Development of a Serious Game for Ankle Rehabilitation with T-FLEX

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Undergraduate Project

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Abstract

Stroke is the second cause of disability in the world. Although conventional physical therapy effectively improves the sequelae and restore function and quality of life for stroke survivors, repetitive exercise therapy may cause a lack of interest and demotivation. Results from literature show that the inclusion of advanced technology and robotic devices potentially increase and enhance patient's efficiency in therapy. T-FLEX ankle exoskeleton showed improvement in motor recovery but exhibited a lack of interaction with the patient during the session. Hence, the inclusion of feedback strategies, such as serious games, proves to be a significant improvement in these areas. This project introduces the development and preliminary verification of the healthy subject based on a serious ankle rehabilitation game after stroke.

Initially, a theoretical perspective was adopted from the review and interpretation of documents focused on motor learning and cognitive rehabilitation to develop this project. Additionally, feedback mechanisms and recent research on implementing serious video games for ankle rehabilitation were analyzed. Principles and elements in the design of games for therapy with robotic devices were defined. The design principles included rewards, challenges, clear objectives (i.e., both at the game and the therapeutic level), and evaluating performance methods. A serious 2D adventure game controlled by plantar and dorsal flexion movements to jump on enemies was developed. The developed environment has motivational strategies before, during, and after the game. Also, the game included visual and auditory feedback in the form of messages.

The game, Jumping Guy, was assessed in a healthy subject for five minutes for each level considering two conditions: with and without wearing T-FLEX. The adaptability and usability evaluations were performed through the game results (e.g., score and progress over time). Finally, a test was carried out to quantify the participant’s level of satisfaction.

The results demonstrate a complete interface with strategies that included a calibration stage, a tutorial, and even a database to store the information. In terms of the game results, an average precision greater than 95% could be observed. The results did not vary significantly using and not using the exoskeleton. However, greater adaptability was observed without using the device. Following this, it was concluded that the game could potentially be used in pathological patients. However, the game's design must consider the session time decrease or additional graphic strategies to capture the user's attention during several sessions. In the future, it is expected to combine the game with other strategies to achieve the final objective of implementing it as an affordable rehabilitation strategy at home.

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1. INTRODUCTION

This first chapter presents the general motivation and the theoretical framework of the work presented in this thesis. This work's motivation includes world statistics of stroke, advantages of using robotics in therapy, and the need for feedback. The project is articulated with the T-FLEX exoskeleton that frames the study for ankle rehabilitation. From this, the study's objectives are presented in addition to the contributions and the document organization.

1.1 Motivation

The World Health Organization (WHO) defined disability as a problem in body function or structure, limiting or making it difficult to execute a task or an action. There are currently more than 2 billion disabled people globally, 37.5% of the world's population [1]. In Colombia, around 15% of the population has disabilities, where about 44% of them have alterations in the nervous system [2], [3]. Nevertheless, according to the Global Burden of Disease Study (GBD), stroke is the second cause of death globally and one of the leading causes of disability [4]. Approximately 90% of stroke survivors have impairments associated with severe and long-term reduction in functionality [5]. The expected prevalence of stroke will affect 350 million people by 2030, close to 5% of the world population [6].

After a stroke episode, one or more effects may be triggered, such as muscle weakness, hemiparesis, hemiplegia, fatigue, and spasticity [5]. In hemiparesis, the loss of capacity to generate normal muscle force levels reduces the paretic lower limb's capacity to maintain normal functions like balance and posture. Hemiparesis can also make difficult the initiation and control of movement. Foot problems after a stroke are common and harm mobility [7]. Although there is limited information regarding the ankle after stroke, about one-third of stroke survivors have abnormal or asymmetrical foot posture that causes walking difficulties [8]. Those affectations are related in turn to limitations in the execution of different Activities of Daily Living (ADL), restriction in participation, and a high degree of dependency on third parties [5].

Conventional physical therapies help counteract those after-effects and recover functionality and quality of life for the survivor. However, the inclusion of robotic devices (e.g., powered ankle-foot orthoses) in motor rehabilitation programs has been shown to improve automatic repetitive training after stroke [9]. Advanced technology for gait rehabilitation allows the patient to achieve the highest level of functional independence. Thus, it is offered a therapeutic advantage to promote new motor skill acquisition and training to stimulate restorative neural plasticity [10][11].

Despite the advantages of robotic devices in the therapeutic setting, there is a challenge associated with patient adherence and motivation to determine rehabilitation outcomes [12], [13]. The motivation and adherence of patients to robot-aided treatments can be significantly influenced by the biomedical robot's design features, besides the motor task's difficulty level, the awareness of the performance obtained, and the quantity and quality of feedback presented to the patient [13]. Low motivation and engagement with physical therapy are real and prominent concerns that significantly affect therapy's success; situations like these make repetitive exercises uninteresting and tedious [14]. In this context, serious games are video games designed for a specific function where the user can achieve a particular therapeutic purpose through participation in the interactive experience [15]. The combination of these both pedagogical and entertainment components, through serious games, can offer the potential for a significant therapeutic benefit to engage a person’s attention [16].

This project aims to present an interactive interface based on serious games that integrate different ankle neurorehabilitation feedback mechanisms with T-FLEX. In this way, strategies to promote motivation, concentration, and commitment to patients' therapy with ankle dysfunctions are proposed. Moreover, the present work aims to carry out and report a first usability evaluation with a non-pathological user.

1.2 Related Project

T-FLEX is a portable ankle exoskeleton that incorporates bioinspiration and variable stiffness performance (Figure 1). The main objective of this exoskeleton is to help the dorsiflexion-plantarflexion movements of the ankle joint without restricting the other movements (i.e., eversion, inversion, pronation, and supination) [17], [18]. T-FLEX emulates muscle functions using bidirectional agonist-antagonist action and incorporating a flexible composite material with a mechanical behavior similar to the Achilles tendon. Therefore, T-FLEX employs an electrical actuation mechanism through two servomotors (Dynamixel MX106T, Robotics, USA) positioned at the back and front of the user's leg. These motors are linked in the elastic elements fixed to the user's heel and forefoot using a personalized insole [17].

Figure 1. T-FLEX Ankle Exoskeleton [15].

The orthosis functions in two different ways: the gait and the therapy mode. In gait mode, the sensors detect the gait phase to control the actuators and assist foot movement (Figure 1)[17]. In contrast, therapy mode consists of repetitive and configurable flexion and extension movements of the ankle [18]. After a case study with a stroke survivor, this device's therapy mode improved the patient's motor recovery and reduced spasticity. Moreover, the results showed that during the therapy session, the participant exhibited improved ankle control underway [18]. However, despite the multiple benefits of rehabilitation with the T-FLEX orthosis, there was a lack of interaction with the rehabilitation program [18]. Considering the above, including user interaction with the T-FLEX therapy mode would improve the results already obtained with the device and also contribute to the user's commitment to it.

1.3 Objectives

1.3.1 General Objective

Develop a serious game that allows the integration of feedback mechanisms in assisted neurorehabilitation with the T-FLEX ankle exoskeleton.

1.3.2 Specific Objectives

- Perform a literature review to understand the different feedback mechanisms in rehabilitation and implementing serious games in ankle rehabilitation.

- Develop a serious gaming platform that encourages the user's motivation and commitment in the therapeutic process assisted with T-FLEX.

- Evaluate the platform usability in a non-pathological participant.

1.4 Contributions

The development of this undergraduate project made the following contributions regarding the integration of a visual and interactive interface in the robotic rehabilitation field:

- The approach of the main criteria and considerations for developing a serious game in rehabilitation after stroke.

- Design and integration of the first version of a serious game in T-FLEX exoskeleton that motivates increases the concentration and challenges the motor recovery process.

- Preliminary experimental protocol to validate the video's performance with the device and the participant’s experience, adaptability, and satisfaction level with the interface.

1.5 Publications

Contribution of “T-FLEX Ankle Exoskeleton with a Serious Game for Stroke Rehabilitation” by **Angie Pino**, Daniel Gomez-Vargas, Marcela Múnera, and Carlos A. Cifuentes in “WeR11. Digitalization and Artificial Intelligence applied to Wearable Technologies and Ergonomics” at International Symposium on Wearable Robotics (WeRob2020) (Appendix 1).

1.6 Document Organization

This document contains six chapters divided into Introduction, Literature Review, Methodology, Results and Discussion, Conclusions, and Recommendations and Future Works.

The second chapter presents the Literature Review. Initially, it is presented the theoretical framework by which this study is supported. This chapter considers concepts such as motor learning, neurorehabilitation, feedback (i.e., definition, types, display modalities, and strategies), and video games in rehabilitation. Finally, it presents a literature review of recent studies related to ankle rehabilitation using robotic devices and serious games to motivate physical therapy.

The third chapter presents the methodology used in this project. First, the game's methodology is established according to the strategies reviewed in the literature. Then is carried out the development of the interface, describing the process and tools used in its design. After this, the data acquisition module, calibration process, and integration method with the T-FLEX exoskeleton are explained. It is described as a protocol for the integration and usability evaluation of the designed multimodal strategy.

Following, the fourth chapter shows the results and discussion of the data obtained after following the methodology. It considers the virtual environment's qualitative evaluation, the video game metrics oriented to user performance and user perception.

Chapter fifth presents the conclusions and the fulfillment of the objectives initially set. The last chapter of this document has the recommendations and future works divided into short, medium, and long term.

2. LITERATURE REVIEW

This chapter presents a theoretical perspective on motor learning, neurological rehabilitation, and feedback mechanisms. Furthermore, a literature review is presented with the latest research on implementing serious video games in neurorehabilitation.

2.1 Ankle Biomechanics

The ankle is made up of thirty-three bones and joints that include long bones of the lower limb. Most of the foot and ankle movement is produced by twelve external muscles, which facilitate human gait. The ankle complex's critical movements are plant flexion and dorsiflexion that occur in the sagittal plane; ab-/adduction occurs on the cross-section, and inversion-eversion occurs on the frontal plane (Figure 2). The range of motion (ROM) of this joint is different, caused by individuals' geographical and cultural differences in daily life [19].

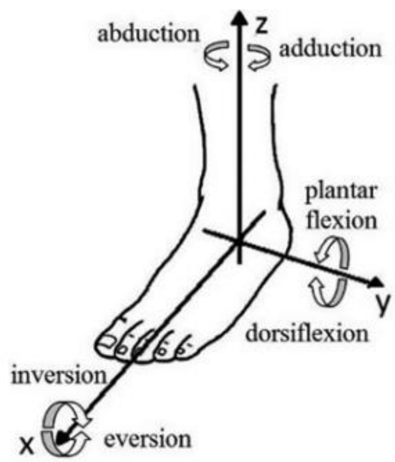


Figure 2. Rotational ankle movements [20].

The primary deficit after stroke is the loss or reduction of descending input to the spinal centers that result in the incapability to activate muscles voluntarily and in a reduced muscle force [21]. The gait analysis results showed an increase in the ankle joint's stiffness and insufficient dorsiflexion due to motor disability. In this case, the spastic ankle tends to show over 50% more resistance than the average ankle in the displacement [22]. The biomechanical changes at the ankle joint after stroke are associated with muscle fibers' changes in the gastrocnemius or the triceps. The restricted movement range is a significant factor behind the increase in the Achilles tendon's passive stiffness [22].

Other complications following the impaired ankle function include sports-related ankle sprains, spastic cerebral palsy (SCP), and even age-related degenerative processes (e.g., osteoarthritis) [19]. Each pathology has its impairments because while joint injuries or damage are related to ankle instability, neurological injuries are related to a foot drop (i.e., difficulty lifting the front of the foot) [23], [24], [25]. In this way, in cerebrovascular diseases, the therapeutic objective via rehabilitation is to recover independence and improve quality of life, helping the patient to re-learn the skills that have been lost when part of the brain was affected [25].

2.2 Rehabilitation and Motor Learning

Rehabilitation is considered when people with motor and cognitive impairments achieve functional independence through targeted exercise [26]. The rate of functional improvement has been demonstrated to be faster in the lower limb, during activity rehabilitation, than in the upper limb [27]. However, regaining the skills practiced depends mainly on processes that involve cognitive and motor methods related to practice or experience [26].

Motor learning implies the acquisition of skilled movements through practice [28]. It leads to changes at neurological or performance levels, supported in part by the implicit memory system or by the effect of explicit information in the form of feedback. Notably, for exercise relearning after stroke, variable exercises may be more beneficial than closed exercises [26]. This type of practice and its intensity is related to exercise dependent neuroplasticity, task-specific practice, and motivation to optimize motor learning and recovery [26]. An improvement in motor learning has been found due to the perception of self-control during training employing physiotherapy practice, feedback, and physical assistive devices [26].

2.2.1 Neurological Rehabilitation

Neurorehabilitation is related to the facilitation of adaptive learning based on experience and learning processes [29]. The brain structure, including the striatum, cerebellum, and motor cortex regions, are essential for obtaining and maintaining skilled movement. Early learning mainly involves the cortical-cerebellar-thalamocortical circuit loop, and late learning includes the cerebellar motor system and the cortico-basal ganglia-thalamocortical loop. Since well-learned movements are developed, cortical-striatal and cortico-cerebellar systems have a functional contribution to motor learning and skill acquisition [30]. The striatal system involved motor planning, reward-based evaluation, movement control, and execution, while the cerebellar motor circuit is related to temporal aspects of movements [26]. In this way, it is essential to emphasize that stroke's impact wholly abolishes any neural processes involved in implicit motor learning and retention. The main types of stroke damage affect the motor cortex, sensorimotor cortex, and basal ganglia [26].

2.2.2 Neuroplasticity

Neuroplasticity is how the brain reorganizes its structure, functions, and connections to respond to intrinsic or extrinsic stimuli [29]. Neuroplasticity is the principal objective of any neurorehabilitation system related to the brain's ability to change in response to learning processes or gradual recovery from brain damage [11], [31]. In neurological rehabilitation, motivation, attention, and skill acquisition promote optimal learning and are also vital factors in the success of therapies to induce neuroplasticity [27], [30]. It has been shown that enhancing neuroplasticity during poststroke rehabilitation might help patients overcome their motor impairments [32], [33].

