers, and special characters. With regard to keywords, they will be well-known terms that have been taken from the therapeutic area, the gamification area, the game mechanics area, and from the 3D graphics area. To describe the rules that define each one of the tokens, the Extended Bakus–Naur form (EBNF), a notation for specifying languages, is used. The definition of the lexicon will be shown together with the specification of the language syntax.

Next, PEL syntax will be presented, while using the EBNF notation. Moreover, the meaning and semantic constraints of each one of the language constructions, which is, their semantic aspects, are simultaneously explained.

General structure of an input

At a global level, the participation view of an exergame defined in PEL comprises the following general components: (1) description, (2) setup, (3) virtual_nodes, (4) trajectories, (5) gameplay, (6) constraints, and metrics.

Therefore, the structure of any PEL string is as follows:

```
PEL  ::=  DESCRIPTION ‘,’ SETUP ‘,’ VIRTUAL_NODES ‘,’
          TRAJECTORIES ‘,’ GAMEPLAY ‘,’ CONSTRAINTS ‘,’
          METRICS
```

Each of these blocks will be specified below, highlighting lexical (especially keywords), syntax (phrase structure), and semantic (meaning) aspects. This description will be supported by the listings shown in this paper, which can be potentially used for the specification of personalized exergames.

Description component

In the description block, a descriptive information of the exergame will be included. The EBNF grammar for description block is the following:

DESCRIPTION	::=	'"' **description** '"' ':' BLOCK_DESCRIPTION
BLOCK_DESCRIPTION	::=	'{' '"' **text** '"' ':' **string** '}'

The terms description and text are PEL keywords. With the attribute text, a textual description of the exergame is stored. string is a token defined, as follows:

string	::=	'"' { alphanumeric | whitespace } '"'
alphanumeric	::=	alphabetic | numeric
alphabetic	::=	lower_case | upper_case
lower_case	::=	a | b | c | d | e | f | g | h | i | j | k | l | m | n | o | p | q | r | s | t | u | v | w | x | y | z
upper_case	::=	A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | U | V | W | X | Y | Z
numeric	::=	0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9
whitespace	::=	' '

Setup component

In the setup block, the information about the exergame configuration will be included, such as the used avatar, the camera information, the clock restrictions, the required repetitions, and the score to address the integration of this simple gamification technique to reward patients.

The EBNF grammar for the setup block is specified above, where the terms setup, avatar, **id_avatar**, posture, positions, rotation, camera, **id_camera**, repetitions, **max_number_repetitions**, score, clock, activated, and **countdown_time**, are keywords; and, the tokens **type_posture**, real, integer, and boolean are defined, as follows:

type_posture	::=	standing | seated | lying-down
real	::=	numeric { numeric } '.' numeric { numeric }
integer	::=	numeric { numeric }
boolean	::=	true | false

With respect to the component setup, avatar allows for specifying what virtual avatar will be used in the exergame, through the attribute *id_avatar*. Moreover, the avatar placed in the 3D space by means of the attributes posture (standing, seated or lying-down), positions, and rotation.

The element camera allows to define, in a similar way, what camera will be used (*id_camera*), along with its position and orientation. On the other hand, the element clock contains the attribute activated, whose boolean value makes it possible to activate the timer in the exergame. If that is the case, the attribute *countdown_time* represents the maximum time in seconds that the patient will have to perform the exergame. Secondly, the object repetitions allows to establish whether the patient must perform a certain number of repetitions, specified in *max_number_repetitions*, or whether, on the contrary, the exergame simply contemplates the possibility of the patient performing as many repetitions as possible in the time stored in *countdown_time*. Finally, the object score allows tfor controlling the activation of the exergame score through the attribute activated.

Listing 1 in Section 4 shows an example of PEL definitions regarding the description and setup components.

SETUP	::=	"' **setup** "' ':' BLOCK_SETUP
BLOCK_SETUP	::=	'{' LIST_ATTRIBUTES '}'
LIST_ATTRIBUTES	::=	AVATAR ',' CAMERA ',' CLOCK ',' REPETITIONS ',' SCORE
AVATAR	::=	"' **avatar** "' ':' BLOCK_AVATAR
BLOCK_AVATAR	::=	'{' DEFINITION_AVATAR '}'
DEFINITION_AVATAR	::=	ID_AVATAR ',' POSTURE ',' POSITION ',' ROTATION
ID_AVATAR	::=	"' **id_avatar** "' ':' **string**
POSTURE	::=	"' **posture**"' ':' **type_posture**
POSITION	::=	"' **position** "' ':' VECTOR3
ROTATION	::=	"' **rotation** "' ':' VECTOR4
VECTOR3	::=	'[' **real** ',' **real** ',' **real** ']'
VECTOR4	::=	'[' **real** ',' **real** ',' **real** ',' **real** ']'
CAMERA	::=	"' **camera** "' ':' BLOCK_CAMERA
BLOCK_CAMERA	::=	'{' DEFINITION_CAMERA '}'
DEFINITION_CAMERA	::=	ID_CAMERA ',' POSITION ',' ROTATION
ID_CAMERA	::=	"' **id_camera** "' ':' **string**
CLOCK	::=	"' **clock** "' ':' BLOCK_CLOCK
BLOCK_CLOCk	::=	'{' DEFINITION_CLOCK '}'
DEFINITION_CLOCK	::=	ACTIVATED ',' COUNTDOWNTIME
ACTIVATED	::=	"' **activated** "' ':' **boolean**
COUNTDOWNTIME	::=	"' **countdown_time** "' ':' **integer**
REPETITIONS	::=	"' **repetitions** "' ':' BLOCK_REPETITIONS
BLOCK_REPETITIONS	::=	'{' DEFINITION_REPT '}'
DEFINITION_REPT	::=	ACTIVATED ',' MAXNUM_REPT
MAXNUM_REPT	::=	"' **max_number_repetitions** "' ':' **integer**
SCORE	::=	"' **score** "' ':' BLOCK_SCORE
BLOCK_SCORE	::=	'{' DEFINITION_SCORE '}'
DEFINITION_SCORE	::=	ACTIVATED

Virtual_nodes component

In the *virtual_nodes* block, the collision spheres in the 3D space are defined. They will be used as trigger events in certain types of exergames, specifically in those where the patient interacts with with elements of the scene displayed in fixed positions. An example would be the classic exergame, where targets appear, in predetermined positions, which move towards the player, so he/she must take his/her hand to one of those positions.

The EBNF grammar for the *virtual_nodes* block is the following:

VIRTUAL_NODES	::=	"' **virtual_nodes** "' ':' BLOCK_VNODES
BLOCK_VNODES	::=	'[' LIST_NODES '{' NODE '}' ']'
LIST_NODES	::=	{ '{' NODE '}' ',' }
NODE	::=	ID_ACTOR ',' CLASS_ACTOR ',' POSITION ',' RADIUS
ID_ACTOR	::=	"' **id_actor** "' ':' **string**
CLASS_ACTOR	::=	"' **class_actor** "' ':' **type_actor**
RADIUS	::=	"' **radius** "' ':' **real**

The terms **virtual_nodes**, **id_actor**, **class_actor**, and radius are keywords. **id_actor** uniquely identifies the associated virtual node, while **type_actor** is a token defined, as follows:

type_actor	::=	up | upper-left | upper-right | bottom | bottom-left | bottom-right

The component *virtual_nodes* hosts a list of 3D nodes, and each one of them contains, in turn, a unique identifier (attribute *id_actor*), the values of a coordinate in the 3D space (attribute position), and the radius of the collision sphere associated to the node (attribute radius).

Trajectories component

The component trajectories is used to store the trajectories associated with the movements that a patient will make when performing an exergame. In this case, and unlike the component *virtual_nodes*, the points or nodes in the 3D space do not need a unique identifier, since the identity of the element is represented by each path (*id_trajectory*), and not by individual points in 3D space. As an example, an element defined by the component trajectories would be the route or path associated to a shoulder abduction exercise. Thus, the component trajectories stores a list of individual paths, each one of them being identified by the value of the attribute *id_trajectory* and defined by the attribute *3d_path*. This attribute will contain an ordered list or sequence of points in 3D space that form the path. Single nodes can be used as part of a path.

The EBNF grammar for trajectories block is the following:

TRAJECTORIES	::=	‘”’ **trajectories** ‘”’ ‘:’ BLOCK_TRAJECTORIES
BLOCK_TRAJECTORIES	::=	‘[’ LIST_TRAJECTORIES ‘{’ TRAJECTORY ‘}’ ‘]’
LIST_TRAJECTORIES	::=	{ ‘{’ TRAJECTORY ‘}’ ‘,’ }
TRAJECTORY	::=	ID_TRAJECTORY ‘,’ PATH ‘,’ RADIUS
ID_TRAJECTORY	::=	‘”’ **id_trajectory** ‘”’ ‘:’ **string**
PATH	::=	‘”’ **3d_path** ‘”’ ‘:’ ‘[’ VECTOR3 { ‘,’ VECTOR3 } ‘]’

The terms trajectories, **3d_path**, and **id_trajectory** are PEL keywords.

The Listing 1 in Section 4 shows an example of the two components associated to the elements of the 3D space used to represent virtual nodes or paths: *virtual_nodes* and trajectories.

Gameplay component

The gameplay component contains the information related to the game dynamics, which is based on the interaction between joints and virtual nodes in the 3D space. A game dynamics establishes the relationships between three fundamental aspects in an exergame:

1. Trajectory or virtual path associated to the movement of the exergame.
2. Interaction mechanism used by the patient to perform the exergame, associated, in turn, to (i) the parts of the body that the patient must exercise and (ii) the interaction mode.
3. Feedback provided to the patient as he/she performs or completes a repetition of the exergame.

The EBNF grammar for *gameplay* block is the following:

GAMEPLAY	::=	‘”’ **gameplay** ‘”’ ‘:’ BLOCK_GAMEPLAY
BLOCK_GAMEPLAY	::=	‘[’ LIST_GAMES_DYNAMIC ‘{’ GAME_DYNAMIC ‘}’ ‘]’
LIST_GAMES_DYMAMIC	::=	{ ‘{’ GAME_DYNAMIC ‘}’ ‘,’ }
GAME_DYNAMIC	::=	ID_GAME_DYNAMIC ‘,’ ID_TRAJECTORY ‘,’ MAXTIME ‘,’ INVOLVED_JOINTS ‘,’ INTERACTION ‘,’ ON_REPT_COMPLETED ‘,’ ON_REPT_FAILED

The terms gameplay, **id_game_dynamic**, **max_time_between_path_nodes**, **involved_joint**, interaction, type, **interaction_time**, **on_repetition_completed**, **repetition_increment**, **score_increment**, **on_repetition_failed**, and **action**, introduced next, are keywords. The tokens **type_joint**, **type_interaction**, and **type_action** are defined, as follows:

type_joint	::=	hip-center | spine | shoulder-center | head | shoulder-left | elbow-left | wrist-left | hand-left | shoulder-right | elbow-right | wrist-right | hand-right | hip-left | knee-left | ankle-left | foot-left | hip-right | knee-right | ankle-right | foot-right
type_interaction	::=	on-touch | hold
type_action	::=	retry | skip

ID_GAME_DYNAMIC	::=	“” **id_game_dynamic** ‘”’ ‘:’ **string**
MAXTIME	::=	“” **max_time_between_path_nodes** ‘”’ ‘:’ **integer**
INVOLVED_JOINTS	::=	“” **involved_joint** ‘”’ ‘:’ **type_joint**
INTERACTION	::=	“” **interaction** ‘”’ ‘:’ BLOCK_INTERACTION
BLOCK_INTERACTION	::=	‘{’ DEFINITION_INTERACTION ‘}’
DEFINITION_INTERACTION	::=	TYPE ‘,’ INTERACTION_TIME
TYPE	::=	“” **type** ‘”’ ‘:’ **type_interaction**
INTERACTION_TIME	::=	“” **interaction_time** ‘”’ ‘:’ **integer**
ON_REPT_COMPLETED	::=	“” **on_repetition_completed** ‘”’ ‘:’ BLOCK_ORC
BLOCK_ORC	::=	‘{’ REPETITION_INCR ‘,’ SCORE_INCR ‘}’
REPETITION_INCR	::=	“” **repetition_increment** ‘”’ ‘:’ **integer**
SCORE_INCR	::=	“” **score_increment** ‘”’ ‘:’ **integer**
ON_REPT_FAILED	::=	‘”’ **on_repetition_failed** ‘”’ ‘:’ BLOCK_ORF
BLOCK_ORF	::=	‘{’ ACTION ‘}’
ACTION	::=	“” **action** ‘”’ ‘:’ **type_action**

The attribute *id_game_dynamic* identifies each one of the game dynamics available in the exergame. *id_trajectory* and *max_time_between_path_nodes*, contained in the each game dynamic, are related to its trajectory. The attribute *id_trajectory* contains the unique identifier of a virtual path previously defined in PEL (*trajectories* component). PEL allows to set what should happen if this restriction is not met. To do this, the element *on_repetition_failed* allows to set an callback action (attribute *action*), such as informing the patient that he/she must start the repetition again (value *retry*).

The attribute *involved_joint* and the element *interaction* are associated with the interaction mechanism. Thus, *involved_joint* allows for registering the joint that the system must monitor, while *interaction* is used for specifying the type of interaction (*on-touch* for a simple interaction, or hold for one that requires the patient to hold the position during a time defined in the attribute *interaction_time*).

Finally, PEL allows to define what happens when a repetition is completed or not in a game dynamic, thus providing feedback to the patient. The elements *on_repetition_completed* and *on_repetition_failed* specify it. The current PEL version considers two possible values for *on_repetition_completed*: *repetition_increment* to indicate the update of the number of repetitions in the exergame, and *score_increment* to indicate the update of the patient’s score. On the other hand, *on_repetition_failed*, as introduced above, determines what happens when the patient does not perform a repetition in a correct way.

Listing 1 in Section 4 shows an example of the use of this component gameplay.

Constraints component

The constraints components stores information regarding the defined restrictions in the exergame, typically associated with those parts of the body that the patient should not ideally move to compensate for the lack of mobility or strength of the body part to be rehabilitated.

The EBNF grammar for constraints block is the following:

CONSTRAINTS	::=	'"' **constraints** '"' ':' BLOCK_CONSTRAINTS
BLOCK_CONSTRAINTS	::=	'{' JOINTS '}'
JOINTS	::=	'"' **joints** '"' ':' '[' LIST_JOINTS ']'
LIST_JOINTS	::=	**type_joint** { ',' **type_joint** }

The terms constraints and joints are keywords. Although this component may seem to be very specific and there is a change in the abstraction level with respect to the other components, the fact is that most virtual rehabilitation commercial tools allow for explicitly indicating which parts of the body a patient should not move when doing rehabilitation. In this sense, the current PEL version considers the element joints as a list of specific joints associated to this restriction.

Listing 1 in Section 4 shows an example of the component constraints.

Metrics component

The metrics block stores information about those aspects of the patient's exergame execution that need to be assessed by the therapists. This component represents a list of key performance indicators (KPIs) to monitor the performance and evolution of the patient. Depending on the indicator, PEL contemplates the definition of some attributes or others. Currently, the KPIs that are considered in the current PEL version are five:

1. performance, which allows the definition of a patient's performance in an exergame, using the values specified in the attribute labels and the ranges contemplated in the attribute score. Note that the value of the score in an exergame will be conveniently updated according to the value of the element *on_repetition_completed* included in the component gameplay. As an example, and internally in the parsing module of the automatic exergame generation system, the label not-bad would be associated to a score lower or equal to 300 points (in this example), the label good to a score higher than 300 and lower or equal to 700, and the label perfect to a score higher than 700 points.
2. *rehabilitation_time*, which allows for recording the time that it takes for a patient to complete certain parts of the exergame when evaluating the exercise. This component defines several KPIs, such as the time that elapses between a limb passes through the virtual nodes, the time employed by the patient in order to complete a repetition, and the time that is needed by a patient to rest after completing a repetition. Another KPI is defined to record the time it takes for a patient to complete the activity, which is added in the listing shown below.
3. mobility, which allows for specifying and monitoring a list of joints to measure their degree of abduction, adduction, extension, and flexion, respectively. Furthermore, this component allows to record the velocity of the joints. This list is defined by the attribute points.
4. displacement, which allows measuring aspects that are related to exercises that involve gestures of movement. In other words, exercises that mimic the gesture of static walking and exercises that require the execution of lateral steps. The defined KPIs allow to evaluate walking measuring, the amount of static steps or the amount of lateral steps. Furthermore, there are two KPIs for recording both the highest and the widest step.
5. balance control, which allows for evaluating aspects that are related to balance. This component defines a KPI to measure and evaluate the base support of a patient. Apart from this, another KPI is established to measure and evaluate the patient's gravity center.

The EBNF grammar for metrics block is specified next:

METRICS	::=	‘“’ **metrics** ‘”’ ‘:’ BLOCK_METRICS
BLOCK_METRICS	::=	‘[’ KPI { ‘,’ KPI } ‘]’
KPI	::=	REHAB_TIME | MOBILITY |
		BALANCE_CTRL | DISPLACEMENT |
		PERFORMANCE
REHAB_TIME	::=	‘“’ **rehabilitation_time** ‘”’ ‘:’
		BLOCK_REHABTIME
BLOCK_REHABTIME	::=	‘{’ DEFINITION_REHABTIME ‘}’
DEFINITION_REHABTIME	::=	TIME_ACTIVITY ‘,’ TIME_VNODE ‘,’
		TIME_REPETITION ‘,’ TIME_REST
TIME_ACTIVITY	::=	‘“’ **time_activity** ‘”’ ‘:’ BLOCK_TIME
TIME_VNODE	::=	‘“’ **time_vnodes** ‘”’ ‘:’ BLOCK_TIME
TIME_REPETITION	::=	‘“’ **time_repetition** ‘”’ ‘:’ BLOCK_TIME
TIME_REST	::=	‘“’ **time_rest** ‘”’ ‘:’ BLOCK_TIME
BLOCK_TIME	::=	‘{’ DEFINITION_TIME ‘}’
DEFINITION_TIME	::=	TIME ‘,’ LABELS
TIME	::=	‘“’ **time** ‘”’ ‘:’ VALUES
VALUES	::=	‘[’ **integer** ‘,’ **integer** ‘,’ **integer** ‘]’
LABELS	::=	‘“’ **labels** ‘”’ ‘:’ ” LABELS ”
LIST_LABELS	::=	**type_label** { ‘,’ **type_label** }

MOBILITY	::=	‘“’ **mobility** ‘”’ ‘:’ BLOCK_MOBILITY
BLOCK_MOBILITY	::=	‘{’ DEFINITION_MOBILITY ‘}’
DEFINITION_MOBILITY	::=	EXTENSION ‘,’ FLEXION ‘,’
		ABDUCTION ‘,’ ADDUCTION ‘,’
		JOINT_VELOCITY
EXTENSION	::=	‘“’ **extension_degree** ‘”’ ‘:’ **real**
FLEXION	::=	‘“’ **flexion_degree** ‘”’ ‘:’ BLOCK_JOINTS
ABDUCTION	::=	‘“’ **abduction_degre** ‘”’ ‘:’ BLOCK_JOINTS
ADDUCTION	::=	‘“’ **adduction_degre** ‘”’ ‘:’ BLOCK_JOINTS
JOINT_VELOCITY	::=	‘“’ **joint_velocity** ‘”’ ‘:’ BLOCK_JOINTS
BLOCK_JOINTS	::=	‘{’ JOINTS ‘}’
BALANCE_CTRL	::=	‘“’ **balance_control** ‘”’ ‘:’ BLOCK_BCTRL
BLOCK_BCTRL	::=	‘{’ DEFINITION_BCTRL ‘}’
DEFINITION_BCTRL	::=	BASE_SUPPORT ‘,’ GRAVITY_CENTER
BASE_SUPPORT	::=	‘“’ **base_support** ‘”’ ‘:’ BLOCK_DEF_BCTRL
GRAVITY_CENTER	::=	‘“’ **gravity_center** ‘”’ ‘:’ BLOCK_DEF_BCTRL
BLOCK_DEF_BCTRL	::=	‘{’ DEF_BASE_SUPPORT ‘}’
DEF_BASE_SUPPORT	::=	2D_POSITIONS ‘,’ LABELS
2D_POSITIONS	::=	‘“’ **2d_coords**‘”’ ‘:’ VECTOR2
VECTOR2	::=	‘[’ **real** ‘,’ **real** ‘]’

DISPLACEMENT	::=	"' **displacement** "' ':' BLOCK_DISPLACEMENT
BLOCK_DISPLACEMENT	::=	'{' DEFINITION_BLOCKDISP '}'
DEFINITION_BLOCKDIS	::=	STATIC_STEP ',' LATERAL_STEP ',' HEIGHT_STEP ',' WIDTH_STEP
STATIC_STEP	::=	"' **static_steps** '"' ':' BLOCK_STEP
LATERAL_STEP	::=	"' **lateral_steps** '"' ':' BLOCK_STEP
HEIGHT_STEP	::=	"' **height_step** '"' ':' BLOCK_STEP
WIDTH_STEP	::=	"' **width_step** '"' ':' BLOCK_STEP
BLOCK_STEP	::=	'{' DEFINITION_STEP '}'
DEFINITION_STEP	::=	JOINTS ',' AMOUNT ',' LABELS
AMOUNT	::=	"' **amount** '"' ':' VALUES
PERFORMANCE	::=	"' **performance** '"' ':' BLOCK_PERFORMANCE
BLOCK_PERFORMANCE	::=	'{' DEFINITION_PERFORMANCE '}'
DEFINITION_PERFORMANCE	::=	SCORE_PERFORMANCE
SCORE_PERFORMANCE	::=	"' **score_performance** '"' ':' BLOCK_DEF_PERF
BLOCK_DEF_PERF	::=	'{' DEF_SCORE_PERF '}'
DEF_SCORE_PERF	::=	SCORE ',' LABELS
SCORE	::=	"' **score** '"' ':' VALUES

The terms metrics, **rehabilitation_time**, **time_activity**, **time_vnodes**, **time_repetition**, **time_rest**, **time**, **mobility**, **extension_degree**, **flexion_degree**, **abduction_degree**, **adbuction_degre**, **joint_velocity**, **balance_control**, **base_support**, **gravity_center**, **displacement**, **static_steps**, **lateral_steps**, **height_step**, **width_step**, **2d_coords**, amount, performance, **score_performance**, score, and labels are keywords. The token **type_label** is defined, as follows:

type_label ::= not-bad | good | perfect

Listing 1 in Section 4 shows an example of the component metrics.

3.2.3. Automatic Exergame Generation and Authoring Tools for Therapists

When the specification of the exergame has been completed, the system can be requested in order to automatically generate the exergame, considering the final deployment hardware platform. This generation depends on a game engine on which to execute the source code generated from PEL sentences. In the current version of this work, the Unity 3D (https://unity3d.com/) game engine is used. This choice is based on its portability and the large amount of multimedia resources available for its integration in exergames.

The automatic generation of an exergame is carried out through a software module of hierarchical analysis of the exergame information in PEL/glTF. This module receives through a URI (Uniform Resource Identifier) the location of the .gltf file with all the content of the exergame, that is, both the multimedia resources and the design itself through PEL sentences. Note that PEL makes use of the glTF extensions, particularly through the field extras, in which the specific behavior linked to the exergame design methodology previously introduced is specified. The automatic analysis process of this field extras is integrated in a sub-module that is responsible for parsing in the form of a syntactic analyzer. This is supported by the implementation of glTF to make the de-serialization of the glTF coded elements as efficient as possible.

The idea of providing a language for the definition of personalized exergames, whose sentences can be automatically processed by a software program, has a great impact on the process of adapting physical rehabilitation according to the needs of each patient. Taking this language as a reference, it is possible to build both software modules that work on top of it and authoring tools that make it possible for therapists to easily design exergames in a visual way.

It should be noted that, although the language proposed in this work is simple enough, the therapist is not intended to be the one that use it. As already mentioned, the idea is to have an intermediate language that can be manipulated by advanced subsystems, according to various aspects, such as the interaction of the patient with the exercise. In this context, the therapist may need a high-level authoring tool that facilitates the design of the exergame. This tool would integrate a software module in order to generate the PEL sentences that are equivalent to the graphic definition of the exergame. Although the development and evaluation of this tool is beyond the scope of this article, a first design has been addressed in order to complement the proposed approach.

For the definition of the exercise and rehabilitation objectives specific to each patient, the therapist will be provided with a graphical definition tool that facilitates the definition of key positions, as well as the specification of the different variables and options available in the exergame. This graphic editor encapsulates the glTF and JSON components that will be automatically exported and used by the other components of the tool. Internally, the graphical editor module would employ a description based on the H-Anim standard (ISO/IEC IS 19774-1:2019). As for the bone hierarchy, each animation chain is composed of several *articulated* elements that define transformations from the root of the hierarchy.

There are several specific avatars for rehabilitation, such as [38] or [39], which, however, are not focused on the creation of exercises by non-technical staff without using motion capture techniques. The precise configuration of the positions and rotations of each part of the animation hierarchy is essential when defining rehabilitation exercises. The definition of movement must allow for both rapid definition of movements, using in our proposal inverse kinematics (IK), and subsequent fine tuning, using direct kinematics methods.

In the virtual avatar integrated in the proposed tool, every element of the kinematic chain can be positioned and rotated while using realistic human limitations. This is the most time consuming phase in the generation of a new exergame. As detailed next, a new approach has been devised in order to increase the adaptability and the ease of use by the therapist. The graphic editor will allow defining start and end positions in three different ways:

- Use a set of predefined key positions. This option allows to directly input common positioning settings for each limb.
- Use of a high level adjustment by employing high-level reverse kinematics manipulators.
- Definition, if needed, of the position and rotation details of each bone using direct kinematics.

The skeleton that is defined in the graphical editing module consists of 103 bones (see Figure 2), of which 19 are inverse kinematic manipulators and high-level controls (they influence a set of bones). The use of inverse kinematics and spherical quaternary interpolation [40] facilitates the therapist's work in defining the key poses of the starting and ending positions of the rehabilitation exercises.

In relation to the methods of inverse kinematics, there are three concepts to which special attention is paid: the description of the joints, the angle of rotation, and the degrees of freedom. The physical characteristics of the joints themselves determine the final movement, the angle of rotation describes the rotation allowed for each joint, and the degrees of freedom involve the directions in which each joint moves. In most kinematic configurations, it is essential to define the rotation restrictions in order to avoid constrained configurations and simulate only physically correct positions. There are two ways of dealing with IK: analytical or iterative methods. Analytical methods require prior analysis of the animation hierarchy and, in the case of body movements in humans (like in the proposed tool), the resulting equations are very complex. To face this problem, the proposed graphic editor uses the iterative method Cyclic Coordinate Descent (CCD) [41]. CCD is an iterative method for calculating the IK that minimizes the error of the kinematic configuration for each joint.