2.3 Feedback

It is suggested that regaining skills is the product of repetitive motor activities, and providing feedback is an integral part of the relearning process after stroke [34]. The term "feedback" in human performance systems is the information about the movement outcomes or movement performance [30]. Feedback stimulates goal pursuit in two ways. It can be positive when goal commitment increases or negative when the goal progress is insufficient [35].

On the other side, feedback information could be or not related to the movement the person is learning. In the case of being related to the movement, it is categorized as either intrinsic (or inherent) or extrinsic (or augmented feedback) (Figure 3) [30].

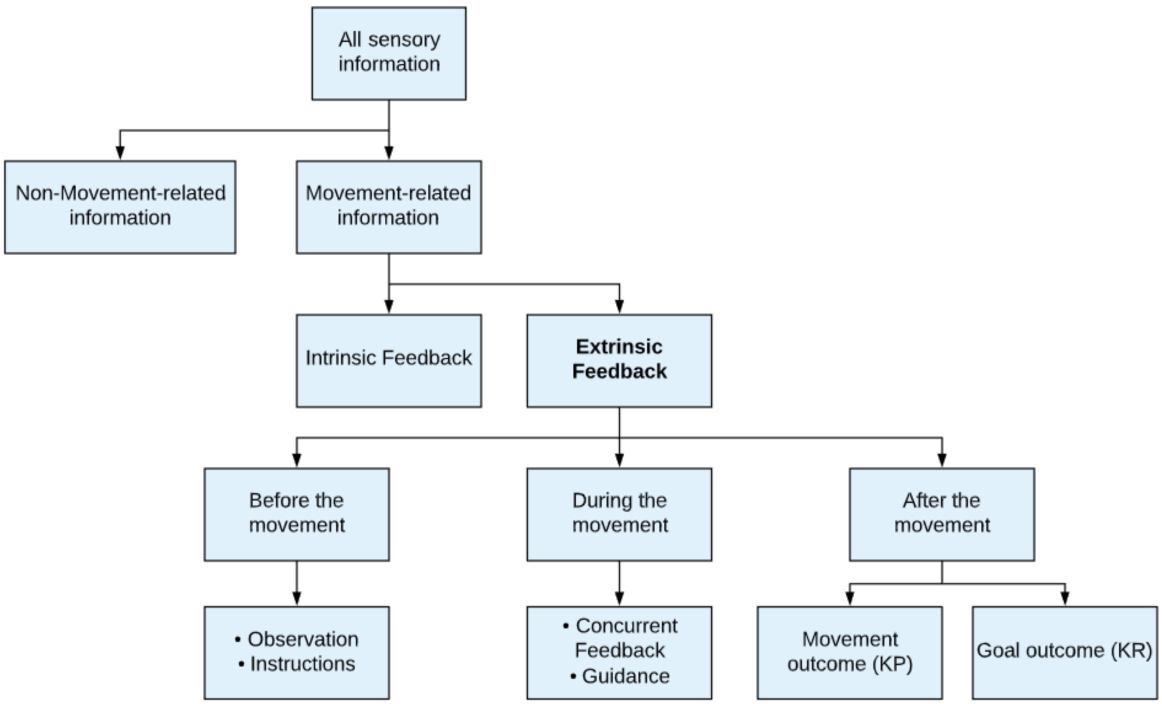


Figure 3. Feedback classification scheme according to the type of information given to the user. Inspired by [18].

2.3.1 Intrinsic Feedback

Intrinsic feedback refers to the information received through the sensory-perceptual system as a natural consequence of making an action (i.e., visual, auditory, or motor sensation) [30], [34]. Generally, intrinsic feedback is compromised after stroke, making it difficult for the patient to determine what needs to be done to improve his performance. In this way, extrinsic feedback is the most critical mechanism for post-stroke patients [36].

2.3.2 Extrinsic Feedback

Extrinsic feedback, also known as Augmented feedback, consists of all learners' information from an external source and intrinsic feedback by some artificial means [30]. This feedback is information that can be controlled. Therefore, it can be given or not, given at different times, and given in different forms (i.e., non-verbal, verbal information, or by the environment) to influence learning [30].

Providing biological information or measurements of a biomedical variable to patients in real-time is known as biofeedback. In physical rehabilitation, biofeedback can be categorized as either physiological (i.e., from the neuromuscular, respiratory, or cardiovascular system) or biomechanical (i.e., measurements of movements, postural control, and force). It has been shown that providing biofeedback during rehabilitation allows the user to improve the accuracy during functional tasks, increase engagement, and reduce the need to contact the healthcare professionals continuously [37].

In general, augmented feedback could produce the motivation to increase effort, provide information about errors as a basis for corrections, and direct the learner’s attention toward the movement goal [30].

- **Motivational Properties:** An essential function of feedback is to motivate learners to act as a “stimulant” to improve the effort to take on tasks. Casual commentaries, giving relatively frequently, motivates to keep going a little longer in practice. Letting learners understand their progress usually translates to more effort for the task, which will benefit their learning [30].

- **Informational Properties:** An essential part of motor learning feedback is its information about the action pattern. This feedback is about error guides for improving future performance [30].

- **Attentional-Focusing Properties:** The main objective of this feedback is to improve performance and learning. This is accomplished by directing the subject's attention to achieving the movement's goal [30].

As seen in Figure 3, extrinsic feedback can be classified considering whether it is performed: before, during, or after the movement. At the point of movement initiation, the feedback focuses on the observation and instructions specifying the operations to be done, their sequencing, and their timing, after and during the movement, including strategies used to differentiate at the moment a process that has been carried out correctly or incorrectly [30].

2.3.2.1 Feedback After the Movement

There are two categories within the augmented feedback. One of these is the Knowledge of Results (KR) related to the information about the success of action concerning the environmental goal. The other category is the Knowledge of Performance (KP), which is information about the movement pattern the learner has just made [30]. In patients with chronic stroke, KP is more effective than KR in learning different tasks [38].

2.3.2.2 Feedback During the Movement

The information given during the movement is used to adjust ongoing actions by providing a basis for correcting errors and improve the movement closer to the action goal [30]. It is used in two methods:

1. **Concurrent feedback**, in which enhanced information about movement errors is provided through verbal, visual, or auditory means [30].

2. **Physical guidance**, through physically restricted guidance devices, to send tactile or motor-sensory information to learners [30].

In a stroke, physical guidance is often used in rehabilitation, based on statements where learning is a repetitive process that, in optimal ways, results in more learning than repeating an incorrect movement. These techniques supported by a robotic device avoid fatigue during a therapy session and improve the number of repetitions performed [30].

In this case, feedback can be positive or negative. Positive feedback enhances or amplifies the person's performance, while negative feedback corrects and regulates its execution. It has been shown that in rehabilitation, it is crucial to handle failure in a positive way. Therefore, patients would not feel failure from their physical limitations and they would be more likely to remain engaged [39].

2.3.3 Feedback Mode or Display Modality

In addition to conventional therapies' verbal performance, the patient's information can be presented via visual displays, auditory, vibrotactile, or multimodal feedback (multiple modes) [40]. It has been found that providing information with any of these strategies can enhance motor learning in user’s stroke rehabilitation [31], [36].

2.3.3.1 Haptic Feedback

Haptic Feedback is intended to induce a kinesthetic sensation that allows us to touch, feel, and interact with an object in the virtual world. It is generally used to complement other senses, such as sight or hearing [41]. Haptic signals seem to be suitable for conveying timing information [11]. Some studies have found this technique useful and low-cost to improve stroke patients' gait symmetry [42]. Besides, recent evidence demonstrates increased excitability of tibial anterior and corticospinal muscles and improved performance after training with a robotic ankle exoskeleton that includes this adaptative feedback [43].

2.3.3.2 Auditory Feedback

Auditory Feedback represents an audio signal automatically generated and played back to the user in response to his actions. It is used in many rehabilitation systems to stimulate the patient’s performance, usually in in-game or virtual reality environments [44]. Nevertheless, in most robotic therapy systems, it is used as background music or task completion tasks. In [44] the auditory technique's use was proposed to reduce the patient's visual distraction during robot-assisted movement training. In this case, the feedback was provided in sequences of simple tonal beeps, in which the repetition rate was proportional to the position tracking error. The results confirm using this feedback mode to provide additional and alternative information and increase effort and performance during the exercises' execution [44].

Another study investigated the influence of two kinds of auditory feedback on the kinematics of hemiplegic stroke patients. Simple feedback consisted of an increasing volume as soon as the patient approaches the target, and spatial feedback was related to the orientation to the target. It was found that auditory feedback is not suitable for spatial guidance. This was argued due to the higher patient's dependence on visual feedback to ensure constant movements. In this way, auditory feedback may not be suitable for providing knowledge of performance in stroke patients. They claim that brain disease may make it difficult for patients to distinguish the characteristics and changes in sounds [38].

In [45] auditory feedback was designed to help improve a patient's fluency during therapy. In this occasion, music's temporary nature is used to indicate qualities such as smoothness/jerk and speed of movement. In this sense, musical gestures to movement variations have highly encouraging results in patients and improved both the speed and smoothness of stroke rehabilitation movements [45].

2.3.3.3 Visual Feedback

Visual Feedback considers information based on graphical illustrations to change body perception and stimulate optimal movement patterns. Usually, this technique used visual demonstrations, images shown in a monitor, image projection, video recording, videogames, and even virtual reality [46].

A study realized to examine the effects of visual feedback training shows that visual feedback improved balance ability when the ankle joint strategy exercises were performed by stroke patients. In this case, visual feedback was provided with a full-length mirror conducted by physical therapists. This report's positive effects have been associated with continuous visual information that activated the brain's motor areas [47]. As [48], other studies used video technology as a therapeutic medium for patients with brain injuries. The results of the comparison of the effects of a video and a conventional verbal procedure indicated that video feedback is a useful technique that improves the patient's abilities to identify their strengths and weakness [48].

Lokomat driven gait orthosis (DGO) is a device that uses computerized visual Feedback for gait rehabilitation. The motor output in robot-assisted gait training has a similar effect using and not using visual feedback. However, visual feedback optimizes gait rehabilitation and motor learning, involving the patient in an active learning process. Patients reported improved motivation and concentration during the training process with visual feedback [49]. Moreover, in a similar study in a robotic environment, this strategy has encouraged a specific increase in force production. In this case, users used the visual feedback to set a visual goal for each level and respond to keep the goal constant. In this way, visual feedback seems to be a way to encourage to exceed the maximum self-assessment. Tasks, where users believe that vision provides more precise feedback, tend to dominate kinesthesia in the robotic environment [50].

2.3.4 Feedback Strategies in Stroke Rehabilitation

Among the strategies that stand out to provide feedback to users, it is highlighted that overloading with too much information and providing more feedback than can be processed effectively for movement correction is not useful and can decrease the performance and learning process. In this way, feedback should focus on the most relevant errors, based on the learner's information-processing and memory capabilities [30].

In general, feedback about movement errors has a varying level of precision. It can be expressed in terms of either the direction of the error (qualitative) or the magnitude of the error (quantitative) to align the movement with the goal. The feedback's precision depends on the learner's skill and is based on the accuracy level with which the feedback describes the movement or outcome [30].

In terms of frequency of feedback, it could be an absolute frequency of feedback, referring to the total number of feedback presentation given to the user across a set of trials, or relative frequency of feedback, referring to the percentage of trials receiving feedback [30]. In this sense, there are different methods to give feedback related to its frequency:

- **Faded Feedback** is a method where the feedback is given at a high relative frequency (practically 100%) in first practice and reduced gradually to prevent developing a dependency on this feedback and accomplish permanent skill learning [30].

- **Bandwidth Feedback** combines qualitative and quantitative types of information, reducing the relative proportion of feedback, but each feedback is given based on a preset degree of acceptability of performance. In this method, if specific performance metrics fall within an acceptable level (or "range") of correctness, no feedback will be given. It indicates the error's amount and direction if the performance exceeds the acceptable range [30].

- **Summary Feedback** is a method where the feedback information of a series of experiments is kept, and then each entire series are summarized. Through this method, dependency-producing effects of frequent feedback might be prevented [30].

Considering stroke patients, feedback content should be adjusted for the user's learning stage and faded feedback. In the early stages of learning, it must be more frequent, it must make use of keywords to highlight correct performance or indicate progress, and it should consider the time when the practitioner internalizes their proprioceptive feelings of the skill; whereas in a later stage, feedback can be more precise and with a reduced in frequency [11], [34], [36].

That said, three intervals can describe the feedback time: while in progress, it is usually called concurrent feedback. The time interval from the exercise's completion to the appearance of feedback is called the feedback delay interval, and the interval after providing feedback to the start of the next action is the post-feedback delay interval (Figure 4) [30].

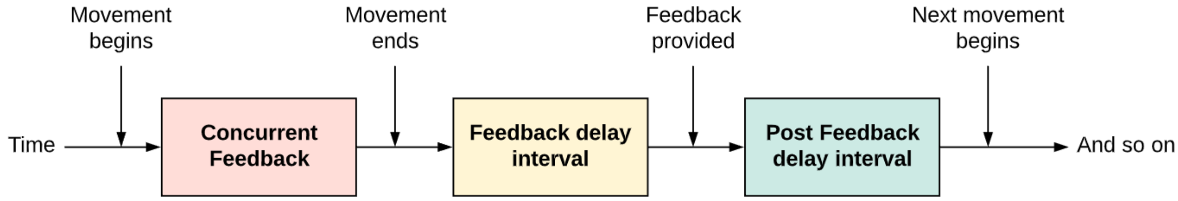


Figure 4. Time representation at which Feedback can be delivered. Inspired by [18].