Thus, each kinematic chain defines its own set of rotation changes, so that the final composition of the animation is obtained using non-linear animation (NLA) techniques [41]. In NLA, each piece of animation (action) is focused on the definition of a certain action (e.g., moving the right arm). These actions are combined with others, each of them defining a certain animation layer.

When generating PEL sentences, this independent treatment will allow exporting the restrictions that are defined by the therapist in a simple way. On the other hand, each exergame is defined by several actions (or animation channels). Basic SLERP interpolation [40] will be used to concatenate the different defined sub-actions (e.g., raising the whole arm and then rotating the forearm 90° around the torso).

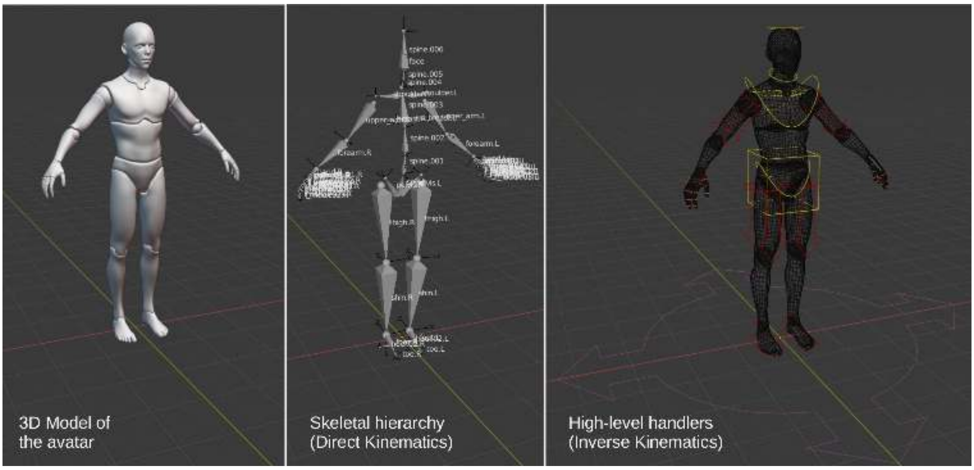

Figure 2. Definition of the 103 bones of the humanoid skeleton according to the specification of HAnim 2.0 (**Left**) avatar representation. (**Center**) definition of the kinematic chains. (**Right**) high-level reverse kinematics controls.

Obtaining realistic movements is probably the most important element to consider in the representation of rehabilitation exergames. The animation must faithfully represent the exercise to be performed by the patient. The results obtained related to the proposed approach will generate high quality results, which are independent of the final representation. In addition, an approach that is based on keyframe animations produces more accurate, clean, and understandable results than motion capture based techniques, with a lower computational cost in the context of high-demand application domains [42].

The pose editor

One of the main problems related to the creation of rehabilitation exercises is the time needed for their definition and the level of knowledge regarding 3D animation tools. Despite the development of new techniques to facilitate the animation of virtual characters (such as inverse kinematic controls and key poses), an experienced user may require between five and 10 min. to define a realistic movement. Because of the initial knowledge that is required to work with these types of tools, this phase requires special attention in the proposal.

An exercise editing module has been designed (see Figure 3) to facilitate the definition of rehabilitation exergames. The therapist will be requested in order to choose basic settings of shape and orientation of the extremities in a direct way. Firstly, he/she will choose the joint, and then he/she will pick, from a catalog of key poses, the one that is most similar to the one he/she wants to perform. This configuration can be refined later while using reverse kinematics controls and, if necessary, direct kinematics controllers for the final tuning.

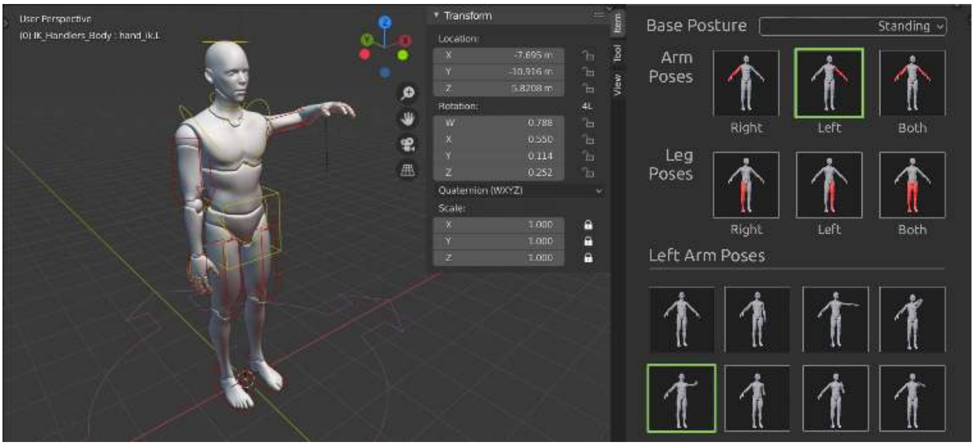

Figure 3. Pose editor of the proposed graphical tool. On the right, a subset of poses available for the arm is shown.

In the current proposal, 48 basic positions were defined for the arms and 12 basic positions for the legs. By using an exercise editor like this, the time that is needed to specify a new exercise can be reduced by a 90%, obtaining results of similar quality.

Finally, the exercise definition system has been designed to be handled as a plug-in within the Blender animation suite. Blender existing functionalities can be used for animation, keyframe definition, or playback, among others, which facilitate the subsequent export process to glTF + JSON (see Figure 4).

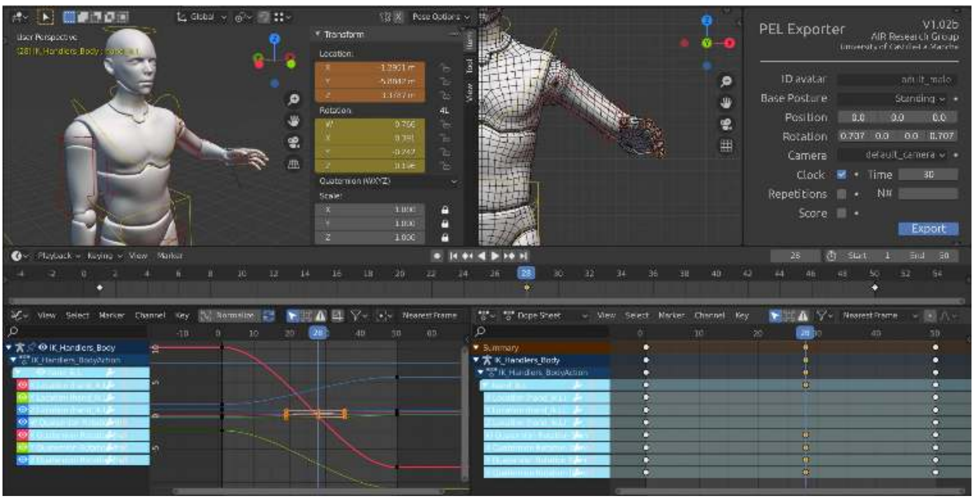

Figure 4. Plug-in view within Blender general interface. In the lower area, the Blender Timeline is shown, which will allow working with keyframes. On the right, the plugin will allow specifying the values of properties that will be later exported to PEL sentences (such as the virtual camera, the number of repetitions of the exercise, or the time-related constraints.

4. A Case Study Using PEL

In order to evaluate the proposed system, we have conducted two studies to assess different aspects of the system, which is design around PEL, the cornerstone of our software to generate personalize exergames automatically. The first one is related to stroke patients. The second one to therapists.

Regarding the first case, a quasi-experiment with real stroke patients has been conducted in order to evaluate the understanding and adequacy of a set of exergames that are defined with PEL by a therapist with the assistance of a developer. Regarding the second case, and considering that the therapists are responsible for designing routines or exercises with the best therapeutic value, a questionnaire has been designed in order to know how much this system contributes to patients in the context of home rehabilitation and exergames that are generated from PEL sentences.

4.1. Study with Stroke Patients

The study included 17 real associated to the General Hospital Nuestra Señora del Prado (https://sanidad.castillalamancha.es/ciudadanos/centros/hospital-nuestra-senora-del-prado), located in Talavera de la Reina. A positive report by the ethical committee in clinic research of such hospital was issued prior to conducting this study on September 24th, 2019 (project id 30/2019). The group of patients evaluated was randomly selected with ages ranging from 37 to 86 years. When the experiments were carried out, it was explicitly stated at the beginning of the test that the collected data would be treated confidentially and exclusively for this study. The ethic approval and consent form statement, which is available for the reader (https://www.esi.uclm.es/www/dvallejo/PEL_Applied_Sciences), was filled by every single patient before conducting the experiment.

4.1.1. Method

The quasi-experiment was divided into three stages:

- **Preparation**. An instructor presented the system to each participant for about 10 min. During the explanation, an example was projected on the wall so that the patient could follow the explanation perfectly and understand the activity to be performed.
- **Development**. Each patient performed an exercise routine included in the system according to their condition, which is, if the stroke caused the patient to lose mobility in the left, right, or both parts of their body.
- **Evaluation**. Once the patient had completed the previous step, he or she was encouraged to fill in a questionnaire to evaluate the exergames and the software system using *Microsoft One Drive Forms* (https://forms.microsoft.com/), in order to facilitate their subsequent digital processing.

The exergames that were performed by the patients were based on rehabilitation exercises to train the upper body, thus involving the arms. All of them were automatically generated from PEL language definitions, when considering both left and right arm versions. Particularly, the exercises associated to the generated exergames were those of (i) bringing the right and left hand from the hip to the shoulder, (ii) bringing the right and left hand from the hip to the mouth, and (iii) bringing the right and left hand from the hip to the head. In addition, (iv) right and left shoulder abduction exercises were performed. Figure 5 shows the visual aspect of some of the generated exergames in the initial version of the rehab system, all of them in the context of a virtual gym. On the other hand, Listing 1 shows the full PEL specification of the exercise right shoulder abduction. At this point, it is important to remark that there exists a normalization process so that, independently of the patient's height and width, the dimensions of the virtual avatar remain the same for every generated game.

Listing 1. Full PEL definition for the exergame right shoulder abduction.

```
{
''description'': { ''text'' : ''Shoulder abduction'' },
''setup'' : {
''avatar'' :  { ''id_avatar'' : ''avatar-1'',
''posture''   : ''standing'',
''position''  : [7.27, 0.00, 4.45],
''rotation''  : [0.00, 0.00, 0.00, 0.00] },
''camera'':  {  ''id_camera'' : ''camera_1'',
''position''  : [7.34, 1.08, 1.15],
''rotation''  : [0.00, 0.00, 0.00, 0.00] },
''clock''       : { ''activated'' : true, ''countdown_time'' : 120 },
''repetitions'' : { ''activated'' : true, ''max_number_repetitions''  5 },
''score''       : { ''activated'' : true }
},
''trajectories'': [
{
''id_trajectory'' : ''right-shoulder-abduction'',
''3d_path''       : [ [7.93, 1.50, 4.46], [7.73, 1.67, 4.46],
[7.53, 1.78, 4.46] ],
''radius''        : 1.00
}
],
''gameplay'' : [
{
''id_trajectory''  : ''right-shoulder-abduction'',
''involved_joint'' : ''hand.right'',
''interaction''    : { ''type'' : ''touch'', ''interaction_time'' : 0 },
''on_repetition_completed''  : {
''repetition_increment'' : 1,
''score_increment''      : 100
},
''on_repetition_failed'' : {
''action'' : ''retry''
}
}
],
''constraints'': {
''joints'': [ ''spine-naval'', ''spine-chest'' ]
},
''metrics'' : [
{
''mobility'' : {
''joints_extension_degree'' : {
''joints'' : [''hip-left'', ''hip-right'',
''knee-left'', ''knee-right'']
}
}
},
{
''performance'' : {
''score_performance'' : {
''score''  : [300, 700, 1000],
''labels'' : [''not-bad'', ''good'', ''perfect'']
}
}
}
]
}
```

Each exercise was projected on a large screen. This allowed the patients to correctly visualize the movement that they had to make, as well as the gamification elements provided by the system.

The purpose of the test was to analyze the use of the generated exergames by real patients in terms of understanding and adequacy. Thus, the steps defined in [43] were followed, while using a template *Goal-Question-Metrics*.

Firstly, patients were asked if they had already used any system of these characteristics in order to find out the advantages or weaknesses that the proposed approach might have with respect to other rehabilitation systems.

Then, they were asked to complete a questionnaire with a total of 22 questions (see Table A1 in Appendix A), scored with a Likert scale (1: totally disagree; 5: totally agree), grouped in five dimensions: activity perception, cognitive load, utility, game elements, and the TAM (*Technology Acceptance Model*) framework. These five dimensions are briefly described below.

- **Perception of activity**. This dimension is composed of a set of questions to measure interest (INT), effort (EFF), and ease of learning how to use the system (LEA).
- **Cognitive load**. This block includes a series of statements inspired by the Cognitive Load Theory (CLT) [44], which allows measuring the cognitive load imposed by the software, the complexity of the developed task (TD) and the complexity that is required by both the software and the device

used (DD). In addition, two questions were added to measure the patient's effort in relation to the activity performed (E).

- **Utility**. The third block consists of questions related to the patients' opinion regarding the exergame-based rehabilitation system, that is, if they prefer to use it at home instead of attending rehabilitation centers (PREF), if the system encourages them to be more consistent when performing rehabilitation exercises (CONS), if the system enhances motivation (PAS), and if they like the application to look like a game (GAM).
- **Game elements**. The fourth block contains questions related to the degree of suitability of each of the elements included both in the user interface and in the exergame scene itself, which is, aspects, such as the avatar representation, the number of repetitions, the score, or the visually decorative elements.
- **TAM**. The fifth block consists of questions based on the TAM framework [45], which are used to measure the perception of system usability (PEU), the utility perception (PU), and the intention of use (ITU).