Providing immediate feedback instead of delaying a few seconds is not suitable for learning because it prevents the user from dealing with inherent feedback. On the other hand, when delays are too long (greater than 5s), other activities that require attention may occur between a given exercise and its feedback. In relatively complex tasks, the interval maybe longer, but a long interval may reduce motivation and cause inefficient or cease the practice if they are not elaborate. Therefore, post feedback delay intervals are necessary for self-error detection and creating different movements to eliminate the errors signaled by feedback [30].

2.4 Videogames in Rehabilitation

Interactive feedback strategies like video games in rehabilitation and even virtual reality systems have been shown to provide solutions to discouragement problems in long-term therapy and be a useful therapeutic complement for gait rehabilitation, motor function, balance, and mobility [51], [52]. Several reviews have provided computer gaming as a safe and effective intervention that promotes physical that advantages more significant than traditional exercises [52].

In general, video games can incorporate different motivation levels inherent to the task and elements that satisfy plasticity and motor learning principles. These computational environments facilitate motor learning thanks to the ease with which users can manipulate and adapt to the extrinsic visual, auditory, and haptic feedback [26]. Some of the advantages in rehabilitation are the enhanced interaction between the patient and the therapy, limiting boredom, fatigue, and lack of enthusiasm [26]. Thus, when the intrinsic motivation is improved indirectly by augmented feedback, the user believes in his physical ability, increase effort into the activity, and challenge himself to achieve better rehabilitation outcomes [26].

2.4.1 Serious Games

Serious games are interactive tools specially designed for a specific function to achieve a particular therapeutic purpose through interactive experience [15]. These games are not only fun and entertainment, but they also have a pedagogic component that makes them “serious” for the development of knowledge and skills [16][53]. In this way, serious games are seen as a relevant solution to motivate the patient to complete his rehabilitation process because it involves cognitive and motor activity that engages the person´s attention [16].

2.4.2 Game Features for Rehabilitation Programs

There are some considerations to introduced serious games in rehabilitation. These standards are not only based on industry game design principles. It includes an interdisciplinary methodology that, besides the game design, includes the neuroscience motivation and motor learning principles that have been shown to improve long-term retention (Figure 5) [51].

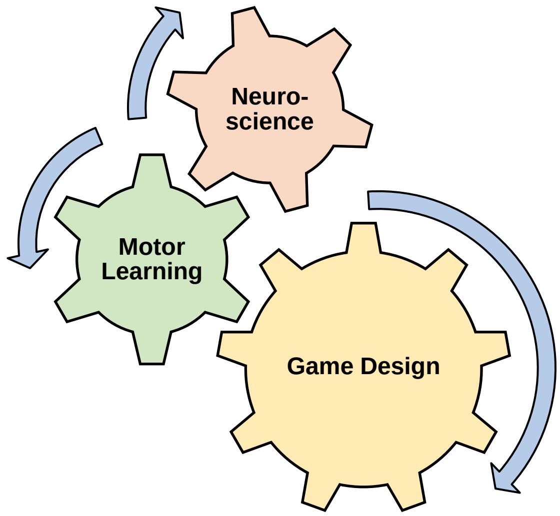


Figure 5. Schematic representation of the principles of designing a video game for rehabilitation. Inspired by [41].

An essential element for serious rehabilitation games is the interaction with the technology and how the user relates to the virtual environment considering the several sensory modalities (visual, auditory, or haptic). Now, in terms of the game functionality, it must be defined the game interface (i.e., two-dimensional or three-dimensional), the number of players, the game genre (e.g., simulation, strategy, related with movement), the adaptability in the game difficulty, and the performance feedback to know the effectiveness with which the skill was done. Moreover, the system can save patient results and the game portability (i.e., to be used at the home, hospital, or clinic) [16].

Besides the feedback, there is additional evidence that suggests the reward, optimal challenge, and clear goals indispensable in game design to increase engagement and adherence and are liked with successful rehabilitation [26], [51], [54]. The therapeutic intervention's tasks and goals must be individualized to the learner's motor abilities and enjoyment [26].

- **Reward:** In general, gameplaying is motivated by rewarding experiences where dopamine is associated with reward-based learning and motivation [51].

- **Difficulty/Challenge:** It is necessary to avoid boredom or frustration by always giving a scaffold practice from easy to difficult, and that at the same time lead to a more significant skill transfer [51].

- **Clear goals:** Developing clear objectives and instructions has been shown to increase user motivation and avoid frustration or confusion when interacting with the platform [51].

2.4.3 User Gameplay Evaluation

In rehabilitation, evaluating the individual player execution and experience in serious games is crucial during the process of player-game interaction. This process depends on the kind of serious game designed. However, there are different measurements to analyze user efficiency. One of the most effective is based on the individual player experience focusing measure their progress in achieving goals or progression in their skills over time [55]. This quantification of the performance/skill level can be achieved through performance metrics like completion time, the number of hits, trajectories features, etc [56]. Parameters as adaptability enable one to know the learner's progress and actions within the game. Besides, strategies like learning, gaming experience, and usability are some other subjective attributes that should be assessed through surveys, scenario analysis, psychometrics, video observation, or interviews to inform how the practice impacts the participant [57], [58].

2.5 Related Works

The literature review included 68 records from the electronic databases searchers (IEEE Xplore, Scopus, PubMed, ResearchGate, and CRAI from *Universidad del Rosario*) using combinations of the following terms: ankle robotic rehabilitation, video games, and serious games (Figure 6).

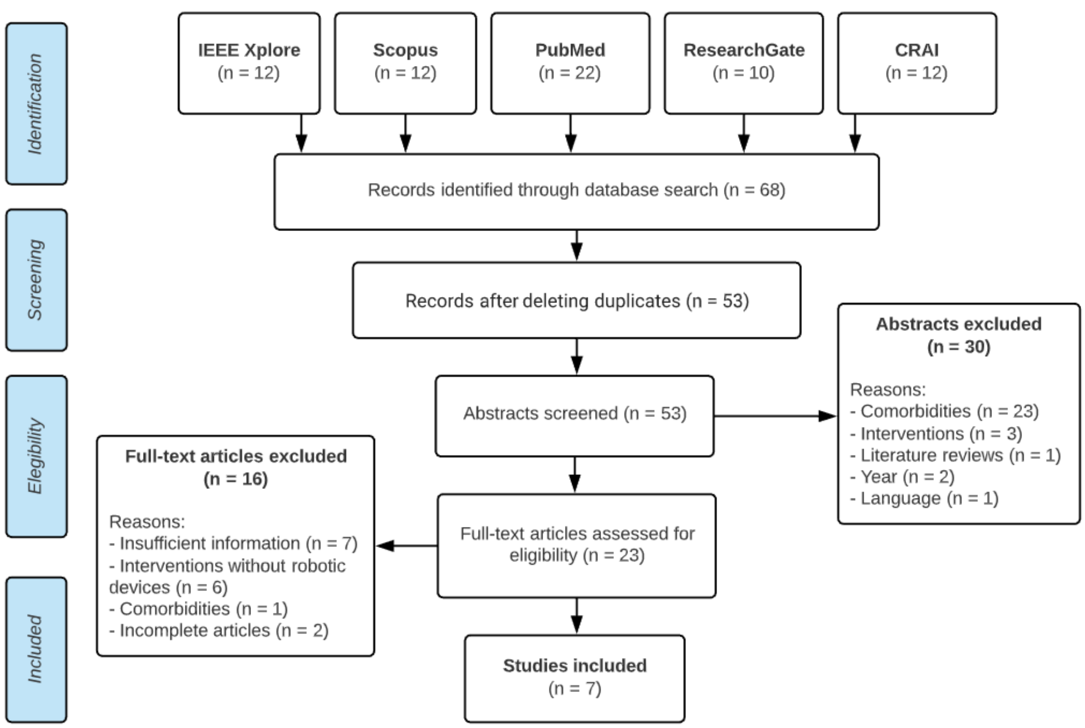
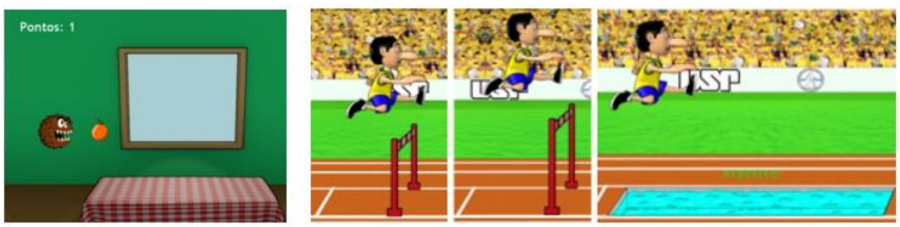


Figure 6. Literature review flow chart of recent articles on video game design for post-stroke ankle rehabilitation using robotic devices.

In the eligibility criteria, articles in English were included, related to video games in robotic rehabilitation and focusing on the lower limb's motor recovery for stroke survivors. Besides that, within the exclusion terms, the quality of the information provided, the study type, old publications (i.e., before 2010), and the language. Following this, seven articles related to the research topic of this project were selected.

One of the literature review studies was about serious games connected to ankle rehabilitation's robotic platform (RePAir). This device allows the patient to make the dorsiflexion and plantarflexion movements. It was designed to improve motor recovery in stroke survivors while seated and interacting with two virtual games. The first game, “O Guloso,” consisted of an animal picture whose vertical movement was associated with the foot's dorsiflexion range of motion (Figure 7.a). This game evaluated the ankle joint's range of motion while the subject tries to collect food items continually moving. The design maintains a predefined routine, including periods with randomly positioned food items, short periods where the patient's maximum dorsiflexion was stimulated, and resting periods. This routine was repeated six times, with 78 items for approximately 5 minutes [59].



(a) (b)

Figure 7. Serious games graphical interface used with RePAir. (a) "O Guloso" and (b) "O Atleta” [59].

The second game, “O Atleta,” was focused on muscle strength using obstacles that the subject needed to avoid by performing a dorsiflexion torque to jump them. Graphically, this second game included a sidebar that displayed the torque amount required to skip the obstacle and the torque made by the patient. The game difficulty parameter and the patient’s muscle strength challenge were performed through three obstacles: a lower hurdle, a higher hurdle, and a pool (Figure 7.b). Like the previous one, this design also considered a predefined routine that repeated two times for approximately 2 minutes, where the patient handled 24 obstacles. The usability evaluation of both serious games was carried out with 19 hemiparetic and 19 healthy patients during only one session. The evaluation focused on the range of motion analysis, dorsiflexion torque analysis, and the game results. It is essential to highlight that before the begging of the virtual games, measurements of the ROM and maximum dorsiflexion torque were performed to define the training requirements. Finally, this study showed that virtual games with the proposed platform could be used as an alternative system for rehabilitating ankle movements [59].

In [60] a wearable robotic device was implemented with interactive games for acute stroke in-bed training. This device consisted of a rotating actuator assembly, a force sensor, a leg brace, an encoder, and a foot holder. The video games allowed the user to drive a car or kick soccer balls while they are watching their ankle motion feedback on the screen (Figure 8). In addition to including bright color graphics and background music, the interface allowed the operator to select exercises and parameters (e.g., range of motion, level of difficulty, training modes) according to the patient. In this way, the patient’s intention to move was detected by the force sensor, and the level of the device assistance (i.e., active assistive or resistive) depended on joint recovery status [60].

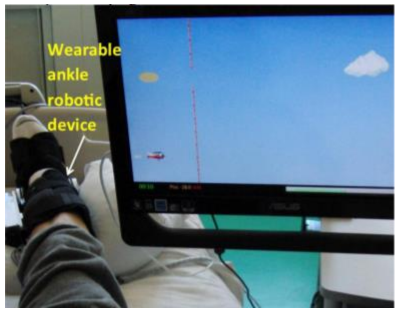


Figure 8. Setup with the wearable ankle robotic device and interactive games in-bed training [47].

As well as [59], this game design included a torque threshold that was established initially. However, in this specific case, the clinical testing evaluated ten post-stroke subjects in a 50-minute training session (five sessions per week) with a task based on the patient's condition. All training sessions contained 10-15 minutes of feedback strategy. Before and after each one, the muscle strength, the active and passive motion range of the ankle joint, and the functional mobility were recorded. Results showed that the progressive augmented real-time feedback (with specified and controlled tasks) guided motor learning. Improvements in motor control were reflected in the increasing results of all the evaluated variables [60].

On the other hand, AnkleBot is one of the most studied ankle exoskeletons that seeks to adapt games for ankle movement rehabilitation. These studies aim to improve the already commercial gaming version to a more intuitive and softer video game that improves the rehabilitation experience. For that purpose, in [61] was designed a game that challenged the patient with a scenario of two pads moving vertically with dorsiflexion movements and two other additional pads moving horizontally with eversion and inversion movements (Figure 9). In this sense, the user needed to hit the ball with the pads to avoid the ball to fall from the platform. The user movement was acquired through a TCP server that communicated the game and the device. These movements considered the whole ROM of the ankle (i.e., elliptical movements) where the device was assisting the patient’s movements or imposing resistance [61].

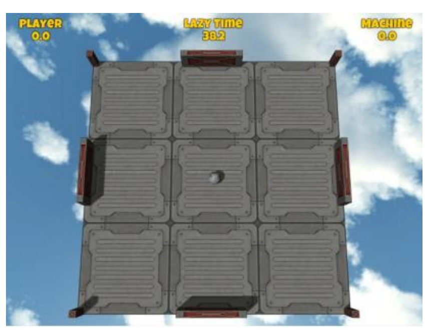


Figure 9. Double Pong Graphical Interface for AnkleBot exoskeleton [61].

The first evaluation of this game was performed with a healthy subject in three tests: free play (i.e., without any actuation forces), assisted play (i.e., forces helping user's movements), and resisted play (i.e., forces against the user's movements). Preliminary test results showed that the game movement was successfully adjusted according to the ankle movement allowing natural actions. Additionally, the serious game included a system calibration performed at runtime, which allowed the game to adjust for each patient and each new achievement in the patient's exercise [61].

A more recent study focused on AnkleBot is an interactive visual task designed as a simple soccer video game in treadmill walking. In contrast with those presented previously, this game focused on whole-body task-oriented gait training. In a penalty kick scenario, the soccer ball is controlled towards the goal by the patient's ankle torque (Figure 10). The game design was based on a single input (i.e., the human torque) and a single output (i.e., ball position) with an adaptive learning algorithm that challenged the patient based on the performance. Also, the soccer game assists during the swing phase or to assist during the stance phase. This way, data taken through a TCP/IP connection detected gait events and estimated human torque to stimulate the ball position [62].

Figure 10. Soccer Game Graphical Interface [62].

Game requirements included the relevant and motivational tasks, the functional ability to switch movements, real-time display and computation of performance, clear indications, and execution challenges. The game model's validation and testing used data from a chronic stroke survivor to validate the video game's performance and its clinical feasibility. It included the analysis of the ball movement accuracy and the auto-adjust accuracy in task difficulty. Results showed that the dorsi and plantar movements in the gait kinetics were reflected accurately in the game. Moreover, the adaptative auto-adjustment of game difficulty was essential for cooperative learning [62].

The study carried out in [20] proposed an integral rehabilitation with a serious game and facial expression recognition to improve patient engagement in the rehabilitation process. This game was handled with an ankle rehabilitation parallel robot with dorsiflexion and plantarflexion movements to command the character game to jump over obstacles (Figure 11). Its design is considered as a simple visual interface with simple control for a faster learning process. It was designed for young people between 12 and 20 years old in two rehabilitation modes: active and resisting training. This serious game contained three levels of difficulty where the patient's force and angle must increase as level up. Each level has different specifications and objectives: the first level was focused on mobility, the second one on strength, and the last one on mobility and strength [20].

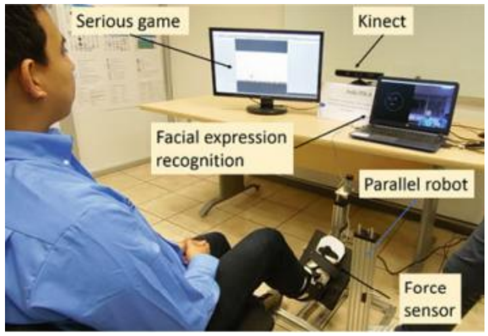


Figure 11. Components of the ankle rehabilitation integral system [20].

As previously mentioned, the system was supported by facial expression recognition with a Kinect sensor (Figure 11). Its main goal was to modify the game's strength and frequency based on the subject's emotional state (e.g., motivation, demotivation, or pain). The system also allowed to store information about the strength, the number of movements performed, and therapy times. This interface was evaluated with six healthy people in two 10-minute therapies while recognizing their facial expressions was performed. As a result, although the interface allowed for fast and entertaining learning, it was necessary to add more challenges in more extended periods. However, the communication game-device allowed fast responses with the characters' movements, and the facial expression recognition effectively allowed the difficulty variation of each level [20].

Another report aimed to characterize the ankle joint's performance in virtual game environments with the vi-RABT robotic ankle trainer system. This system was composed of force sensors in the device locked mode and angular measurement sensors in the device free-running mode. Besides the robotic footplate, the interactive visual-motor tasks included a projection screen where two games (board game and maze game) were displayed. In the board game, the user objective was to reach and stay on 30 target boxes for 1 second, with a board that represented the footplate angular position. In this game, the horizontal and vertical box lines provided information about each axis's angular position. On the other hand, the maze game consisted of a freely moving purple ball with the primary objective of collecting all the 25 goals or green boxes (Figure 12). The game range was planning for each person according to the maximum range of motion or the maximum voluntary contraction recorded before playing [56].

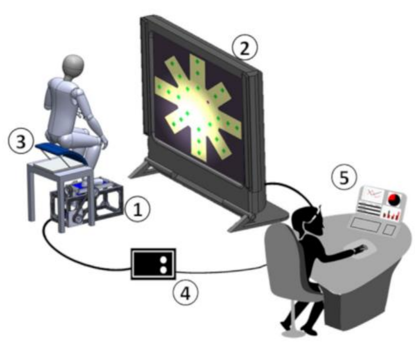


Figure 12. Components of a robotic ankle trainer system: (1) robotic footplate, (2) projection screen, (3) adjustable chair, (4) real-time data acquisition, and (5) therapist's station [56].

Twenty-seven healthy subjects used the ankle force or position to track control tasks in the virtual game. The experimental evaluation was considered a familiarization component where subjects learned how to interact with the system through practice trials. In this way, four games were played in each session, considering two conditions of force and two for position measurements, for a total of 388 trials in each session. The performance was quantified as a function of accuracy, completion time, and characterization of trajectories. Moreover, subjective questionnaires were implemented about the perceived difficulty. According to the evaluation results, the ankle provides better control over position rather than force. The results from questionnaires confirmed a difficulty of control with force considering the perceived intensity. Likewise, task complexity led to a neural-cognitive burden [56].

Finally, Asin-Prieto et al. proposed a video game visual feedback with the Biomot ankle robot and the additional use of haptic adaptive feedback. The video game's objective was to follow the trajectories delineated by a sequence of 20 items (gas bottles) (Figure 13). The user collected bottles with a character whose angular position depended on the ankle dorsiflexion and plantarflexion movements. The score during the session was displayed to encourage the patient to improve the performance. To increase the challenge, the system automatically adjusts the task's difficulty according to the performance. Moreover, it included robot disturbance torque profiles to stimulate agonist and antagonist muscle groups [43].

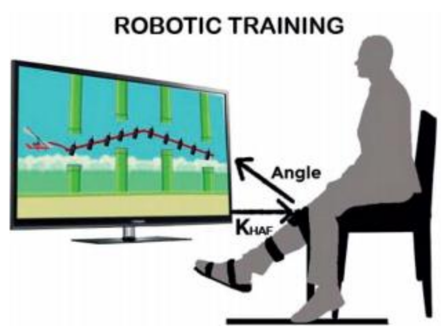


Figure 13. Setup configuration for trajectory videogame using Biomot ankle robot [43].

Ten healthy subjects and one post-stroke patient were involucrate in the usability study in a 4-day intervention. The daily training included 40 randomized repetitions and an assessment with ten repetitions with five possible intervention trajectories. The metrics used to quantify the user performance were the changes in ROM, velocity, the score (i.e., collected items percentage), and the root means squared error (RMSE) considering the performed trajectory and the ideal linear path. A clinical assessment, a neurophysiological assessment, and a satisfaction questionnaire were included in the evaluation process. The study revealed improvements in task performance and motor outcomes. In this way, results suggested that the strategy can be explored for ankle rehabilitation in stroke survivors. Nevertheless, the study showed some limitations in the therapy duration and intensity [43].

Table 1 presented the summary of the finding records included in this study, where it is considered the different strategies used for the design of video games for ankle rehabilitation after stroke. Here is a detailed objective of the designed games, the type of evaluated participants, the feedback strategies, the reward, and the strategies used to evaluate the user's performance.

Table 1. Literature review. Summary of study characteristics in publications related to the development of video games for ankle rehabilitation after stroke.

Interaction Technology	Serious Game Name	Game Objective	Feedback Strategies	Reward	Participants	Measurement of User Performance
RePAiR (2014) [59]	• O Guloso • O Atleta	• Collect food items • Avoid obstacles	Visual Feedback (sidebar)	Collected items	19 Healthy patients and 19 Stroke patients (30-85 years old)	• Dorsiflexion range of motion • Torque • Game results
Wearable ankle robotic device (2016) [47]	N/I*	Reach the target	Visual Feedback	N/I*	10 post-stroke subjects	• Muscle strenght • Ankle ROM • Functional mobility
AnkleBot (2016) [61]	Double Pong	Avoid the ball to fall from the platform	Visual Feedback (sidebar)	N/I*	Healthy subject	Ankle ROM
AnkleBot (2018) [62]	Soccer Game	Control the ball towards the goal	Visual Feedback	Score	Chronic stroke survivor	• Torque in ankle movements • Ball movement accuracy • Auto-adjust accuracy in task difficulty
Ankle rehabilitation parallel robot (2018) [20]	N/I*	Jump over obstacles	Visual Feedback	N/I*	6 Healthy people	• Strength • Number of movements performed • Therapy time
vi-RABT (2019) [56]	• Board Game • Maze Game	• Reach and stay on box targets • Collect goals	Visual and Auditory Feedback	Score and Sounds	27 Healthy subjects (20-40 years old)	• Force and position values • Game completion time • Number of collisions • Characterization of trajectories • User perception
Biomot (2020) [43]	Trajectory Game	Follow the trajectories delineated by some items	Visual and Haptic Feedback	Collected items	30 Healthy individuals and a post-stroke patient	• Score (percentage of collected onscreen items) • Root mean squared error (RMSE)

*N/I: The study reported no information.

Different strategies of serious games applied to ankle rehabilitation show that, in general, the use of these interactive tools improves the patient's commitment to therapy. Firstly, in the analysis of the interfaces' graphic design, it was observed that most of them use bright colors that generate contrast. Of the seven articles studied, four use characters that users control to achieve each game's objectives. These characters, such as those used in [59] improve the patient's interaction and the serious game [63]. Further, following [20], the psychological color of game characters is even more critical. There blue and green tones convey well-being, and red colors capture the players' attention and convey danger [20].

According to this review, serious games are directly related to visual feedback, where the subject perform an action and see the result of it immediately on the screen. Within these visual strategies is seen not only graphic movement record of a character or an object, but it was also viewed in some articles such as [59] and [61], the integration of sidebars that allowed to relate the effort made by the user with the effort necessary to advance in the game. These tools were essential to focus on the game's objective and challenge the user's movements. However, as previously studied, the reward is also a crucial key in the gameplaying design to motivate and challenge the therapy [51]. Most of the studies included the reward in terms of the score or according to the amount of the collected items, seeking to encourage the patient to achieve his highest. Some other analyzed findings showed auditory and even haptic display modes to feed other sensory channels and provide the user with a better experience during the therapeutic process. For instance, in [56], collecting the goal was rewarded with a particular sound, while colliding with walls was penalized with a different audio signal.

Analyzing the different strategies that integrate the patient with the game seek to detect the patient's intention and reflect it simultaneously on the screen. For that, the player interaction with the games, in addition to using robotic technology, makes use of sensors, generally to estimate the position or force of the user. These control strategies are essential not only to fuel games but also to monitor patient performance continually. The study carried out in [56] showed the control over position seems to cause less fatigue and intensity level than the force. This advantage was considered a consequence of lifetime - learned control and the neuromuscular system spanning the ankle joint. Although older people were omitted, this study's results allow defining therapy methods with serious games in terms of the performance control conditions.

Most of the strategies implemented a calibration task before the game according to the control performance. This seems to be one of the most valuable requirements in the design of videogames for rehabilitation. Besides establishing the difficulty for each patient, it looks for a non-excessive effort during the game playing. The calibration tasks are evaluated through short and simple activities that measure the maximum abilities of each user. For example, in [56] the game recorded the maximum range of motion with seven trials along each ax and the maximum voluntary contraction with five maximal contractions of 3s duration for each direction. These tasks can define the robotic device mode, like in [60], or challenge the patient during the game, like in [61]. Other studies set the game's difficulty according to the facial expression recognition [20], or through an automatic system that analyses the performance in real-time to increase challenge [43].

On another note, it is essential to emphasize the other approaches that some of these investigations included. Namely, the research developed in [60] was focused on the therapist's active participation in the rehabilitation system. In this strategy, the challenge and some configuration parameters were drafted under the patient's ability. Another critical approach is in [62], where there are functional requirements in video game development. These were the real-time computation of performance, the system's ability to switch the directionality with dorsiflexion and plantarflexion movements, and the movement measurement's sensitivity. Additionally, this study and [56], considered essential a stage where the game is made known with clear objectives to avoid frustration during the game and allow motor learning.

In the analysis of the user's performance, many of the studies evaluated the execution based on the data thrown by the robotic device or according to the game results (Table 1). Data from the device mainly included a range of motion and muscle strength. Data from the game was related to the score and failure (e.g., number of collected items, number of collisions). In [50], the system stores this information that allows for the therapist's supervision and allows to know the patient's evolution. Nevertheless, the complete analysis observed was in [56] that besides the standard information, it included game competition time, characterization of the user's trajectories, and even the user perception through a Borg's Rating of Perceived Exertion scale.

Finally, following the concepts previously studied, Table 2 presents the main characteristics and requirements for serious game design. This table summarizes the attributes that a game must have to be used in rehabilitation in two main categories. While the general characteristics are related to the game design specifications, the game's functionality focuses on pathological patients' needs in motor learning.

Table 2. Requirements for the Serious Game Design. Inspired by [41], [44], [52].

Category	Requirement	Description
General Game Characteristics	Interaction Technology	Technology used to interact with the system (mouse, keyboard, robotic devices, etc)
	Game Interface	Two-dimensional (2D) or Three-dimensional (3D)
	Number of players	Single-player or multiplayer
	Game Genre	Adventure, action, sports, strategy, etc.
	Game Objective	Clear goals to win the game
	Therapeutic Objective	Specific goals in the rehabilitation process
	Game Portability	Used at home or in a hospital/clinic
Game Functionality	Movement Detection	Type of sensors used to detect the patient's intention to move
	Adaptability	Difficulty/Challenge Tasks
	Reward	Strategies to motivate the therapy
	Feedback	• Positive/Negative (usually positive in rehab) • Display mode • Type of strategy
	Progress Monitoring	Ability to save the results
	User Evaluation	Additional information about the user performance

Based on what was presented in this chapter, serious game design involves a broad range of requirements to include entertainment and learning components on the same platform. In addition to feedback strategies, clear rewards, challenges, and goals are essential to retaining the user's attention to the game. The most recent studies previously analyzed allowed the addition of other strategies that are equally essential. Some examples of them are the graphic design based on characters, the need for a calibration stage, and even the importance of saving the information corresponding to the player's performance. Each of these principles is considered for the serious game design presented in the following chapter. The principal idea is to be able to include each one of them to obtain a proper and complete game set in the rehabilitation process.