Finally, the patients had the opportunity to provide some comments on the system. In this way, it will be possible to improve specific parts of the exergame-based rehabilitation system in future developments. In fact, Section 5 discusses some of the already integrated improvements regarding the first version of the rehabilitation system.

Figure 5. Visual aspect of the generated exergames. (**a**) Right hand to head, (**b**) right hand to mouth, and (**c**) right shoulder abduction.

4.1.2. Results

At the beginning of the survey, the patients answered two questions that were related to the use of systems similar to the one evaluated. 47% of the respondents answered that they had used more than one system in their rehabilitation process, when considering that our proposal is more intuitive and simple to use (see Table 1).

Apart from the analysis that is shown in Table 1, the existence of correlations between different items has been studied (see Table 2). For this purpose, the Shaphiro–Wilk test was applied to contrast the normality of the data set, given that the sample size is less than 50. The result revealed, with a 95% confidence level, that the variables do not fit a normal distribution, which resulted in the use of the Spearman correlation coefficient.

The obtained results show the correlation between INT2 and PU, ITU1, ITU2, CONS, and PSA. This reflects that, as the patients rated the activity as more interesting, they considered that the system would help them perform rehabilitation exercises; they would use it at home; they would recommend it to family members; it would increase their consistency; and, it would motivate them to perform more exercise routines. In addition, the correlation between the variable PREF and variables CONS/PSA indicates that the patients would prefer to use the system at home, because it motivates them and increases their determination.

Table 1. Descriptive statistics of the dimensions evaluated by patients.

Dimension	Item	Mean	Standard Deviation	Mode
Activity Perception	1. INT1	4.41	0.87	5.00
	2. INT2	4.53	0.62	5.00
	3. EFF	4.35	1.06	5.00
	4. LEA	**4.65**	0.49	5.00
Cognitive Load	5. TD	3.71	0.99	4.00
	6. E1	3.82	0.88	4.00
	7. E2	3.65	1.00	4.00
	8. DD	**2.88**	1.17	2.00
Utility	9. PREF	**4.00**	1.22	5.00
	10. CONS	3.88	1.17	4.00
	11. PSA	4.06	1.20	5.00
	12. GAM	**4.71**	0.59	5.00
Game elements	13. GE1	**4.59**	0.71	5.00
	14. GE2	4.41	0.80	5.00
	15. GE3	4.24	0.97	5.00
	16. GE4	**4.59**	0.71	5.00
	17. GE5	**4.65**	0.79	5.00
	18. GE6	3.24	0.75	3.00
TAM	19. PEU	**4.35**	0.79	3.00
	20. PU	3.88	1.11	4.00
	21. ITU1	4.06	1.20	5.00
	22. ITU2	**4.35**	0.79	5.00

Table 2. Spearman's rank correlation coefficient. Significant values (p-value < 0.05) are marked in bold.

	E1	INT2	EFF	GE1	GE2	GE3	GE4	GE5	GE6	GAM	PU	ITU1	ITU2	PREF	CONS	PSA
TD	**0.82**															
E1					**0.53**		**0.49**			**0.36**						
E2			**0.55**													
DD											**−0.41**	**−0.44**	**−0.58**	**−0.49**	**−0.74**	**−0.54**
EFF					**0.72**	**0.62**				**0.34**						
GE2						**0.85**										
GE4										**0.56**						
GE5				**0.56**					**.29**							
GE6				**0.36**												
INT1		**0.67**		**0.47**				**0.44**	**0.30**							
INT2											**0.59**	**0.46**	**0.45**		**0.46**	**0.46**
PREF															**0.66**	**0.58**
PU												**0.81**	**0.75**	**0.38**	**0.64**	**0.69**
ITU1													**0.81**	**0.47**	**0.54**	**0.51**
ITU2														**0.57**	**0.73**	**0.66**
CONS																**0.90**

4.2. Authoring Tool Evaluation with Therapists

The system has been evaluated by six therapists associated to the General Hospital of Nuestra Señora del Prado in order to know its applicability in the context of home rehabilitation. Again, the shown exergames were automatically generated from PEL sentences. The ultimate goal was to evaluate what the rehabilitation system can provide in terms of functionality, which indirectly reflects what PEL can currently offer and usability. The therapists completed with a questionnaire with free text, multiple choice, and single answer questions.

4.2.1. Questionnaire Design

The questionnaire was designed using Microsoft OneDrive Forms both to include multimedia content and facilitate their digital processing. It was divided into two sections:

- **System demonstration**. A demonstrative video for about 3 min was included to explain the features and functionalities of the system.
- **Evaluation of the system**. A set of questions were included with different objectives. Some of them were designed so that they provided valuable information that enable continuously improving the system and how PEL can be adapted to address such improvements. Others were added to measure certain aspects of the system.

The second section of the questionnaire was followed using the Goal-Question-Metrics. Firstly, therapists were asked if they knew virtual rehabilitation systems. In this way, we can study the referred systems in order to improve ours. Secondly, they were asked to indicate which group of people could benefit most from the system. Next, a question was introduced for obtaining feedback from therapists to know what information should be collected when a patient finishes an exercise. Subsequently, they had to select with what frequency they would like to receive the information generated by the system after a patient has performed a rehabilitation activity. Subsequently, they were asked to complete a total of 15 questions (see Table A2 in Appendix B), scored with a Likert scale (1: totally disagree; 5: totally agree) grouped in three dimensions: TAM framework, system perception, and game elements.

- **TAM**. The first dimension consists of questions to measure the perception of system usability (PEU), perception of usefulness (PU), and intention of use (ITU).
- **System perception**. The second dimension is composed of a set of questions to evaluate the motivation that the system can produce in the patient (MOT), the constancy the system can generate in old people (CONST), if the system can improve the rehabilitation process in a rehab center (IMP1), and whether it would improve the rehabilitation process at home (IMP2).

- **Game elements**. The third dimension consists of several questions to measure the adequacy of the user interface from the therapists' perspective.

Once the therapists completed the part of the questionnaire based on Likert scale questions, they could provide some comments about the system. For example, potential actions the system could perform and their advantages to strengthen them in the near future.

4.2.2. Results

The objective of this study was to know the therapists' point of view regarding the use of a system focused on home rehabilitation. At this moment, the system developed is in a preliminary version. However, the professionals, who answered the questionnaire, assessed the prototype as a good starting point for achieving one of our goals, which is, making home rehabilitation accessible. Thus, the obtained results from the questionnaire reflect that the therapists considered the system to be useful and easy to use. Apart from this, they positively evaluated the feature of personalizing exergames. Table 3 shows the obtained results from a descriptive statistical analysis.

Table 3. Descriptive statistics of the dimensions evaluated by therapists.

Dimension	Item	Mean	Standard Deviation	Mode
TAM	1. PEU1	4.50	0.83	5.00
	2. PU1	4.50	0.54	5.00
	3. PU2	3.33	1.03	4.00
	4. PU3	**4.83**	0.40	5.00
	5. ITU1	4.67	0.51	5.00
	6. ITU2	4.67	0.51	5.00
	7. ITU3	**4.83**	0.40	5.00
System perception	8. MOT	3.50	0.54	4.00
	9. CONST	3.83	1.16	5.00
	10. IMP1	**4.50**	0.54	5.00
	11. IMP2	4.33	1.21	5.00
Game elements	12. GE1	3.83	0.75	4.00
	13. GE2	4.33	0.81	5.00
	14. GE3	4.17	0.98	5.00
	15. GE4	**4.50**	0.54	5.00

5. Discussion

5.1. Patients

With regard to the results that were obtained from the data collected in the first questionnaire, as reflected in Table 1, the evaluated exergames have been well received by the patients, achieving a good overall score (most items obtained a value of 4 or greater) in all the dimensions. In the first block (activity perception), the patients considered the activity to be fun (INT1) and interesting (INT2). In addition, they considered that they tried to perform the activity well and that the learning with respect to the use of the system was simple (LEA).

Most patients scored high on the cognitive load imposed by the activity (TD), since many of them, due to their condition, needed a high concentration to move the required limb. Furthermore, this implied that they were concentrated during the activity (E1, E2). However, several of the patients considered that the rehabilitation exercises were not complicated for them using this system (DD), since it helped them follow the movement that they had to perform.

On the other hand, practically all of the patients would prefer to use this system at home, rather than having to attend rehabilitation centers (PREF), since most of them had difficulties in being able to move around, either due to the inability to drive a vehicle or to limited economic resources. However, this does not imply, from our point of view, replacing the role of the therapist or reducing the rehabilitation time spent in specialized centers, since they are of vital importance for patients in poor condition or for patients who begin to use rehabilitation systems. On the contrary, the exergames that are generated from PEL sentences can help those patients with good progression, but who present certain logistic difficulties, such as those previously mentioned. On the other hand, most patients considered that the tested system would motivate them (CONS, PSA) to do more exercises because of its game aspect (GAM). This aspect is significant, since one of the drawbacks in the rehabilitation process is the patients' lack of motivation.

As for the game mechanics, the patients satisfactorily evaluated the avatar design and decorative elements (GE1, GE5). In addition, the information about the repetitions and score achieved in the activity were positively evaluated (GE2, GE3). In these cases, the use of gamification techniques can generate a healthy competition, where patients themselves compete with each other to achieve maximum scores. The element that obtained the highest score was the virtual trajectory composed of 3D spheres that indicate the path the patient should follow (GE4). They found it to be intuitive and helped them to execute the required exercise correctly. However, the description of the activity to be performed did not have a significant score, which may indicate that its design needs to be improved (GE5).

In relation to the last part of the questionnaire, the patients believed that the system is easy to use (PEU) and considered that it can help them improve their physical rehabilitation (PU). Furthermore, most of them would use it at home (UTI1), apart from recommending it to a relative with a similar condition. This fact may be associated with the motivation (PSA) that the system generates, which implies that it increases the frequency with which they exercise.

In addition, the patients had the option of leaving comments regarding the system, of which we highlight the following ones:

- In some cases, it is difficult to interpret the depth of the spheres used to guide the movement of an exercise.
- The system encourages rehabilitation exercises.
- It would be ideal if the system were more portable, that is to say, to remove the dependence on personal computers.

5.2. Clinicians

Our data exploration has consisted in a statistical analysis description given the low number of therapists surveyed (n = 6). In general, the data reflect that the therapists have valued the prototype well, obtaining a good score in all dimensions. This reflects the goodness of the functional capabilities that are offered by PEL.

In the first dimension, the therapists believed that it is useful that the system integrates voice input, so that the patients can interact easily with it (PEU1). They also positively valued that the system prevents patients from wearing sensors on their bodies (ITU3), since it can make difficult the rehabilitation at home. However, they considered that the system needs to be improved so that it can be deployed in a scenario where the patients do not require a professional (PU2), that is, where they can perform rehabilitation autonomously. On the other hand, the therapists considered the system can help patients to perform rehabilitation (PU1). Furthermore, they indicated that they would use the system (ITU1) if they had it, apart from recommending it to other professionals (ITU2).

The second dimension of the questionnaire is related to the perception of the therapists with regard to the system. In this block, the therapists considered that exergames can motivate patients to keep them engaged with their rehabilitation (MOT). This implied that they perceived the tool as a good complement in face-to-face sessions (IMP2). On the other hand, they believed that the system may increase the perseverance of the patients (CONST), being able to help those who present difficulties to go to a rehabilitation center (IMP2) (for example, cases where patients live in small villages far from the city).

Finally, in the third block of the questionnaire, therapists were asked for the game elements of the system. The avatar design was positively evaluated (GE1), as was the component that was related to repetitions and scores (GE2, GE3). The best scored item was the trajectory composed of virtual spheres that indicate the movement a patient's limb needs to follow (GE4). The result obtained in this block allows for interpreting that PEL is a fundamental component of the system, since this language maintains rules for collecting data to be analyzed and for designing game mechanics that engage a patient during his rehabilitation.

Apart from this, the therapists had the option of providing feedback with the objective of improving the system. Next, we highlight some of them:

- Adapting the avatar position for people in wheelchairs to feel them integrated in the system.
- Adding activities of the daily living (ADLs), for example, taking a glass and making the gesture to drink.

5.3. Improving the Rehabilitation System

The conducted evaluation, both with patients and therapists, allowed for the identification of several aspects that can be improved. Some of these have been already incorporated into the current version of the rehabilitation system, while others are being considered in the context of future lines of research. In this sense, Figure 6 shows the updated version of the user interface that the system offers to patients when carrying out rehabilitation. The main improvements that have been incorporated are summarized below:

- The removal of visual noise so that patients can focus on performing the exergames and only the relevant information is displayed. This improvement has been added to enhance the patients' concentration when using the system, but maintaining an adequate level of immersion (currently through the virtual gym scenario) to continue motivating them.
- New interaction mechanism based on contextual voice commands (see the upper right part of Figure 6). Thus, the patient can communicate with the rehabilitation system in a more natural and direct way. This functionality is especially important for patients with motor disabilities. This improvement has been integrated when considering the predisposition of the evaluated patients to use the system at home in an autonomous way.
- New visual representation of the 3D path that is associated with the exergame execution, based on the use of a color code and the size of the virtual spheres. The white spheres represent that part of the exercise that has already been done, while the orange ones represent the remaining part of the exercise. On the other hand, the sphere with a radius slightly larger than the rest is associated with the next step considering the current position of the related patient's joint. This improvement has been added as a result of some patients having difficulty interpreting the position of the spheres. However, it is considered to improve the lighting of the scenes, so that the shadows cast by the spheres can also facilitate the exercise interpretation by the patients.
- The integration of visual components to represent which part of the body is worked in each exergame and show an animation with the correct execution of the exergame (central right part of Figure 6). This improvement has been added, because the analysis of results showed that some patients had difficulties in understanding how to perform the exercise.
- Integration of visual components, so that the patient knows what exergame of the routine he/she is performing at every moment (bottom of Figure 6). The number of circles represents the number of exercises that make up the routine. The orange circle represents the position of the current exercise in the list. This enhancement has been added to facilitate the patient's guidance between exercises.