3. METHODOLOGY

In this chapter, the procedure to develop a serious game for ankle rehabilitation with T-FLEX is found. For that purpose, besides presenting the game design's theoretical principles, the present work considers a quantitative and qualitative methodological approach. On the one hand, the strategies for obtaining and processing game information are presented. On the other hand, a subjective perspective through interpretation and observation is also shown.

To accomplish the study's objectives, the project was divided into five different phases (see Figure 14). First, the approach to the game logic shows the main features of the game. Second, the visual interface design describes the method of how the virtual environment was designed. Third, the robotic device's integration with the serious game according to the detection of the user movement intention is presented. Fourth, the system integration tests include some short assessments of game functionality with the device. Finally, the preliminary validation describes the required variables and processes to evaluate the game's usability with a non-pathological user.

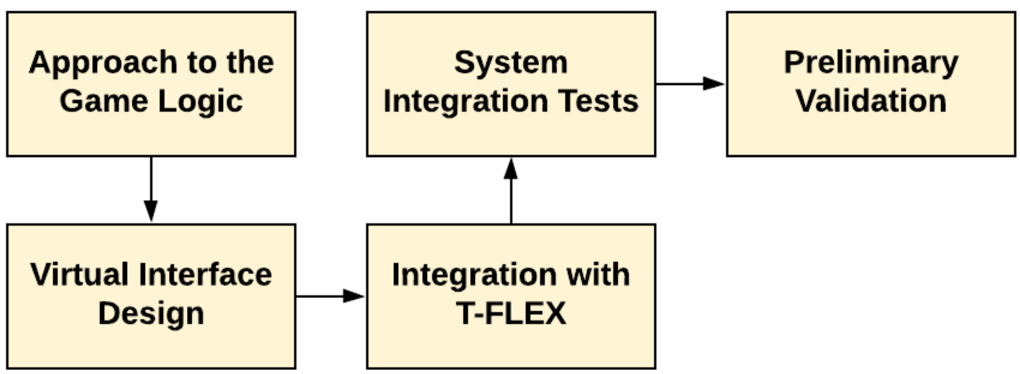


Figure 14. Main strategies of the degree work methodology for the development and preliminary validation of a serious game for motor rehabilitation.

3.1 Approach to the Game Logic

According to the literature review carried out in the previous chapter, a series of concepts and principles were considered to develop the video game with therapeutic objectives. In this sense, a retro 2D adventure game was developed with a single player. It was deemed for a population of men and women between 17 and 70 years old for ankle rehabilitation after stroke. The objective of this game is to evade enemies by jumping over them. Moreover, the therapeutic objective is to induce neuroplasticity through periodic repetition of plantar and dorsal flexion movements. Accordingly, the game was designed with a time similar to the conventional therapies, that is, sessions of 20 minutes.

Here below, Table 3 presents the main requirements for the basis of serious game development, contemplating the additional use of a technological device (i.e., T-FLEX ankle exoskeleton).

Table 3. Serious game main features for ankle rehabilitation with T-FLEX.

Category	Requirement	Description
General Game Characteristics	Interaction Technology	T-FLEX Ankle Exoskeleton
	Game Interface	Two-dimensional (2D)
	Number of players	Single-player
	Game Genre	Retro Adventure Game
	Game Objective	Avoid enemies jumping over them
	Therapeutic Objective	Dorsiflexion and plantarflexion movement repetition
	Game Portability	Used at home
Game Functionality	Movement Detection	IMU sensor
	Adaptability	According to the individual abilities of each subject and the game level
	Reward	Number of obstacles evaded (score and sound)
	Feedback	• Positive Augmented Feedback • Audiovisual and Motivational Feedback • Before, during and after the game
	Progress Monitoring	Monitored in real-time and saved in a database
	User Evaluation	Score, adaptability in time, and user's response to each obstacle

The game's functionality was based on IMU sensors to detect the intention of movement of the patient. Many studies make use of force sensors, soft wearable motion sensors, and strain sensors. However, the present study uses inertial sensors since it has been shown to improve the performance and take advantage of the gyroscope sensor and accelerometer data fusion [64]. Both sensors allow to measure changes in the angle of the ankle joint, and as a consequence, it has been proven to be a useful method in detecting motion intent [64], [65].

As seen in Table 3, the challenging task depends on each subject's abilities, and the difficulty of the game increases the higher the level. The decision to distribute the game in levels was made to provide the user with a better experience with different competitive environments. The game had three levels, and to advance between them, it was necessary to do five sessions of each one. However, regardless of the level, the game always sought to provide augmented and positive feedback. This serious game included the reward with points to increase the motivation during the therapy, which was a tool to measure user performance. These points are achieved through the avatar jumps over the enemy. The avatar jumps were performed with the ankle movements of dorsiflexion and plantarflexion with the robotic device only when the participant exceeded the threshold (i.e., their maximum flexural capacity of the joint).

3.2 Visual Interface Design

The virtual environment and functionalities were performed with Unity software in version 2.3.1 and Windows 10. This game engine was selected because of its 3D and 2D environments and the intuitive game programming process. The game was developed in C# language. The sprites, sounds, and graphic resources were taken from a free retro-type game called “Jumping Guy” [66]. Jumping Guy was the base game for constructing the serious game because its graphics draw the attention of all types of population and its characters comply with the psychology of color to improve interactivity with the game (Figure 15).

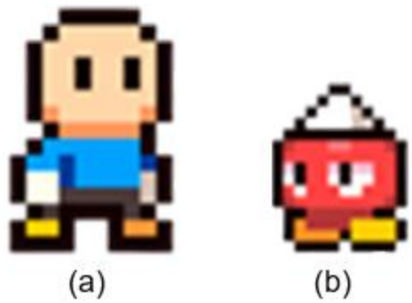


Figure 15. Jumping Guy Characters. (a) Avatar and (b) Enemy.

Additionally, the use of characters was implemented to generate the feeling of "property" and improve user interactivity with the platform [63], [57]. Considering that generally, the patients who have suffered a stroke are mostly older adults, it was essential to consider graphics with colors that generate contrast to avoid eyestrain and distraction while over a long period [51].

3.2.1 Serious Game Strategies

Besides the game, the interface design included three additional sections essential for the primary purpose of ankle rehabilitation after stroke. Those sections were a calibration stage, a tutorial, and a user-password system.

3.2.1.1 Calibration Stage

For the difficulty criteria and formation of the current game parameters, a pre-game calibration task was included to evaluate the ankle's range of motion. This criterion was considered fundamental in games implemented in rehabilitation since people left with cognitive or motor dysfunctions require an even wider-ranging scope of difficulty [63]. In this case, the person was asked to perform five dorsiflexion movements with the ankle and consider each one's maximum ability. This information allowed the set of thresholds that the user must exceed to perform movements with the character.

3.2.1.2 Tutorial

As mentioned in the previous chapters, developing clear objectives and instructions has been shown to increase user motivation and avoid frustration or confusion during the interaction with the platform [63]. Hence, before starting the game, it was essential to present the game's objectives and clear the interactive interface's user position. In this way, through a short practice similar to the in-game interface, the tutorial stage showed the directed movements to reach the game's primary objective.

3.2.1.3 User-password System

The user-password system was integrated to store, in a MySQL database, the information obtained throughout the sessions with the local WampServer (Figure 16). Wamp is a software package for Windows that, throughout Apache, MySQL, and a PHP language, allows mounting a web server on the computer without working on the network [67]. In this way, the development and connection of the database with the game was carried out through the following steps:

1. From the open-source software phpMyAdmin in WampServer, it was created the MySQL local database.

2. The local database created a principal table containing the user's necessary information: name, surname, username, and encrypted password.

3. Using Atom as a code editor, different codes were written with PHP language to manage the database's information.

4. From Unity, there were made a series of co-routines that interacted with the localhost and called the PHP language codes to modify the database. In such a way, it was possible to add data, update, and review the stored information from the game.

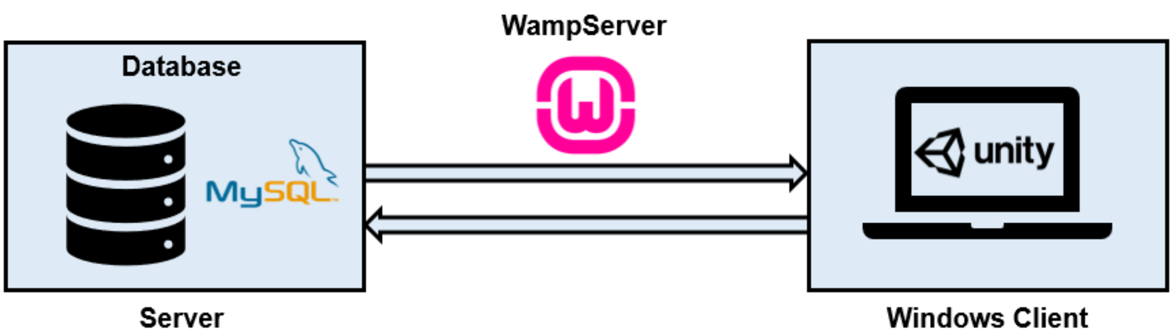


Figure 16. Integration system with the database through WampServer.

The system for database management with MySQL was used because it is a high-performance and safe software. In addition to storing the user's necessary information, the database was designed to store the date and number of the session in which the player was, the level, number of jumps, misses, and the percentage of precision at the end game. This system's main idea was to allow the user and the therapist to know and compare each therapy session's progress.

3.2.2 Feedback Strategies

The increase in the user's commitment to rehabilitation and their learning and participation was fostered through augmented and positive feedback. The term “losing” was not implemented in the game's design because the main idea was to allow the user to reach the maximum score during the established time. In this way, the reward of the game was always optimistic and looking to avoid frustration. Figure 17 shows the different feedback strategies during every session:

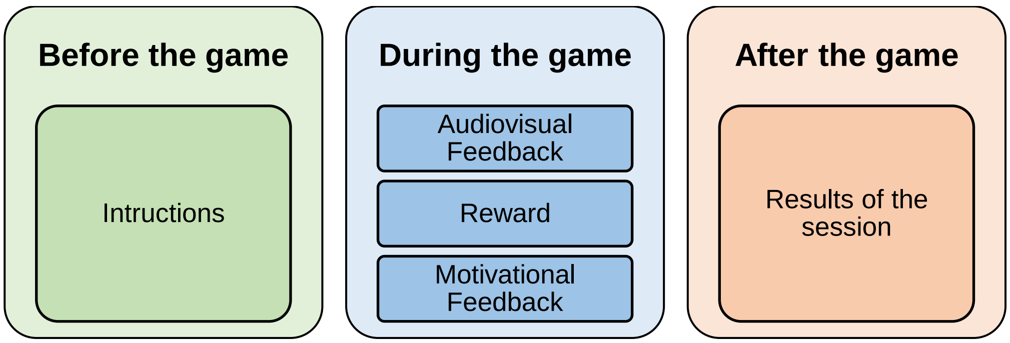


Figure 17. Serious Game feedback strategies before, during, and after the session.

Before the game, the instructions were presented using the tutorial task previously mentioned. Then, during the game, the display modality besides being visual was also auditory. In this sense, the user knew the immediate result of his action because both sensory channels were stimulated. Besides, the reward was displayed continuously on the screen since the user achieves the game's objectives.

During the game, performance-dependent comments were also visually implemented, considering direct and straightforward feedback. There were implemented keywords to highlight correct performance or indicate progress (e.g., Good Job! You beat the record!) according to the score reached for time intervals during the game. This motivation used fade feedback, which was more frequent during the initial learning stage (i.e., during the first levels). The frequency considered a delay time in the feedback while the user internalized his proprioceptive feelings of the skill performed [68].

Finally, with the database, additional augmented feedback was included with the Knowledge of Results (KR), where the user knows and compares their results into the broader context of the game. In addition to motivating the process, the above was thought to fulfill the informative function to improve motor learning.

3.2.3 User Performance Evaluation with the Interface

The evaluation of the user's progress during the game was based on the number of jumps and misses avoiding the enemies, the percentage of precision during the entire session, and the type of response in front of each enemy. In this last parameter, it was empirically evaluated the time when the action was effected to achieve the point, considering that is the player who has control over this. An ideal skip was counted as one in which the avatar passes without approaching the enemy. From this, the anticipated or a delayed time response were those in which the enemy was gently closer in his back or front respectively

(Figure 18). In this way, “Early” was classified as a jump 0.15 s before the ideal jump, and “Late” was a jump 0.34 s after the ideal. On the other side, the system also evaluated the user's precision recorded over time (i.e., user accuracy every 20 s) to evaluate the user’s adaptability during the session.

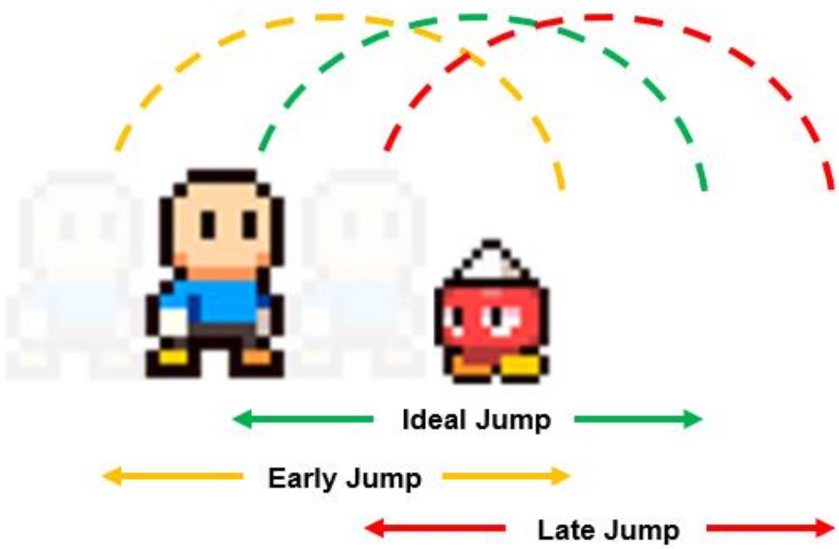


Figure 18. Possible user responses to the enemy: Ideal, Early, or Late.

3.2.4 Additional Strategies

In addition to the strategies shown above, the system had secondary strategies like the pause option that allowed the user to stop the process in case of an emergency during the game. This strategy was designed under situations that, for external reasons, forced to interrupt the therapy session (i.e., muscle tension by the participant, external interruption, or network failure).

3.3 Integration with T-FLEX

This section refers to the integration processes that were developed between the exoskeleton and the platform. Based on this and the strategies for detecting motion intention, the user had active participation in the game. The main idea was to reflect the ankle movements parallel with the avatar movement when the dorsiflexion movement had exceeded the threshold. For that purpose, the set up with T-FLEX, as is seen in Figure 19, had three critical components:

1. **T-FLEX Ankle Exoskeleton:** Its principal function was to assist the dorsiflexion and plantarflexion movements to control the game's avatar.

2. **Graphic Interface:** It presented a serious game to engage the user in the therapy process.

3. **IMU:** Inertial sensor (100 Hz, BNO055, Bosch, Germany), located at the tip of the paretic foot. It allowed estimating the user movement intention.

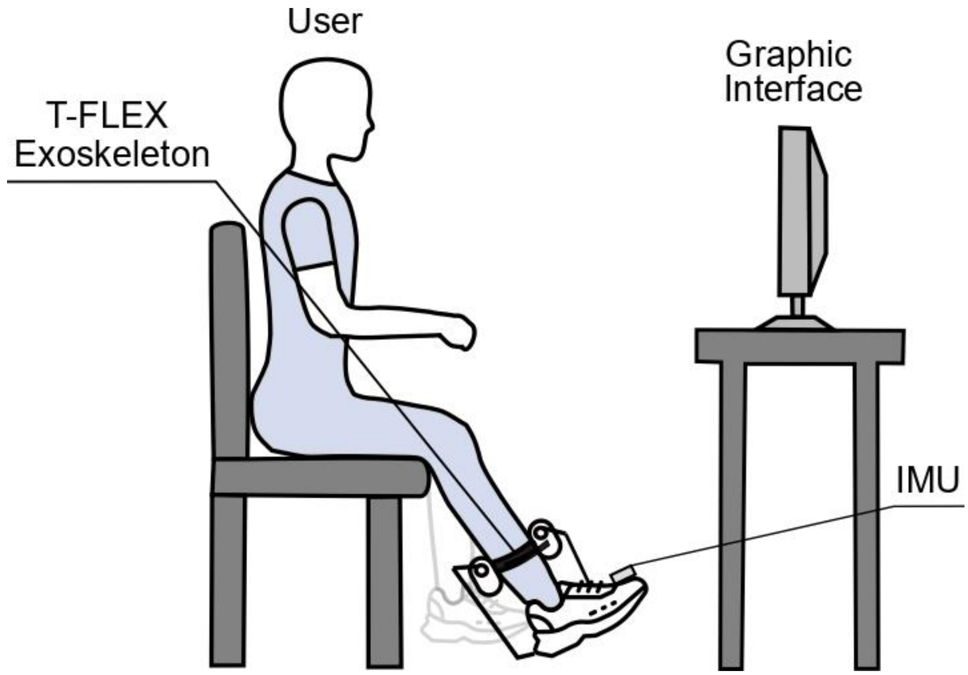


Figure 19. Set-up proposed for the interaction with the system.

As seen in Figure 19, the participant must be seated in a chair with ninety-degree knee flexion. The lower member where the device is located must be raised avoiding contact with the ground. Moreover, the orthosis must be used in its therapy mode [18].

3.3.1 User movement intention

The user intention module ran in the Robotic Operating System (ROS) on a Raspberry Pi 3 since the controllers for the orthosis actuators run in this framework [18]. The programming language used was Python, from which a code with specific classes and functions was designed. In Figure 20, the system consisted of an input signal corresponding to the user movement assisted with the robotic device. Specifically, these plantar and dorsal flexion movements were identified with the inertial sensor data (i.e., the angular velocity along the sagittal plane). The data taken from the sensor passed through a preprocessing module to adjust the obtained data. There, the information was grouped in windows of 10 data, where a 4th-order Butterworth low-pass filter (cutoff of 6 Hz) removed the electromagnetic noise [64].

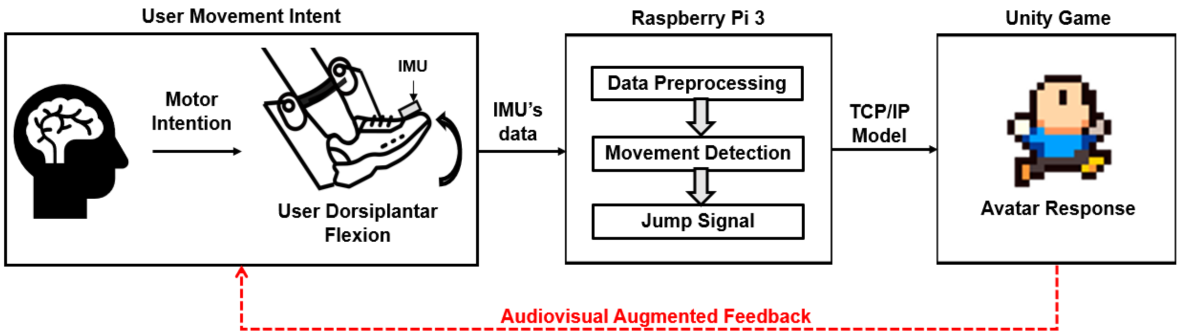


Figure 20. General motion control model during the game considering the data acquisition and processing on the Raspberry Pi 3 and the graphical game response in Unity.

After filtering, the data was analyzed in code to detect in real-time if it was a movement intention. To do this, windows data were averaged, and it was analyzed if the data within it presented changes more significant than 1 g (G-force). It was considered a user action, which was sent to the game to perform the avatar response. The feedback, according to the movement performed, allows the person to correct their movement strategy subsequently.

3.3.1.1 Threshold Setting

The serious game contained three fundamental parts that included user action. These were: calibration, tutorial, and game. Firstly, all the data entered the pre-processing stage (i.e., yellow blocks in Figure 21), and from there, it went on to calibration (i.e., green blocks in Figure 21). In the calibration stage, the threshold value was set with the angular velocity average of five movements' intentions performed by the user and detected by the system. This stage only ended until the number of movements requested and were achieved. Once the threshold had been established, the system could proceed to either the game stage or the tutorial stage since both worked under the same threshold terms. In both, the filtered data were compared in real-time with the threshold value calculated before, and the participant was asked to perform his best dorsiflexion movement. In this way, the avatar jumped, and the exoskeleton executed a repetition only when the angular velocity was higher than the threshold. Therefore, the result observed on the screen was the one that provides feedback on whether or not the execution made by the participant was sufficient to move the avatar.

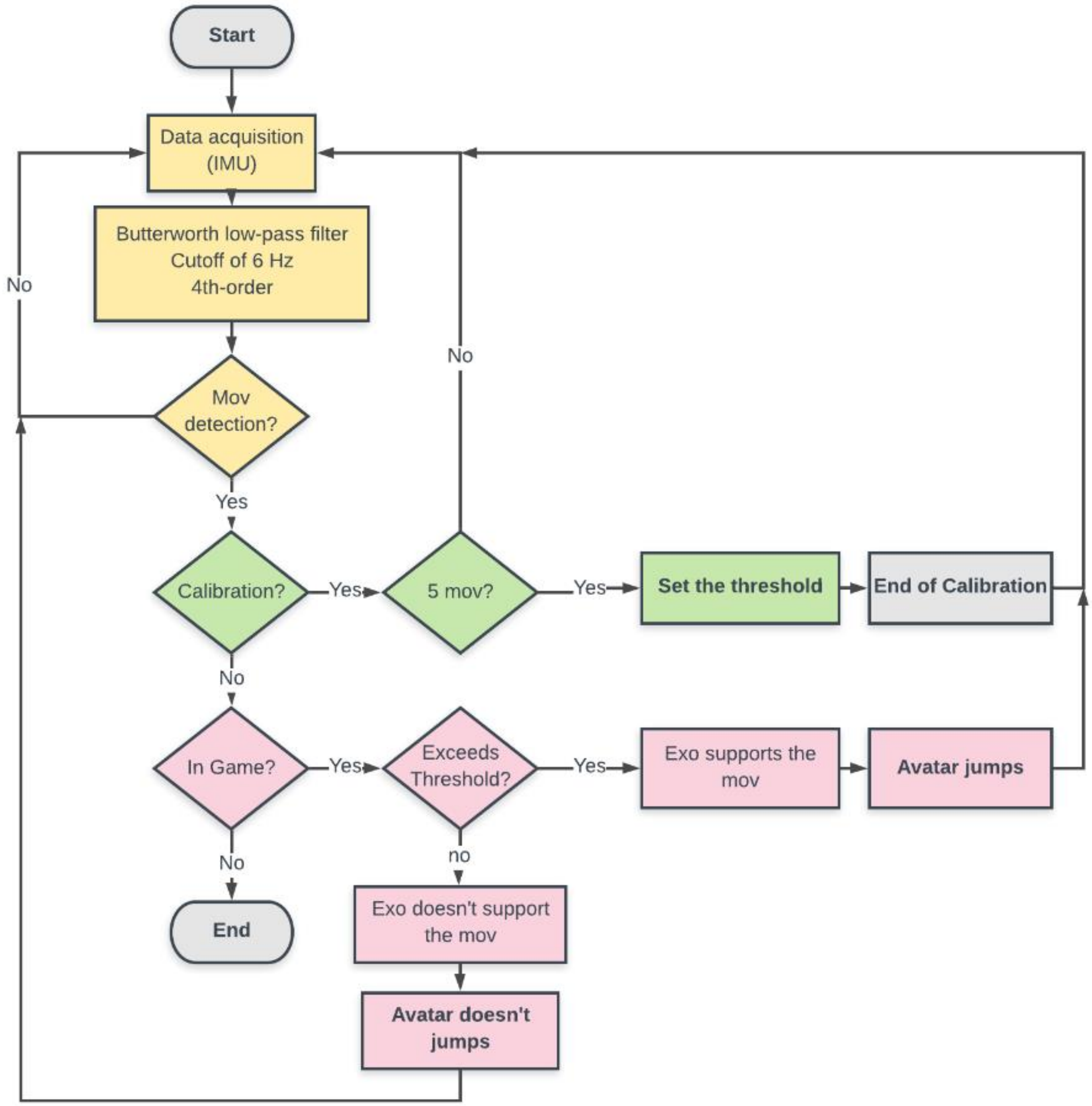


Figure 21. Blocks diagram of the user movement intention through the game.

3.3.2 Communication game-device

The communication between the exoskeleton and the game was conducted with a TCP/IP model to connect over a network. The Transmission Control Protocol (TCP) was used as a host-to-host protocol due to the stable connection between the origin and the destination that guarantee the highly reliable delivery of the data [69]. The TCP communication was configurated through a pair of sockets for each connector. One works as a server listening to the incoming messages, and the other one as a client connecting to the applications. In this sense, the data exchange considered the server in the Unity interface and the Raspberry Pi client (Figure 20). Thus, the sockets were opened in both cases with the IP direction and the port. The information sent by the client was a string "jump" when the movement detection exceeded the threshold. In this way, only when the game had received this word, the avatar jump was executed.

3.3 System Integration Tests

After making the graphical interface and integrating the game with the robotic device, a qualitative evaluation of the virtual environment was carried out. There were three short 20 minutes tests whereby it was ensured the game's viability during the therapy by the developer. The performed tests were the following:

- **Graphical Feasibility Test:** It consisted of the subjective appreciation of the graphic adjustments. The main objective here was to guarantee good screen resolution and refresh rate during long sessions. As mentioned previously, the tests were qualitative. Hence the game performance was analyzed under a high-demand parameter, not only in time but also in the amount of data processed. Additionally, corroborated other parameters, such as the speed of the character movements and the motivational feedback frequency.

- **Game Integration Test with T-FLEX:** In this case, the evaluation was completely functional, which means it was based on the user's interaction with the game and the exoskeleton. For this, it was subjectively tested the response of the avatar to the ankle flexion after exceeding the threshold. This was done by looking for natural movements that were reflected in real-time on the game screen.

- **Final Test of Operation:** In this last assessment, the study considered both the serious game's graphic and functional parts. This means that before the preliminary evaluation with the healthy user, the system's correct functioning was ensured. In this last test, the corroboration of the system's results was also considered, as well as the game-device connection for long periods, and the variables saved in the database.

3.4 Preliminary Validation

This phase refers to evaluating the degree of acceptance and the impact that this proposal has on ankle rehabilitation with T-FLEX. In this way, an experimental protocol was designed to evaluate a healthy subject's usability with a serious game. Due to the COVID-19 pandemic, this test was carried out with a unique healthy user for biosecurity purposes and to prevent any possibility of contagion. This first test with a unique user represents a first approach towards the functional validation of the system. It is well known that a single test subject is unrepresentative, therefore, it is envisaged in the future to work with a larger sample of subjects.

Taking into account the above, the study was conducted on a 20-year-old female without any type of cognitive or motor pathologies. To evaluate the functionality of the proposed system, the methodology implanted consisted of a single session accomplishing all the game levels wearing and without using the ankle exoskeleton (see Figure 22). The level time of the game was about 5 minutes with rests of 5 minutes between each gaming level.