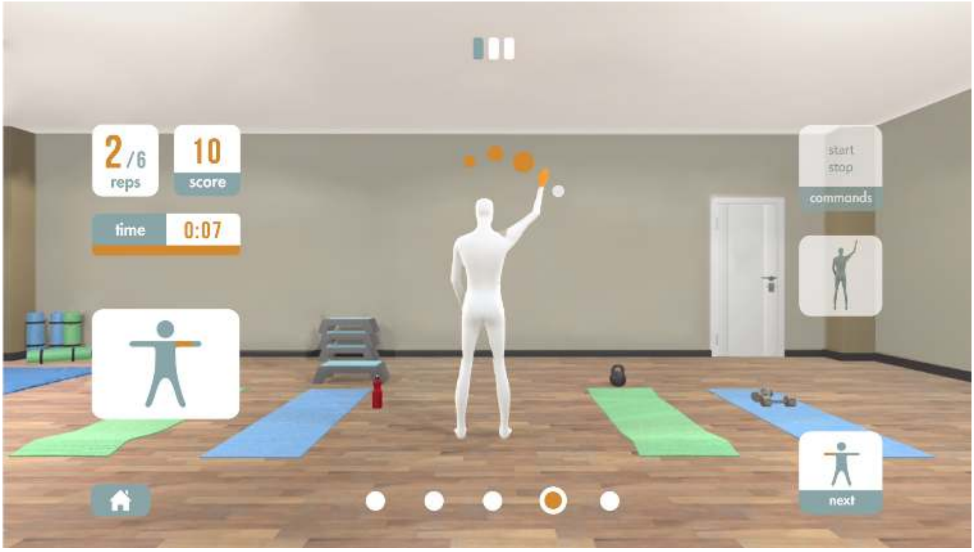

Figure 6. Visual aspect of the graphical user interface for the patient after the integration of some improvements. The feedback was obtained from the questionnaires completed by patients and therapists.

The improvements integrated in the latest version of the system will be evaluated in the future through further experiments with patients and therapists.

6. Conclusions

PEL (Personalized Exergames Language) has been defined to allow for the automatic generation of customized exergames within the context of the physical rehabilitation of patients affected by stroke. PEL relies on glTF, an open standard that is devised to efficiently send and load 3D models and scenes in applications. Particularly, the design of PEL was discussed paying special attention to the lexical and semantic aspects, since the syntactic component depends on the JSON format, which is used by glTF. The underlying software system is able to generate and execute exergames from PEL sentences.

A methodology for the effective design and generation of personalized exergames has also been proposed. This methodology follows a five-step process: (i) exercise definition, so that the therapist can establish the therapeutic objectives, (ii) definition of the interaction scheme between the patient and the exergame, typically through the definition of the trajectory of the rehabilitation movement, (iii) definition of feedback and motivation mechanisms, so that patients are engaged when performing the exergames, (iv) definition of metrics to measure the patients' performance and monitor their progress, and (v) generation of the exergame, an automatic process that transforms the exergame definition in PEL into an actual exergame that can be executed.

A number of exergames, defined while using PEL, were generated in order to assess how patients and therapists from one hospital and two community centers perceived the exergames understanding and suitability. From a general point of view, the feedback they provided was very positive, when considering that one of the potential uses of the system consists in performing the exergames at home. This feedback has been studied to improve specific aspects of the rehabilitation system, which have been integrated in the current prototype.

This first version of PEL, and the underlying software that automatically generates personalized exergames from PEL sentences, opens the door to potential improvements, such as the integration of authoring tools that can be used by therapists in order to graphically define exergames. These tools, like the one introduced in Section 3.2, will have to include a software module that is able to translate the visual definition of exergames into PEL sentences. From them, it is now possible to automatically generate exergames. At the same time, representing the exergames with sentences that can be processed by a computer facilitates the automatic personalisation of rehabilitation routines, depending on the dynamic evolution of the patient's progress. Another potential line of work would involve the integration of the care-giver avatar by expanding the setup component devised in PEL. Thus, the care-giver could physically assist the patient when he/she cannot perform the exergames in an autonomous way. Because the used hardware can track multiple bodies, this would be possible from the technical point of view. However, aspects, such as the impact of partial occlusions and data filtering, should be carefully assessed.

Author Contributions: Conceptualization, D.V., C.G.-P., and C.G.-M.; Methodology, J.J.C.-S., D.V.; Software, C.G.-P.; Validation, J.A., J.J.C.-S., C.G.-M.; Investigation, J.J.C.-S., D.V.; Visualization, J.A., C.G.-M.; Writing—Original Draft Preparation, C.G.-P., D.V.; Writing—Review & Editing, J.A., J.J.C.-S., and D.V.; Supervision, D.V.; Project Administration, D.V.; Funding Acquisition, J.A., J.J.C.-S., C.G.-M., D.V. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Textual Description of the Items Evaluated by Patients

Table A1. Textual description of the items evaluated by patients.

Dimension	Item	Description
Activity Perception	1. INT1	This activity has been fun for me
	2. INT2	I found this activity interesting
	3. EFF	I have worked to do it well
	4. LEA	It has been easy for me to learn how to use this system
Cognitive Load	5. TD	The activity required a lot of concentration
	6. E1	I have been very concentrated during the activity
	7. E2	I have had to work pretty hard to get the activity done
	8. DD	I have found difficult to perform rehabilitation exercises using this system
Utility	9. PREF	I would rather use this system at home than have to go to a rehab center
	10. CONS	This system would make me more consistent in performing the exercises at home
	11. PSA	I believe that using this system to do rehabilitation exercises can be motivating
	12. GAM	I like the application has the format of a game
Game elements	13. GE1	Avatar
	14. GE2	Repetitions
	15. GE3	Score
	16. GE4	Trajectory to be followed by the avatar
	17. GE5	Decorative elements
	18. GE6	Description
TAM	19. PEU	This system is easy to use
	20. PU	Using this system could help me in performing the rehabilitation exercises
	21. ITU1	If I could borrow this system, I would use it at home
	22. ITU2	I would recommend my friends to use this system to do the exercises at home

Appendix B. Textual Description of the Items Evaluated by Therapists

Table A2. Textual description of the items evaluated by therapists.

Dimension	Item	Description
TAM	1. PEU1	Voice interaction facilitates the use of the system
	2. PU1	The system could help people to perform rehabilitation
	3. PU2	The system is useful to perform exercises autonomously
	4. PU3	It is interesting that the system can personalize exercises based on the needs of patients
	5. ITU1	If I had the system, I would use it with my patients
	6. ITU2	I would recommend other therapists to use this system
	7. ITU3	The system encourages patients to be used because they do not need to wear sensors
System perception	8. MOT	Games can be motivating for people to perform rehabilitation
	9. CONST	The system could increase the constancy of old people to perform exercises
	10. IMP1	The system can improve the rehabilitation in a rehab centre
	11. IMP2	The system could help people to perform rehabilitation at home
Game elements	12. GE1	Avatar
	13. GE2	Repetitions
	14. GE3	Score
	15. GE4	Trajectory to be followed by the avatar

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2.2 Other articles published in indexed scientific journals

An Intelligent Tutoring System to Facilitate the Learning of Programming through the Usage of Dynamic Graphic Visualisations

- Title: An Intelligent Tutoring System to Facilitate the Learning of Programming through the Usage of Dynamic Graphic Visualizations [37]
- Authors: Santiago Schez-Sobrino, Cristian Gmez-Portes, David Vallejo, Carlos Glez-Morcillo and Miguel Á. Redondo
- Type: Journal
- Journal: Applied Sciences
- Publisher: MDPI (Basel, Switzerland)
- E-ISSN: 2076-3417
- Year: 2019
- DOI: 10.3390/app10041518
- Category: Engineering, Multidisciplinary
- Impact Factor (2020): 2.679
- JCR Ranking: Q2
- Related to the current research topic: No, although the underlying work of this publication has allowed to acquire a deep understanding of computer graphics, advance interaction mechanisms and real-time processing. Thus, this knowledge has contributed to the software solutions implemented and the visual prototypes developed.
- Related figure(s): 2.1
- Abstract: The learning of programming is a field of research with relevant studies and publications for more than 25 years. Since its inception, it has been shown that its difficulty lies in the high level of abstraction required to understand certain programming concepts. However, this level can be reduced by using tools and graphic representations that motivate students and facilitate their understanding, associating real-world elements with specific programming concepts. Thus, this paper proposes the use of an intelligent tutoring system (ITS) that helps during the learning of programming by using a notation based on a metaphor of roads and traffic signs represented by 3D graphics in an augmented reality (AR)

environment. These graphic visualisations can be generated automatically from the source code of the programs thanks to the modular and scalable design of the system. Students can use them by leveraging the available feedback system, and teachers can also use them in order to explain programming concepts during the classes. This work highlights the flexibility and extensibility of the proposal through its application in different use cases that we have selected as examples to show how the system could be exploited in a multitude of real learning scenarios.

Home Rehabilitation Based on Gamification and Serious Games for Young People: A Systematic Mapping Study

- Title: Home Rehabilitation Based on Gamification and Serious Games for Young People: A Systematic Mapping Study [15]
- Authors: Cristian Gmez-Portes, Carmen Lacave, Ana I. Molina, David Vallejo
- Type: Journal
- Journal: Applied Sciences
- Publisher: MDPI (Basel, Switzerland)
- E-ISSN: 2076-3417
- Year: 2020
- DOI: 10.3390/app10248849
- Category: Engineering, Multidisciplinary
- Impact Factor (2020): 2.679
- JCR Ranking: Q2
- Related to the current research topic: Yes.
- Related figure(s): 2.2
- Abstract: Physical rehabilitation of people who suffer from some motor disability involves an intensive treatment to reduce pain and improve quality of life. Research studies have proven the benefits of technologies based on home-rehabilitation, which complement regular therapy in hospitals. Although there is a significant number of studies that face this challenge when dealing with adults, it has not been explored with young people. In this research article, we focus on this population, since the repetition of physical exercises decreases the youth's motivation, which entails a high risk of dropping out of therapy. That is why we present a systematic mapping study of the

techniques, devices, and methods used to address home rehabilitation for children and teenagers. The conclusions indicate that it is essential to use gamification techniques to adopt a plug-and-play metaphor, based on natural interaction mechanisms and on the use of non-intrusive devices, and to customise the rehabilitation process for each individual along with a methodology. We also present the improvements applied to an existing gamification-based software prototype for home rehabilitation. In this system, physical exercises can be customised, laying the foundations to promote precision rehabilitation within the context of young people

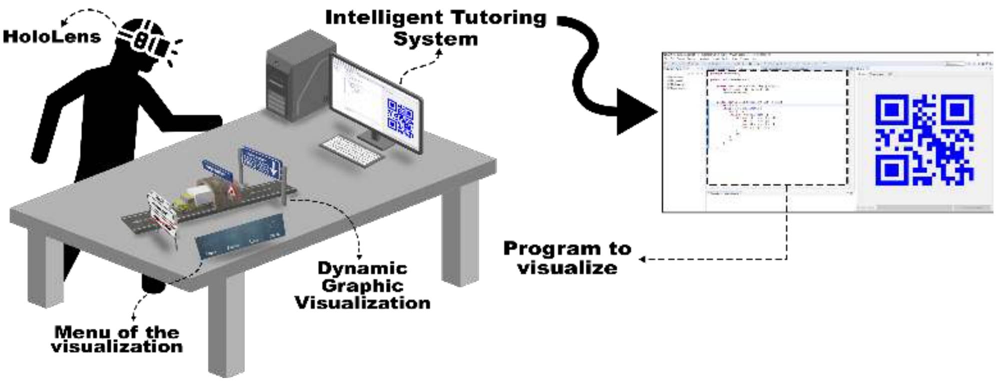

Figure 2.1: General overview of the proposed intelligent tutoring system to facilitate the learning of programming.

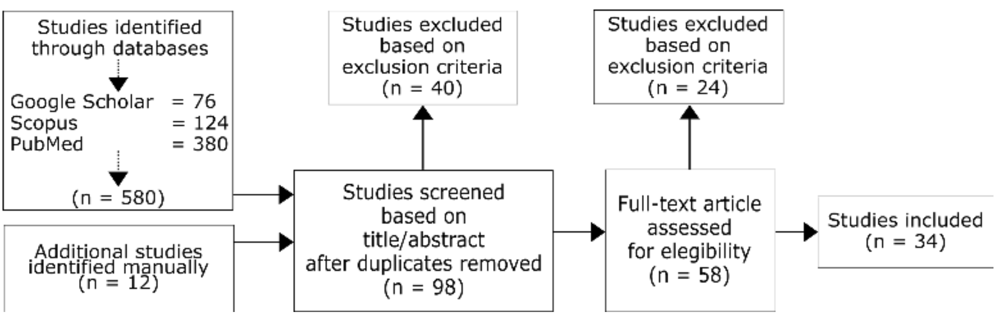

Figure 2.2: Flow diagram of the different phases of the systematic mapping study.

Multi-analysis surveillance and dynamic distribution of computational resources: Towards extensible, robust, and efficient monitoring of environments

- Title: Multi-analysis surveillance and dynamic distribution of computational resources: Towards extensible, robust, and efficient monitoring of environments [1]
- Authors: Javier Albusac, David Vallejo, Jose J. Castro-Schez, Santiago Sanchez-Sobrino, Cristian Gomez-Portes
- Type: Journal
- Journal: Expert Systems With Applications
- Publisher: Elsevier
- E-ISSN: 0957-4174
- Year: 2021
- DOI: 10.1016/j.eswa.2021.114692
- Category: Computer Science, Artificial Intelligence
- Impact Factor (2020): 6.954
- JCR Ranking: Q1
- Related to the current research topic: No, although this work has been a key part of this research by studying how to establish theoretically the architecture of a system. Furthermore, this proposal has made it possible to outline the foundations of the monitoring of Key Performance Indicators (KPIs) to analyse the patient's performance in a game.
- Related figure(s): 2.3
- Abstract: Intelligent surveillance has been a hot area of research for the past two decades. However, the integral security of environments remains a challenge due to the presence of new types of threats and the very dynamism and complexity of these environments. To make further progress, new proposals are needed to facilitate the design and deployment of multi-analysis surveillance systems where different types of analysis are simultaneously performed and the available computation resources are limited. Such systems need to provide three main characteristics: extensibility, robustness and efficiency. Extensibility to add new analysis components when new events of interest must be monitored. Robustness to avoid that failures in one analysis component affect the rest. Efficiency to analyse environments in real-time and to support decision-making processes that address the detected anomalies. This paper proposes a formal model for the multi-analysis surveillance of environments by means of the named

components of normality, designed to deploy surveillance systems that satisfies the three previously mentioned characteristics. Extensibility thanks to the activation and deactivation of components of normality based on the monitoring needs of the analysed environment. Robustness as a result of the isolation of these components such that a failure in one of them does not spread to the rest. Finally, efficiency due to the dynamic allocation of resources that benefits the components that detect anomalies at a given time. The experimental results prove that such dynamic allocation improves execution times and reduces.

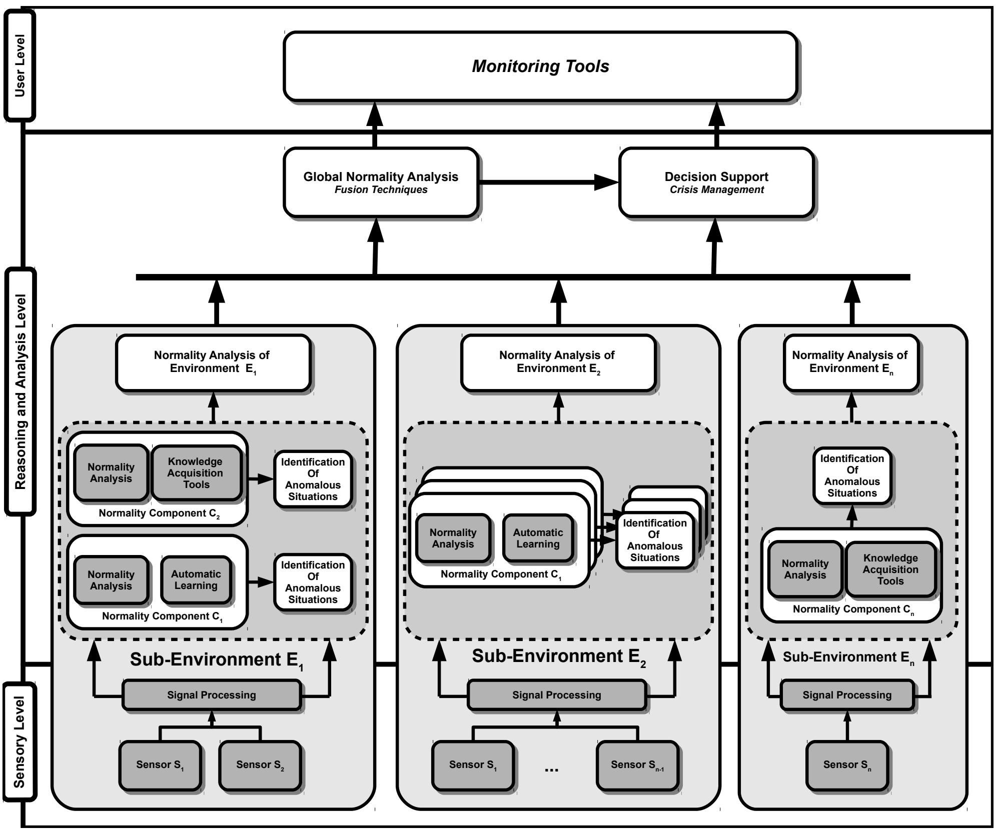

Figure 2.3: Proposed architecture of a general purpose surveillance system based on components of normality.

A Platform Based on Personalized Exergames and Natural User Interfaces to Promote Remote Physical Activity and Improve Healthy Aging in Elderly People

- Title: A Platform Based on Personalized Exergames and Natural User Interfaces to Promote Remote Physical Activity and Improve Healthy Aging in Elderly People [18]
- Authors: Cristian Gmez-Portes, David Vallejo, Ana-Isabel Corregidor-Sánchez, Marta Rodríguez-Hernández, José L. Martín-Conty, Santiago Schez-Sobrino and Begoña Polonio-López
- Type: Journal
- Journal: Sustainability
- Publisher: MDPI (Basel, Switzerland)
- E-ISSN: 2071-1050
- Year: 2021
- DOI: 10.3390/su13147578
- Category: Green, Sustainable Science, Technology
- Impact Factor (2020): 3.251
- JCR Ranking: Q3
- Related to the current research topic: Yes.
- Related figure(s): 2.4
- Abstract: In recent years, there has been a significant growth in the number of research works focused on improving the lifestyle and health of elderly people by means of technology. Telerehabilitation and the promotion of physical activity at home have been two of the fields that have attracted more attention, especially currently due to the COVID-19 pandemic. However, elderly people are sometimes reluctant to use technology at home, mainly due to fear of technology and lack of familiarity. In this context, this article presents a low-cost platform that relies on exergames and natural user interfaces to promote physical activity at home and improve the quality of life in elderly people. The underlying system is easy to use and accessible, offering a number of interaction mechanisms that guide users through the execution of routines and exercises. A relevant feature of the proposal is the ability to customise the exergames, making it possible for the therapist to adapt them according to the user's needs. Motivation is also addressed within the developed platform to maintain the user's engagement level as time passes by. An empirical experiment is conducted to measure the usability and motivational aspects of the

proposal, which was evaluated by 17 users between 62 and 89 years of age. The obtained results showed that the proposal was well received, considering that most of the users were not experienced at all with exergame-based systems.

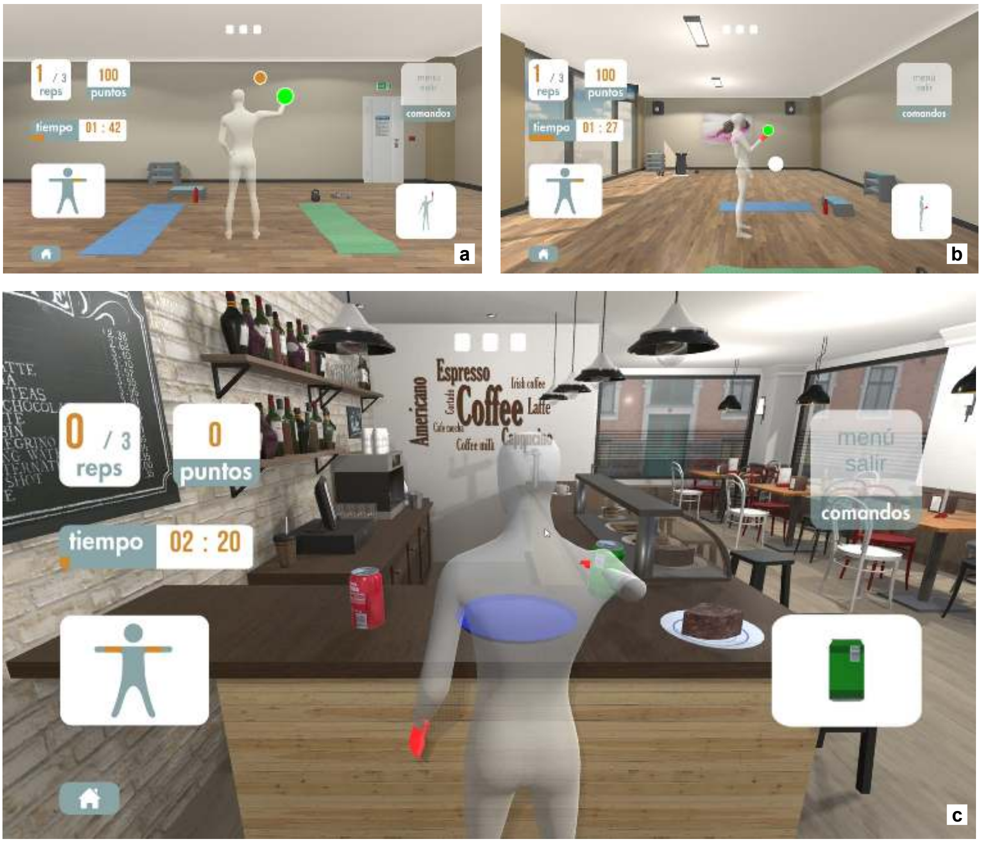

Figure 2.4: Physical exercises used in a conducted experiment. (a) Shoulder abduction, (b) elbow flexion, and (c) restaurant exergame.

2.3 Books or chapters published

A Modern Approach To Personalize Exergames for the Physical Rehabilitation of Children Suffering from Lumbar Spine

- Title: A Modern Approach To Personalize Exergames for the Physical Rehabilitation of Children Suffering from Lumbar Spine [35]
- Authors: Cristian Gmez-Portes, Carmen Lacave, Ana I. Molina, David Vallejo and Santiago Schez-Sobrino
- Type: Chapter
- Publisher: Springer
- ISBN: 978-3-030-75417-4
- Year: 2021
- DOI: 10.1007/978-3-030-75418-1_35
- Related to the current research topic: Yes.
- Related figure(s): 2.5
- Abstract: Physical rehabilitation of people with injuries or illnesses related to the lumbar spine involves an intensive treatment to reduce pain or improve mobility. Research studies have evidenced the benefits of complementing the patient's regular treatment with exercise routines at home. However, in the case of children and adolescents, there is a risk of abandoning the exercise routine if it is not motivating enough. Currently, there is a trend which consists in using games for rehabilitation exercises, called exergames, as a possible solution for motivating patients while they perform physical rehabilitation. However, both customising and creating them is still a task that requires considerable investment both in time and effort. Thus, this paper presents a language along with a system based on the physical rehabilitation of children suffering from some sort of lower back pain, which enables the customisation and the automatic generation of exergames. We have conducted an experiment with children for evaluating the capabilities of our approach. The obtained results show that the tool is fun, interesting and easy to use.

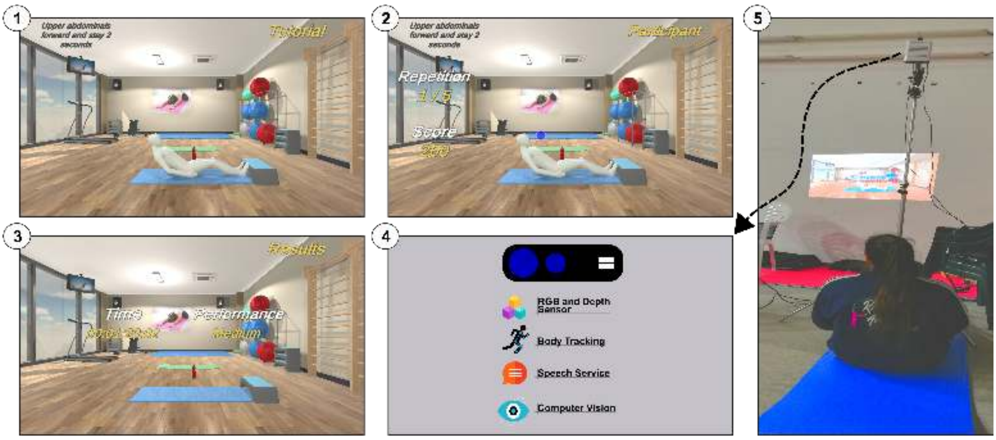

Figure 2.5: Views of a rehabilitation system for children suffering from lumbar spine. (1) tutorial view. (2) Participation view. (3) Result view. (4) Features of the Azure Kinect DK™ device. (5) User using the system.