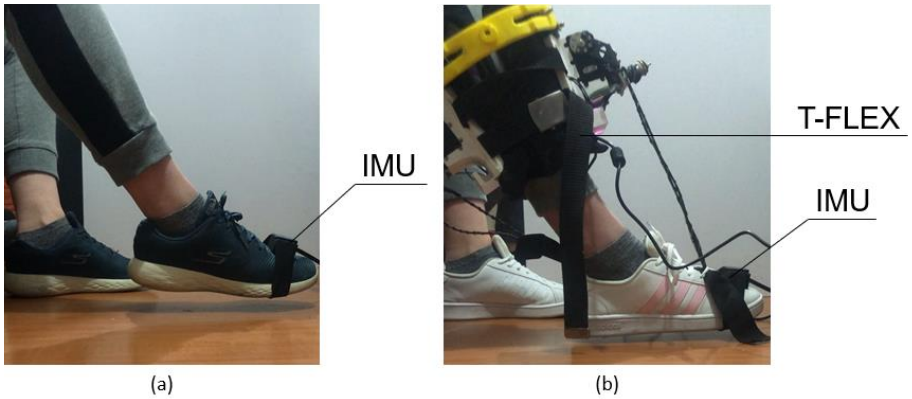


Figure 22. Setup for preliminary validation. (a) without using the device and (b) wearing the ankle exoskeleton.

The video game metrics oriented to user performance throughout therapy were studied to assess the user's adaptability. In this case, the parameter registered by the interface is the success rate and time response to jump the obstacle. Finally, the participant completed a survey to measure the satisfaction level with the strategy proposed. The survey was divided into three parts: experience with the game, adaptability, and satisfaction level.

The participant was informed about the scope and purpose of the experiment, obtaining her written consent before the study (Appendix 2).

3.4.1 Experience with the Serious Game Evaluation

The measurement parameters for the user's evaluation were inspired according to the model defined by [70]. This survey was constituted with criteria for the highest level (first level) usability assessment. The evaluation criteria considered were based on the usability standards reported in [71], [72]. These were:

- **Learning:** Metrics that determine how long it takes users to learn to use specific site features, the ease with which they do it, and the effectiveness of the documentation and help systems.

- **Operability:** Includes the metrics that assess whether the user can operate and control navigation.

- **Attractiveness:** Metrics to evaluate the esthetic and visual aspect.

- **Satisfaction:** Subjective evaluation of comfort of use and familiarity. It also measures the health problems that could be generated during its use.

- **Communication:** Evaluated the communication possibilities offered by the interface for the user.

Each criterion was made up of metrics that constitute the second level parameters. Metrics were not directly measurable but require the definition of attributes [70], [57]. The attributes were declared in such a way that it could be measured qualitatively and quantitatively. The list of attributes was obtained from the analyzes carried out in [70]. For the measurement of each metric, a numerical assessment scale was established with values from 0 to 5, being 0 the lowest score. Each value within this scale was normalized, assigning a rate in percentage terms (Figure 23) [73].

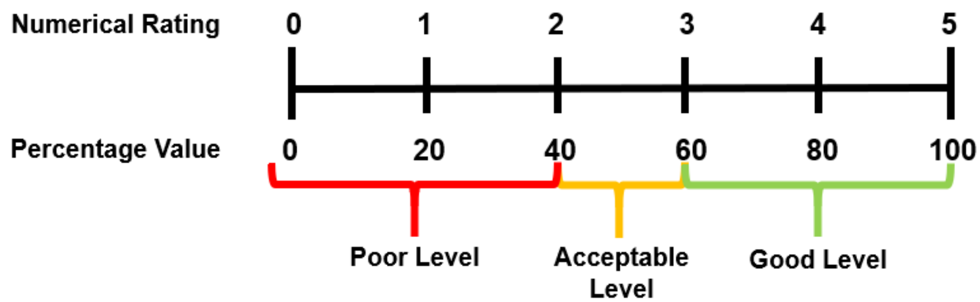


Figure 23. Correspondence between the scale value and its percentage value with the acceptability levels. Inspired by [73].

The acceptability of the usability level evaluation was based in [73], in which three regions were established in a range from 0 to 100% (i.e., the process of compliance satisfactory, acceptable, or unsatisfactory). As seen in Figure 23, the acceptable region was determined to be found with a score between 40 to 60%. A poor level of acceptability is less than 40%, while a satisfactory and good level exceeds 60% [70], [73].

3.4.2 Adaptation Level Assessment

This survey aimed to know the experience and adaptation between the user and the exoskeleton. The participant was asked to respond to 8 statements concerning the use of the device together with the visual strategy. Some of the presented items were taken from Thomas Platz, in [74], as a reference regarding the training process and safety of use. Additionally, other comforts and adaptability criteria were taken from the questionnaire by Gagnon D et al. [75]. All the statements in the questionnaire were phrased positively. For each one of them, it was proposed to indicate a Likert scale number to represent how the subject felt: (1) strongly disagree, (2) disagree, (3) neutral, (4) agree, and (5) strongly agree.

3.4.3 Satisfaction Evaluation

For this study, the user perception was assessed employing a QUEST test with eight items. The survey focused on the user's perception of the entire system, comfort with the robotic device, and ease of interface operation. This information allowed to have feedback from the user regarding operation and structure. The whole questionnaire can be seen in Appendix 3.

4. RESULTS AND DISCUSSION

This section presents the results and analysis of the first version of the serious game, including the virtual interface design, its parts, and the integration with the ankle exoskeleton. Additionally, there are shown the results of the usability and adaptability test with a non-pathological user. In this way, a qualitative evaluation of the virtual environment is carried out, including the graphic characteristics, the feedback mechanisms, and user preferences analysis.

4.1 Visual Interface

To improve the experience during ankle rehabilitation after stroke, an interface was proposed to follow and challenge the user's motor rehabilitation process. In this way, this strategy was thought to be a rehabilitation supplement that, together with interdisciplinary work, contributes to better therapeutic results.

Jumping Guy: Ankle Rehabilitation Therapy with T-FLEX is a serious videogame that includes the ankle exoskeleton device to interact with the system. As mentioned in the previous chapter, it is a 2D adventure game with a single player. The serious game was designed to be compiled on desktop devices with a Windows platform and with an architecture of 32 bits (Figure 24).

Figure 24. Serious Game Executable Icon.

By default, the game is full screen, and its resolution is 640x360. However, the system allows to select the resolution of the game with a display resolution dialog, and even it could be selected the option of a resizable window (Figure 25). This option was provided and configured in Unity to display initially, right after running the game. One of the advantages of this mechanism is that it facilitates interaction with any Windows device, where the user can select the graphic quality of the game and its screen layout according to his or her comfort.

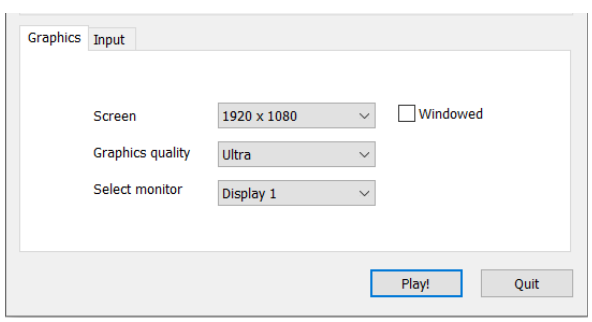
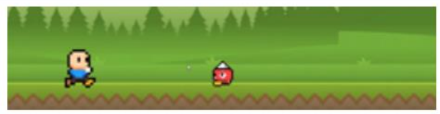
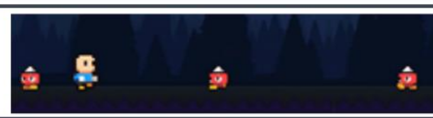


Figure 25. Pop-up window after running the game with graphics configuration. Includes screen resolution, graphics quality, and the resizable windowed option.

4.1.1 Game Objective and Difficulty

The user's objective is to achieve the highest number of points avoiding enemies by jumping on them and considering a time limit of 20 minutes per session. The game has three levels with three different game scenes. The difficulty parameters of each level differ in the distance that separates one enemy from another (i.e., enemy's frequency), which challenges the number of repetitions of the user's movement and the intensity during the therapy. Table 4 shows the designed levels, with the difficulty parameter that differentiates them, the virtual environment, and the number of enemies of each one.

Table 4. Characteristics of the serious game levels for a 20-minute session.

Game Level	Enemy's Frequency	Number of enemies	Environment
Level 1	3s	380	
Level 2	2s	560	
Level 3	1.5s	760	

In the analysis of the gameplay, it has been found studies whose objective of the game is mainly based on achieving objectives or fulfilling specific tasks. The problem with these task-specific treatment approaches like [56], is the lack of user interest in performing repetitive tasks [16]. In this case, Jumping Guy with T-FLEX is a video game that presents a context through two main characters. This gam,e in comparison with [60], allows generating emotions that motivate the user to continue playing. Although games in rehabilitation must meet a specific objective, they must also generate a pleasant experience where they learn simultaneously as they play [72].

According to what has been discussed, it is essential to capture the attention of users in rehabilitation. To do this, the game can display eye-catching images and challenging objectives. In this case, the game developed in this study complied with the previous characteristics and used a movement automation process. This human mechanism not only captures users' attention and avoids distractions, but strategies of this style also promote neuroplasticity, which is a fundamental aspect for motor learning in stroke survivors [72].

4.1.2 Serious Game Interfaces

Once the game started, the welcome interface is directly presented, including the game's name and the user-password system to fill out (Figure 26). The user could only enter the game if he or she had a previously registered username or password. As in standard identification systems, this interface also includes an alert message when the data did not correspond to those registered or when all the requested information is not filled out.

Figure 26. Welcome interface with the user-password system.

By selecting the "Register" button from the home interface, the system allows the enrolling of necessary user information (Figure 27). This includes the first name, last name, username, and password. In this case, it was guaranteed that the user was unique, which avoided the overlap of information.

Figure 27. Registration Interface to join the game through the basic information of the player.

After validating the data in both the start and registration interface, the system enters the calibration process directly by clicking on the "Enter" button. In this stage, the person is asked to perform five dorsiflexion and plantarflexion movements. Visually the user observes both the avatar jump when detecting an intention of movement and the decreasing count of the jumps made (i.e., number in red in Figure 28). Calibration tasks were considered essential to assess the individual capabilities of the participant. Once the count reached zero, two options were automatically offered, one for the tutorial and the other for the game.

Figure 28. Calibration Interface. The box on the right corresponded to the messages and buttons activated after completing the task.

The tutorial button led the user directly through a short game session. In this, five enemies were presented one by one, for which the system paused and guided the user in the execution of the action (Figure 29). This stage also considered the threshold crossing principle to execute the character's movement. However, in this short session, the user can only do this when facing the enemy. This tutorial strategy was one of the tools that have not been reported in any other study, but in this case, it allowed to establish the rules of the game dynamically and creatively.

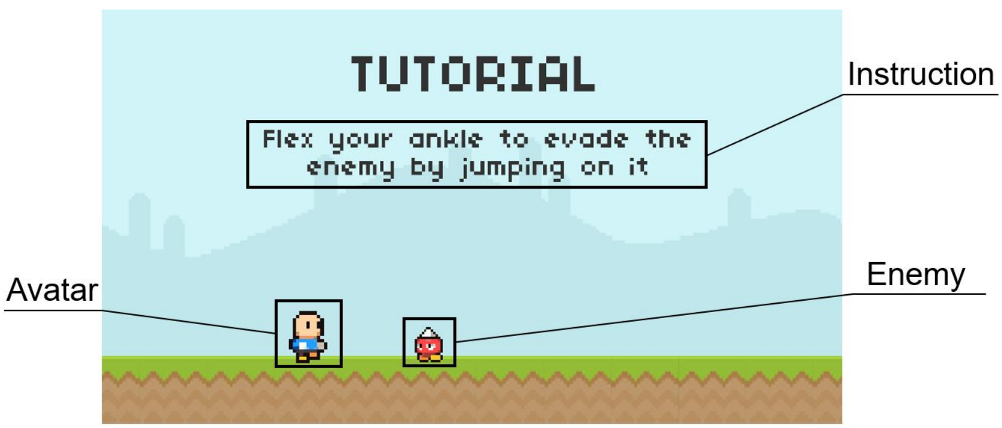


Figure 29. Tutorial Interface with specific instructions to achieve the serious game goal.

Finally, when the person finishes the tutorial session or the option to play is selected, the interface offers three different buttons corresponding to the game levels. In addition to this, the system displays the user's information regarding the gaming session. Therefore, as the user went through the sessions, the buttons were enabled to access the other game levels.

Regardless of the level, when starting the game, the person has information about the session time, the score (i.e., number of successful jumps), and the motivational feedback that appears and disappears according to the person's performance at each level (Figure 30).

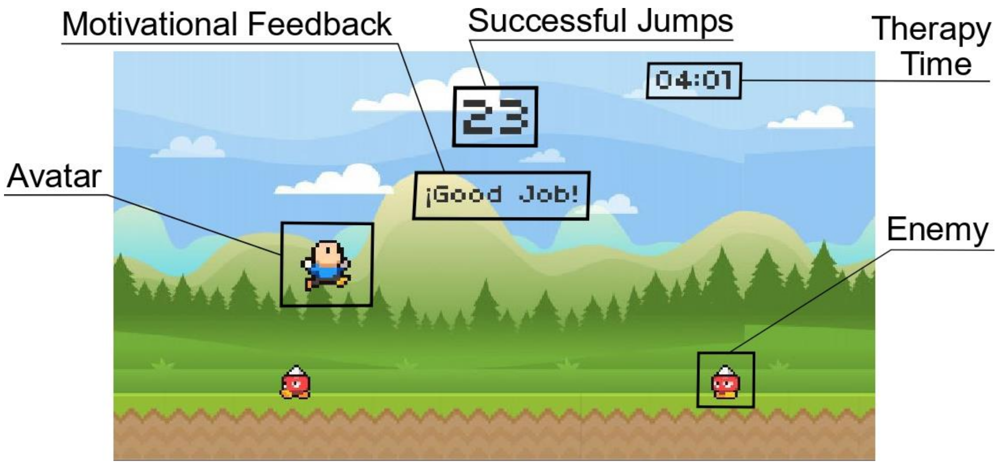


Figure 30. Visual Interface design during the game (First Level).