2.4 Articles presented in national and international conferences

Propuesta y Evolución Multidimensional de una Metáfora Visual para Facilitar el Aprendizaje de la Programación

- Title: Propuesta y Evolución Multidimensional de una Metáfora Visual para Facilitar el Aprendizaje de la Programación [35]
- Authors: Santiago Sánchez, Maria de los Ángeles García, Cristian Gómez, Carlos González, David Vallejo, Javier Alonso Albusac, and Miguel Ángel Redondo
- Type: Conference
- Conference: XX International Conference on Human-Computer Interaction
- Location: Donostia, Spain
- Year: 2019
- Awards: **Jesús Lorés award to the best research article**
- Related to the current research topic: No, although the design of this research has allowed to acquire the knowledge necessary to conduct experiments, analyse data, discuss the results obtained and draw conclusions. This experience has been applied to present the results of this doctoral dissertation.
- Related figure(s): 2.6
- Abstract: Computer programming is a complex task and a challenge for students who are starting to take an interest in it. Specifically, students in the first year of the Bachelor of Engineering in Computer Science show certain difficulties in understanding programming concepts due to the high level of abstraction required for their learning. This process of learning programming can be facilitated by graphical representations that allow the student to establish analogies between the concepts it seeks to understand and other elements of the real world. The current literature proposes certain approaches that provide different alternatives to visualise programs and algorithms, either statically, showing their structure, or dynamically, showing their execution. Some of these approaches limit the potential of visualisation by focusing on showing the source code of programs over a virtual world; others try to explain specific concepts of programming in isolation, causing the student to lose the context of the entire program. This work introduces the proposal and evolution of a new set of graphic representations towards a 3D environment of augmented reality, based on the metaphor of roads and traffic signs, and which

aims to facilitate the learning of programming to beginner students. The visualisations generated from these graphical representations can be constructed automatically thanks to their modular design and used by teachers in order to explain programming concepts during master classes. The proposal has been evaluated with students in order to validate whether the proposed notation is appropriate to represent the concepts it tries to abstract and easy for students to understand.

Aplicación de una metáfora flexible y extensible para la visualización de programas en el contexto del aprendizaje de la programación

- Title: Aplicación de una metáfora flexible y extensible para la visualización de programas en el contexto del aprendizaje de la programación [16]
- Authors: Cristian Gmez-Portes, Santiago Schez-Sobrino, María A. García, Miguel Á. Redondo, Javier A. Albusac, and Manuel Ortega
- Type: Conference
- Conference: XXI International Symposium on Computers in Education (SIIE)
- Location: Tomar, Portugal
- Year: 2019
- ISBN: 978-989-8840-39-4
- Related to the current research topic: No, although the experience acquired in this work developing a scenario based on agents to learn programming concepts has had a direct impact on the implementations of the serious games for physical rehabilitation.
- Related figure(s): 2.7
- Abstract: El aprendizaje de la programación es un campo de investigación con publicaciones relevantes de más de 25 años. Desde sus inicios, se ha demostrado que su dificultad depende del alto nivel de abstracción que ciertos conceptos de programación son requeridos por los estudiantes. Sin embargo, dicho nivel puede reducirse utilizando representaciones gráficas que motiven a los estudiantes y faciliten su comprensión, asociando elementos del mundo real con términos específicos de programación. Así, este trabajo muestra la notación ANGELA, una metáfora de carreteras y señales de tráfico utilizada para visualizar dinámicamente la ejecución de un programa con un vehículo viajando por su estructura ejecutando sentencias. Dichas visualizaciones se pueden ejecutar en una variedad de entornos, los cuales soportan diferentes mecanismos de interacción

dependiendo de la dimensionalidad de las representaciones gráficas. Además, este trabajo destaca la flexibilidad y la extensibilidad de la propuesta mediante su aplicación en diferentes casos de uso, junto con una metodología que hemos seleccionado a modo de ejemplo para mostrar cómo la notación podría ser explotada en un escenario real de aprendizaje.

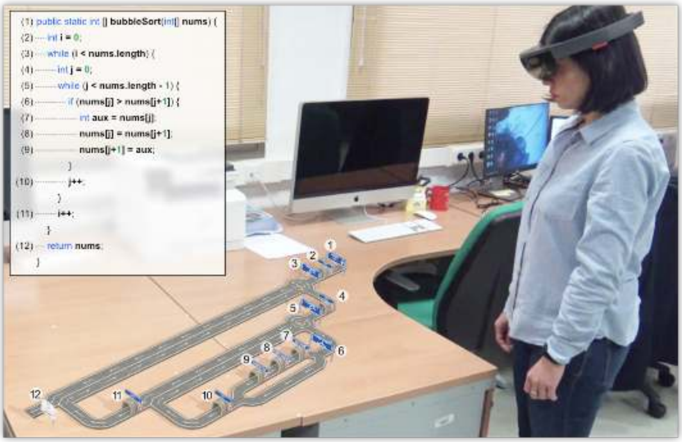

Figure 2.6: A photo taken of a user testing the system to visualize programs represented through the ANGELA notation along with the overlayed processed source code relating each graphic representation from the visualization.

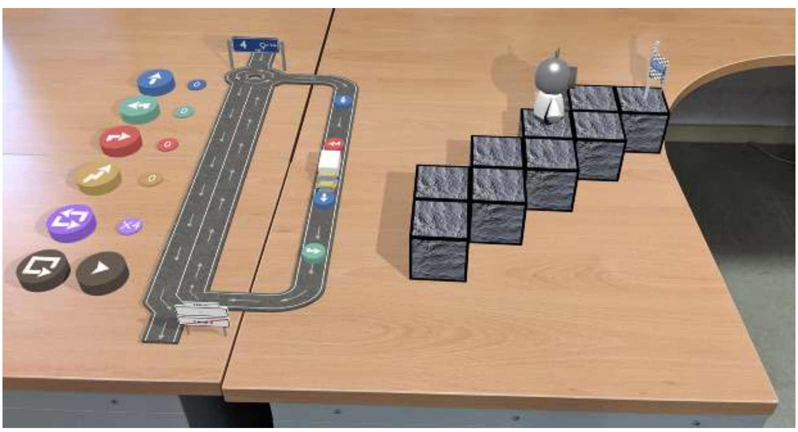

Figure 2.7: On the left side, it is shown the program composed of roads and traffic signs based on the sequence of actions given by the user. On the right side, the main character solving the challenge from the sequence indicated by the player.

ANGELA: A Novel Approach of Graphic Notation Based on the Metaphor of Road Signs to Facilitate the Learning of Programming

- Title: ANGELA: A Novel Approach of Graphic Notation Based on the Metaphor of Road Signs to Facilitate the Learning of Programming [36]
- Authors: Santiago Sánchez, María de los Ángeles García, Cristian Gómez, David Vallejo, Ana Isabel Molina, Carmen Lacave, Carlos González, Javier Alonso Albusac, and Miguel Ángel Redondo
- Type: Conference
- Conference: VII International Conference on Technological Ecosystems for Enhancing Multiculturality (TEEM)
- Location: León, Spain
- Year: 2019
- DOI: 10.1145/3362789.3362871
- Related to the current research topic: No, although the design of the notation and the underlying specification to automatically create visualizations have had a direct impact on the creation of the PEL language. This research has allowed to acquire the foundations of language processors to design its lexicon, syntatic and semantic rules, as well as the translator mechanism to create dynamically physical rehabilitation games.
- Related figure(s): 2.8
- Abstract: Programming is a field that influences other disciplines in a transversal way, so its learning is necessary considering the emergence of new jobs that will require programming knowledge in the future. However, programming raises certain difficulties during its learning, especially in understanding programming concepts due to the high level of abstraction required. This level of abstraction can be reduced by using graphic representations that motivate the student and facilitate the understanding of certain programming concepts that arise at the beginning of the learning process. Therefore, this paper introduces ANGELA, a graphic notation based on the metaphor of roads and traffic signs that is meant to complement the learning process of beginner students who are starting to program by visualising programs. These visualisations can be automatically generated from the source code of the programs, thanks to the modular and scalable design of the notation, and used by teachers to explain programming concepts during classes. The proposal has been evaluated with students in order to validate if the notation is appropriate to represent the concepts it tries to abstract from and if it results easy for the students to understand. Additionally, some use

cases are presented in real-world scenarios in order to demonstrate the flexibility of the proposal.

COLLECE 2.0: Un sistema para el aprendizaje colaborativo de la programación sobre Eclipse, con una metáfora multidimensional para la visualización de programas

- Title: COLLECE 2.0: Un sistema para el aprendizaje colaborativo de la programación sobre Eclipse, con una metáfora multidimensional para la visualización de programas [32]
- Authors: Miguel Ángel Redondo, Santiago Sánchez, Cristian Gómez, Carmen Lacave, Ana Isabel Molina, and Manuel Ortega
- Type: Conference
- Conference: XXVI Jornadas sobre la Enseñanza Universitaria de la Informática (JENUI)
- Location: Valencia, Spain
- Year: 2020
- Related to the current research topic: No, although the work conducted during the course of the referenced research has allowed to extend the knowledge on the use of computing devices with reduced capacities as well as the different communication protocols and codification of the information. This experience has been completely useful to be applied for the software solutions developed for the work of this doctoral dissertation.
- Related figure(s): 2.9
- Abstract: Computer programming is a complex task and a challenge for novice programmers. There are a wide range of difficulties in understanding programming concepts due to the high level of abstraction required to learn them. In order to address these difficulties, we have developed the COLLECE-2.0 system, a plug-in for the Eclipse platform, which provides a real-time, distributed, collaborative programming environment. Its interface has been designed to enhance aspects related to support for group learning. In addition, our proposal makes a special emphasis on the program visualisation, incorporating a set of multidimensional graphic representations based on a metaphor. These representations are applicable to a variety of scenarios that support different interaction mechanisms, depending on the dimensionality of the graphic representations and the devices used for their visualisation. This paper describes the main details of the COLLECE-2.0 system and how it can be used in different scenarios by visualising and interacting with structural aspects of the programs and algorithms.

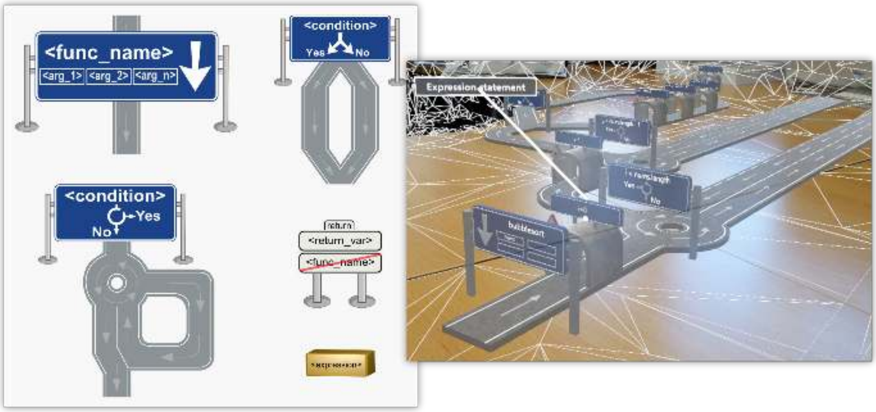

Figure 2.8: New visual and usage improvement to the 2-D (left) and 3-D (right) ANGELA notation.

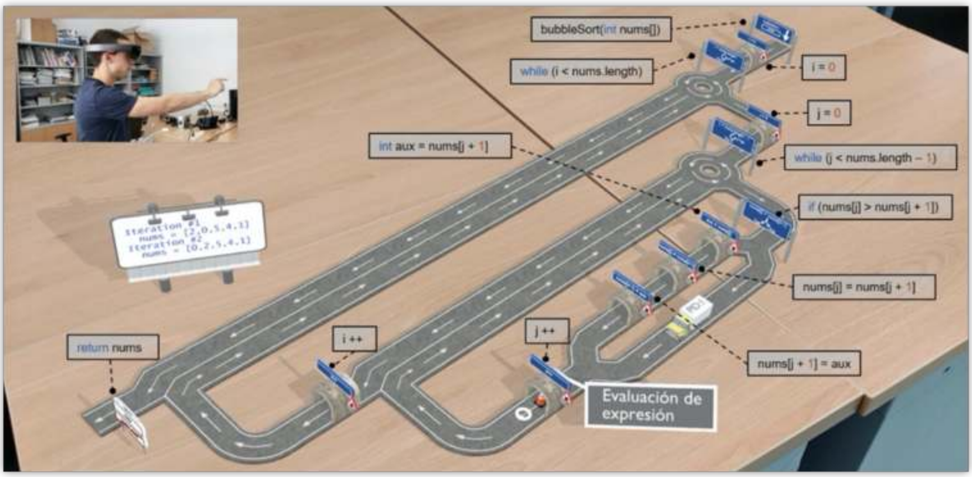

Figure 2.9: Dynamic visualizacion of the bubble sort algorithm as seen through a Mixed Reality device.

Personalising Exergames for the Physical Rehabilitation of Children Affected by Spine Pain

- Title: Personalising Exergames for the Physical Rehabilitation of Children Affected by Spine Pain [31]
- Authors: Cristian Gómez, Carmen Lacave, Ana Isabel Molina, David Vallejo, and Santiago Sánchez
- Type: Conference
- Conference: XXII International Conference on Enterprise Information Systems (ICEIS)
- Location: Online
- Year: 2020
- Awards: **Best Paper Award in the Area of Human-Computer Interaction**
- DOI: 10.5220/0009574005330543
- Related to the current research topic: Yes.
- Related figure(s): 2.10
- Abstract: Injuries or illnesses related to the lumbar spine need great clinical care as they are one of the most prevalent medical conditions worldwide. The use of exergames has been widespread in recent years and they have been put forward as a possible solution for motivating patients to perform rehabilitation exercises. However, both customiSing and creating them is still a task that requires considerable investment both in time and effort. In this project we present a language with which we have designed a system based on the physical rehabilitation of patients suffering from bone-marrow injuries, which enables customisation and generation of exergames. To assess the system, we have designed an experiment with an exergame based on the physical rehabilitation of the lumbar spine. The purpose of this was to assess its understanding and suitability, whose result reveals that the tool is fun, interesting and easy to use. It is hoped that this approach can be used to considerably reduce the complexity of creating new exergames, as well as supporting the physical rehabilitation process of patients with lower back pain.

Automatic generation of customised exergames for home rehabilitation based on physical mobility constraints and key performance indicators

- Title: Automatic generation of customised exergames for home rehabilitation based on physical mobility constraints and key performance indicators [17]

- Authors: Cristian Gmez-Portes, David Vallejo, Ana I. Molina, Carmen Lacave
- Type: Conference
- Conference: 16th International Conference on Intelligent Environments (WISHWell)
- Location: Online
- Year: 2020
- DOI: 10.3233/AISE200020
- Related to the current research topic: Yes.
- Related figure(s): 2.11
- Abstract: Remote rehabilitation systems allow the supervision and monitoring of physical exercises by therapists without the need to move, temporally and spatially, the patients who perform them. The main advantage of this approach is the patient's increased autonomy and flexibility to carry out rehabilitation from home, especially in situations of lock-down and movement restrictions. In order to make the execution of repetitive exercises more dynamic and to motivate patients to perform them from home, in recent years gamification techniques, exergames, and serious games have been extensively used. In this context, and to increase the remote monitoring capabilities of therapists, this paper proposes the use of a language for the specification of exergames oriented to the definition, by therapists, of key performance indicators and mobility constraints adapted to the rehabilitation process of each patient. The sentences of this language can be processed by software, allowing the automatic generation of personalised games for rehabilitation. A case study describing an exergame for the upper limb rehabilitation of stroke patients is also presented.

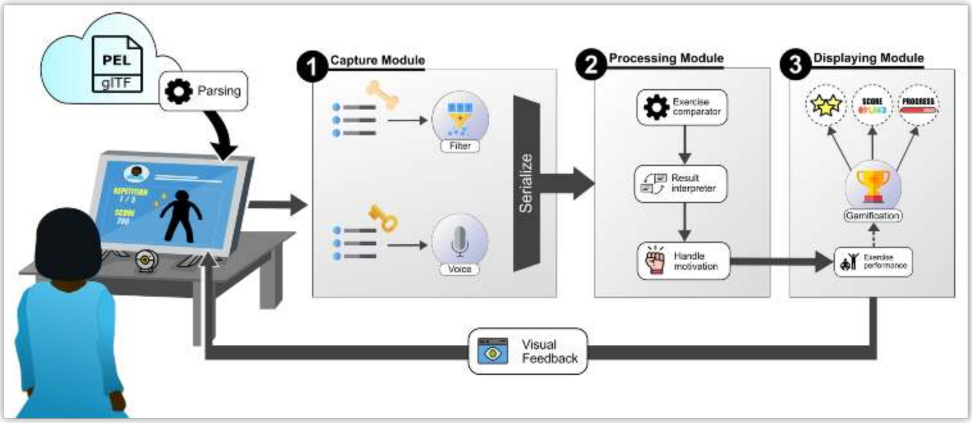

Figure 2.10: Proposed architecture for rehabilitation of patient suffering from bone-marrow injuries.

```
"constraints": [
    {
        "joint_name":  "hip-centre",
        "flexibility": "middle"
    },
    {
        "joint_name":  "spine",
        "flexibility": "low"
    },
    {
        "joint_name":  "shoulder-centre",
        "flexibility": "low"
    }
]
```

```
"metrics" : [
    {
        "kpi"    : "performance",
        "score"  : ["low", "average", "high"],
        "labels" : ["not bad", "good", "perfect"]

    },
    {
        "kpi" : "rehabilitation_time",
        "time_between_repetitions": true
    },
    {
        "kpi"    : "mobility",
        "joints" : ["shoulder-right"]
    }
 ]
```

Figure 2.11: Example of constraints and metrics used for the rehabilitation system.

3

Conclusions and Future Work

In this dissertation, a platform for physical rehabilitation has been designed and developed, which is used to carefully create and design exergames for mainly stroke and elderly patients in an autonomous home environment. This platform and its inherent tools have been validated through several studies that present the results of this work through a compendium of publications where the proposal and methods are deeply detailed.

This chapter presents a brief analysis of the results obtained in relation to the objectives and research questions originally defined, as well as new research directions for future work that emerge from the current state of play.

3.1 Achievement of objectives

The proposal for this Doctoral Thesis is based on a general research question that forms the basis of this thesis. It is divided into several specific ones, posed in section 1.3.1, in order to easily address them through smaller tasks as objectives.

To answer these questions, a main goal was defined, which consisted in the "*development of a technological platform, together with methodological guidelines, based on Artificial Intelligence to provide precision rehabilitation, taking into account the psycho-social dimension and the need for natural interaction methods that increase the patient's autonomy. It proposes a co-creation and participation approach between patients and clinicians, in which the participants involved work together to personalise the patient's rehabilitation process*".

Firstly, the scientific publications used in this doctoral dissertation, which are cited in chapter 2, have presented in depth several systematic reviews and mapping studies to cover the state of the art regarding the automatic generation of physical rehabilitation exercises, serious games and gamification in rehabilitation, motivation towards autonomous rehabilitation, immersive technologies, and their benefits in rehabilitation, among others. This has made possible to achieve the secondary objective **[Obj01, which is the review of the state of the art**.

The achievement of the first objective has led to the design and development of several solutions aimed at assisting patients in their rehabilitation. Firstly, a custom language, called PEL, has been defined to allow the automatic generation of customised exergames for patients mainly affected by neurological diseases. In essence, PEL comprises fundamental components that facilitate the setup of tools and the development of games-based exercises for physical rehabilitation. This approach establishes a co-creation framework involving various stakeholders, including therapists, technicians, and patients, in the design of rehabilitation exercises. Furthermore, its extensibility positions it as a foundational framework applicable to various physical rehabilitation contexts, such as back injuries, and more. Due to its flexible design, it can also be used in other rehabilitation contexts, such as spinal injuries.

Secondly, this solution has been adapted to support dedicated 3D environments for specific rehabilitation use cases that can be visualised through immersive AR devices. The aim is to combine gamification techniques with immersive technologies to involve the patients in the treatment as well to maintain them motivated. The underlying architecture combines declarative, procedural, and conditional knowledge to manage the rehabilitation process, which offers flexibility and scalability to enhance the capabilities of the overall system.

Thirdly, as the exercises are performed by patients at home without the constant supervision of a therapist, a sophisticated recommendation system has been meticulously designed and implemented. This innovative system operates autonomously, harnessing advanced algorithms and patient-specific data to intelligently discern and suggest the most appropriate course of action for each individual during their rehabilitation journey. By analysing the patient's progress, physical condition, and adherence to prescribed exercises, this recommendation system plays a pivotal role in ensuring that the rehabilitation process remains effective and tailored to the specific needs of each patient. It not only enhances the overall experience but also empowers patients to take a more active and informed role in their recovery, fostering a sense of autonomy and confidence in their self-directed rehabilitation efforts. This has made it possible to achieve the secondary objectives **[Obj02] Development of software systems**, **[Obj03] Artificial Intelligence for precision rehabilitation**, **[Obj04] Use of immersive technologies** and **[Obj05]**

Rehabilitation environments.

Several evaluations were also carried out to validate the solutions proposed in the scientific publications in terms of motivation, ease of use, usefulness and intention to use. The prototype which only uses the Azure Kinect DK™ was evaluated overall by 34 patients affected by neurological diseases. The assessment yielded insights indicating that the subjects found the technology to be not only intriguing but also gratifying and advantageous. Such a response is unsurprising given the nature of individuals engaged in repetitive tasks during therapeutic sessions, the very objective of which is to foster greater self-sufficiency. Additionally, these participants expressed a consensus regarding the motivating attributes of the exergames, predominantly stemming from the presentation of the system as a recreational endeavour. Furthermore, the intuitiveness of the system facilitated their engagement with minimal exertion.

The commendable reception of the prototype may be attributed to the perception among participants that its deployment holds potential for enhancing their consistency in augmenting personal autonomy. This perception is notably intertwined with the prospect of employing the system within the domestic environment, as participants suppose that it could capably guide them in the independent execution of exercises, thereby furthering their autonomy-enhancement objectives.

On the contrary, the same prototype underwent evaluation with a cohort comprising 20 female subjects, eight of whom presented various spinal injuries. The prototype received a favourable reception across all participants. However, it is worth noting that this positive reception was notably more pronounced among those who had sustained spinal injuries, an outcome that is logically to be expected. Each participant uniformly found the prototype to be user-friendly, a perception that is unsurprising given their youth and familiarity with technology. Additionally, all participants expressed a positive appraisal of the system, citing its motivational attributes and particularly highlighting the advantage of being able to engage in exercises within the confines of their homes.

Alternatively, an assessment of the mixed reality system was undertaken to substantiate the efficacy of the proposed approach in enhancing precision. A cohort of 25 anonymous volunteers was judiciously selected, a subset of whom were individuals in need of physical rehabilitation. It is noteworthy that the study was confined to upper limb exercises. The experimental protocol entailed two distinct phases: one entailing the execution of exercises with the employment of the Mixed Reality (MR) device, and the other devoid of such technology. Strikingly, the data derived from the experimental inquiry vividly demonstrates that our proposed solution significantly streamlines the intermediary stages requisite for exercise completion, a feat attributable to the provision of visual feedback. Moreover, the precision of exercise execution markedly surpasses that achievable through conventional rehabilitation techniques. Notably, the gamification-based approach employed in tandem with visual and auditory feedback plays a pivotal role in reinforcing patient engagement, as it confers rewards upon those who successfully attain predefined goals.

This has made it possible to achieve the secondary objective **[Obj06] Proposal evaluation and validation**.

Finally, the research questions formulated initially in this work can be answered affirmatively based on the results exposed in the scientific publications [42], [12], [18], where different evaluations were conducted with elderly people and patients affected by stroke. As hypothesised, the experiments demonstrate that physical exercises can efficiently be designed and developed through schemes, descriptions or specifications (**RQ1**). Apart from this, the results confirm that immersive technology improves motivation and increases interest in physical rehabilitation (**RQ2**). Also, this kind of solutions are perceived well by users, having a positive impact in terms of usability, ease of use as, well as their intention. Finally, while experiments have yet to be conducted, the integration of Artificial Intelligence via recommender systems holds great promise as a tool for aiding clinicians in making informed treatment decisions for each patient. This approach considers various factors, including clinical history and environmental variables, to tailor treatments more effectively. The experimentation phase is planned for future stages of our work to validate these promising capabilities. (**RQ3**). Therefore, the main research question (**RQ**) can be positively answered, outlining that immersive technologies along with artificial intelligence techniques can improve the usability and motivation in physical rehabilitation at home setting.

However, we aware that our research may have one limitation. Further evaluation is required to determine exactly, in the long term, how immersive technology affects motivation. Likewise, this similar evaluation should be carried out with respect to Artificial intelligence in order to validate whether the personalisation and adaptation through our system affects positively the patient condition at the end of the therapy.

However, we are currently in the process of developing proposals for projects that emphasise the clinical dimension. After completing the development phase and conducting initial usability tests, our next step will involve conducting a more comprehensive evaluation. This will help us gain a better understanding of how immersive technology impacts motivation in the long term. Similarly, we plan to extend this evaluation to include Artificial Intelligence to determine if the personalisation and adaptation provided by our system positively influence the patient's condition at the conclusion of therapy. This multifaceted approach will ensure a more comprehensive assessment of the impact of our technologies on patient well-being.

3.2 Future work

This section proposes some general directions for future work in the field of home rehabilitation and exergames, based on the the current state of the art and the results obtained in this doctoral dissertation.

- **Integration of Findings into Rehab-Immersive**. An immediate direction for the future is the integration of the findings and methods from this thesis into the Rehab-Immersive[1] project by the AIR Group. The results of this thesis indicate that VR can play a crucial role in upper limb rehabilitation, enhancing the effectiveness and motivation of the recovery process. The cloud-based platform being developed in Rehab-Immersive, leveraging VR, offers a unique opportunity to apply and validate the proposed rehabilitation approaches and protocols from this research. This could allow for mutual enrichment and optimisation of outcomes in both projects.
- **Personalisation and Custom Adaptations**. One of the most exciting aspects that this thesis underscores is the potential for personalisation and continuous adaptation of exercises. Based on the new Large Language Models and machine learning algorithms, clinical and user performance data could be used to tailor much better rehabilitation sessions on an individualised basis. This not only would enhance the efficacy of rehabilitation but could also reduce costs and workload for healthcare professionals.
- **Expsansion of Application Areas**. Beyond upper limb, lower limb or spine pain rehabilitation, VR holds significant potential in various health and well-being-related fields. Rehab-Immersive could consider expanding its platform to include rehabilitation therapies for other body segments, such as hand and fingers when patients suffer sclerosis. The platform could become a versatile ecosystem addressing a broader range of medical and therapeutic needs.
- **Interdisciplinary Collaboration and Clinical Validation**. Interdisciplinary collaboration is crucial for the successful integration of the findings from this thesis into the Rehab-Immersive project. Cooperation with healthcare professionals, occupational therapists, and physicians is essential to ensure the safety and effectiveness of VR therapies. Moreover, rigorous clinical validation must be conducted to demonstrate the efficacy of VR therapies and their capacity to improve rehabilitation outcomes.
- **Scaling and Broadening the Scope**. Involving collaboration with rehabilitation centres on a national and international level could create user communities and explore the possibility of establishing strategic partnerships with medical technology and VR technology companies.

[1] https://air.esi.uclm.es/rehab/

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