During the game, the user can pause the game by pressing the space bar on the computer keyboard. There it can be chosen whether to continue the game or to quit. If the *continue* option is selected, the panel disappears, and the game continues its course. However, if the *exit* option is selected, the game saves the process carried out so far in a text file, and the game closed automatically.

The game ended only when the timer reaches zero. By then, the system is directed to show the results of the session. As shown in Figure 31a, through the drop-down, it is possible to compare the general results obtained in previous sessions. Additionally, by clicking on the "More Details" button, the interface graphically shows the adaptability over time. This graph is related to the user's accuracy record evaluated every twenty seconds during the whole game session (Figure 31b).

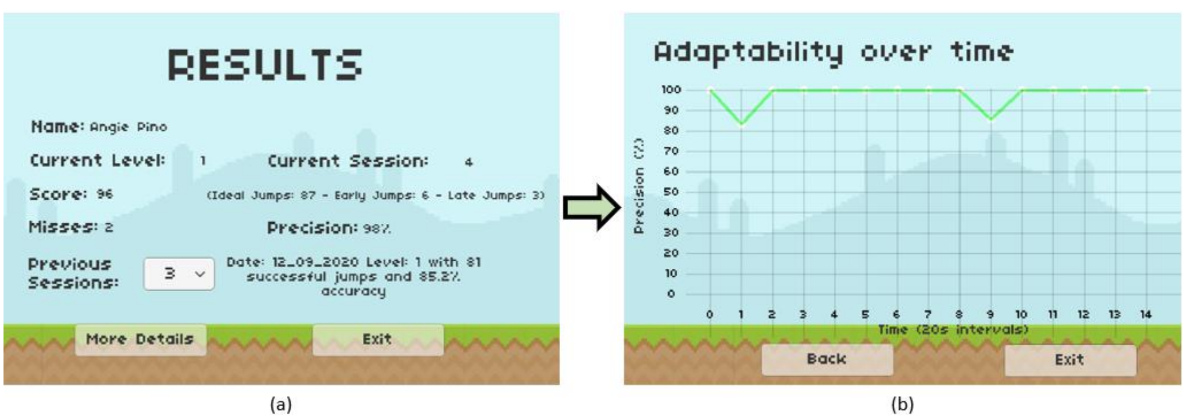


Figure 31. Interface results example: (a) general results and (b) graph of adaptability over time, that is the user accuracy record during the game session.

Analyzing each of the previously presented interfaces, we have a serious game that, in general terms, complied with bright colors that seem to attract attention and promote active development during the sessions. Like [21], this game used characters with differentiable colors, where the use of this psychological technique has been shown to capture the players' attention. This can be corroborated in other studies such as [56] where the game "O Altleta" showed a graphic design in which the character can be confused with the background. This is related to colors that are very similar to each other (Figure 7b). Even though the study did not report it, long-term interaction with the game could generate visual fatigue in users and trigger demotivation or lack of commitment to therapy.

By comparing Jumping Guy with the other findings in terms of feedback strategies, combining audiovisual was essential to encourage the user's rehabilitation therapy. Feeding different sensory channels allowed the user to generate a better experience. Besides, the strategies included motivational properties (i.e., using encouraging messages), informational properties (i.e., through a performance response), and attentional-focusing properties (i.e., with the goal over time). These tools can oversaturate the user if they are not appropriately implemented. However, the frequency and quantity of feedback, mainly at the motivational level, seemed to work well in this game.

In general, the strategies proposed in the design of this serious game allowed us to obtain a very complete and interactive version. On the one hand, the video game development guaranteed the real-time display of the interface without graphical mistakes. On the other hand, the use of the database worked adequately, saving predicted information. In the future has a significant impact since the performance of the player can be evaluated and compared.

4.2 Integration with T-FLEX

The result of integrating the robotic orthosis with the game was significantly satisfactory. The TCP/IP communication between the device and the game was carried out at a time close to the real one, with responses of less than 1s observed in the session film record. This result was favorable concerning other studies, like [20], with responses close to the 10s. According to this, it was possible to observe the natural ankle actions (i.e., dorsiflexion and plantarflexion movements) reflected in the avatar jumps when crossing the threshold. Moreover, the game did not slow down or presented graphical mistakes. In this way, the short tests used to evaluate the performance of the serious game were elementary to ensure adequate functionality before the trial with a healthy subject.

4.3 Preliminary Validation Results

The results obtained during the usability test of the serious game with a healthy participant are presented below. The outcomes include those obtained as a result of the game for the three levels and the survey results at the end of the session.

4.3.1 Serious Game Results

Table 5 presents the general results recorded by the interface during the test with the healthy subject wearing and not wearing the ankle exoskeleton. For these 5-minute sessions, there were 95 enemies for the first level, 140 enemies for the second, and 190 enemies for the last level. The amount of these enemies represented the maximum number of repetitions that the user could do.

The game results analysis revealed that the healthy participant exhibited high success rates for the condition with and without the device. The general average of the movements using the robotic device was 95% versus a vs. 97.6% without using the device. These results showed an improvement over other serious games such as the one designed in [44], where the success rate was 70% in its preliminary test for healthy users. Additionally, it can be seen in Table 4 that effectively, the increase in the repetition frequency at higher levels led to a higher probability of failures for jumping the obstacle. The above is related to a strategy that challenges the participant and motivates him to do increasingly difficult activities. Also, it was observed that there was no significant difference between the use or not of the device. Therefore, motion detection and integration methods appeared to work very well.

Table 5. Game results for the healthy participant using and not using the exoskeleton for all three gaming levels.

	Level 1		Level 2		Level 3	
	Without T-FLEX	**With T-FLEX**	**Without T-FLEX**	**With T-FLEX**	**Without T-FLEX**	**With T-FLEX**
Number of Hits	94	91	137	131	183	181
Number of Misses	1	4	3	9	7	9
Precision percentage	98.9%	95.8%	97.8%	93.6%	96.3%	95.3%

Within other additional results, the user's time response for each level was also evaluated. The graphic representation is displayed in Figure 32, presenting the response types (i.e., Ideal, Early, or Late), the levels, and the device's use condition. In this case, the solid filled bars represent the trial without the device, and the screen filled bars indicate the condition using T-FLEX.

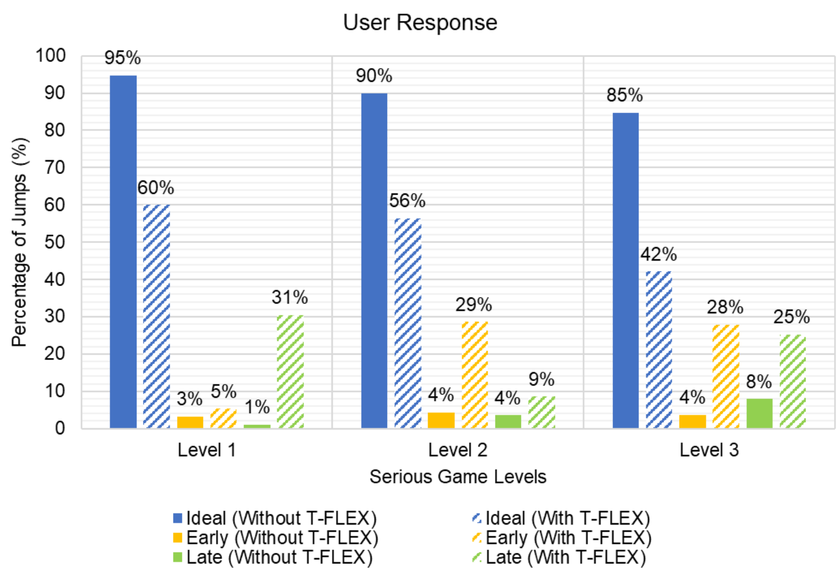


Figure 32. User response in terms of the percentage of jumps for each level.

As seen in Figure 32, the user's response to enemies was ideal in all the levels. Moreover, there were no significant differences between early and late responses in the performance of the healthy user. Nevertheless, the response was sufficient to perform the jump on the enemy. In this same figure, it can also be observed that fewer ideal jumps were presented using the device compared to the stage in which the device was not used. In this way, not using the device seems to allow more ideal results. Those results were related to what was initially expected. It was anticipated that a healthy person would perform a better execution carrying out his natural movements without the Exo. However, this can be a suitable solution for participants who cannot perform this type of movement due to their motor limitation.

On the other hand, user progress was tracked by graphically analyzing accuracy versus time (i.e., every twenty seconds). Figure 33 shows these results for each level, respectively.

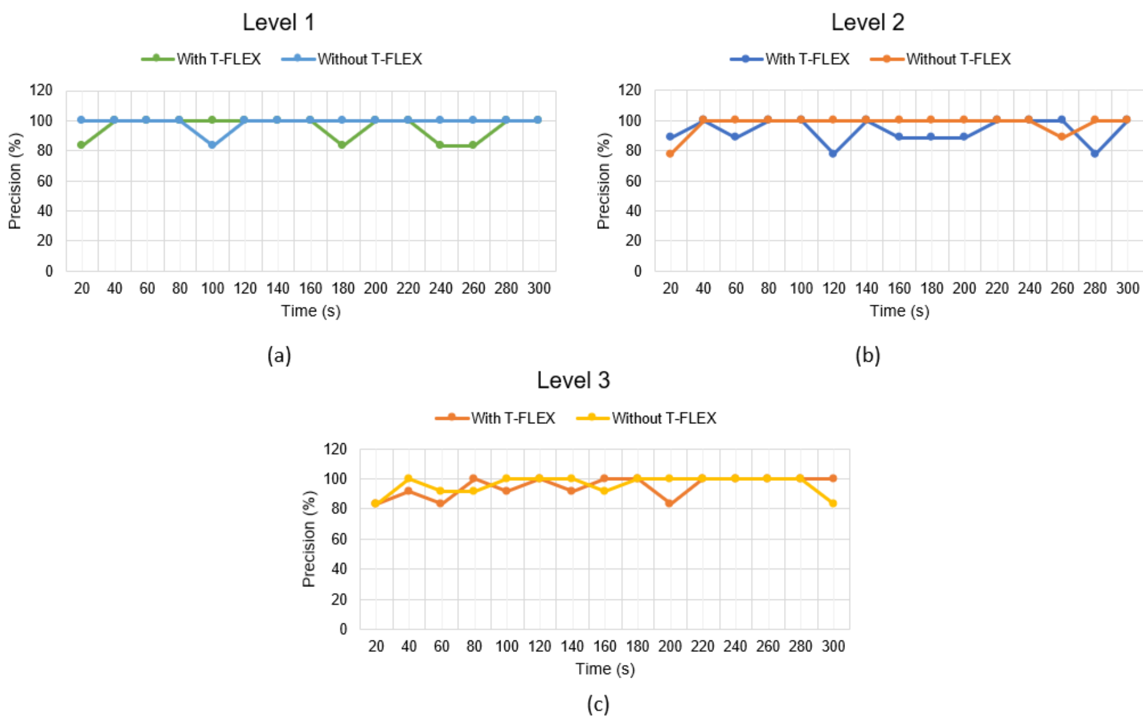


Figure 33. Participant progress during the three-game levels using and not using the orthosis.

Jumping Guy resembles the operation of "O Guloso" y "O Atleta" in [56] and "Trajectory Game" in [44] by including the dorsiflexion and plantarflexion movements of the joint for the control of a character. Similarly, as in these studies, Jumping Guy quantified the user's performance using the number of objects that the subject avoided (i.e., score). However, the user's progress throughout the session made it possible to determine the game adaptability through an evaluation every twenty seconds. This innovative component, which was not recorded in any other study, was a fundamental tool to assess the platform's viability.

Continuing with the analysis of outcomes, the user adaptability process was around 2,6% better without using T-FLEX. The data standard deviation operating the device was 7.6, compared to 5.6 for the data spread without handling the device. Besides, in Figure 33 the notable data dispersion using the orthosis was perceived. The performance decreased in the first two levels even after several minutes of the session. In contrast, in the third level, evolutionary progress was observed using the exoskeleton, where the person achieved better precision in the last minutes of the session. In general, the performance accuracy for each level never dropped below 70%. Additionally, regardless of the evaluation condition (i.e., with or without T-FLEX), a challenging process was remarked for the healthy user. This means the game provided an appropriate difficulty mode to challenge and encourage users.

4.3.2 User Survey Results

The results of the healthy participant preliminary test are presented below. Table 6 summarizes the results of the gaming experience for the initially proposed criteria. Values were assessed on a scale of 0 to 5, being 0 the lowest score. The total valuation corresponds to the weights of each criterion according to the weights of the metrics.

Table 6. Survey results about the gaming experience of the non-pathological participant.

Criteria	Metrics	Total Valuation
Learning	Efficacy	4.27
	Ease of Learning	
	Help	
	Documentation/Tutorials	
Operability	Ease of Use	4.52
	Ease of Navigation	
	Fault Tolerance	
	Accessibility	
	Understandability	
Attractiveness	Interface Attractiveness	4.8
	Customization	
Communication	Message Forms	4.75
Satisfaction	Reliability	5
	Acceptability	
Overall Rating	**4.68**	

According to the results presented in the table above, a relatively correct final rating is observed. Within the evaluation, it is possible to see that one of the best-evaluated criteria was the satisfaction generated by the game. This, considered in therapy, is essential because it needs to generate a playful environment in which users need to learn intrinsically. The learning criterion was one of the strongest judged. This response is because, from a healthy person's point of view, the repetition of known movements does not represent the development of new skills or motor learning. However, an overall rating over 4.68 indicates a satisfactory level of usability acceptability which is directly related to a positive gaming experience.

On the other hand, the adaptation survey for the general evaluation of the system (i.e., robotic orthotics and serious play) equally provided favorable feedback. The participant indicated agreement with an adequate performance of the orthosis and with a fast response time between it and the game. Furthermore, the general system was reported as safe and easy to adapt with a combined score of 4.6. These results approach the possibility of operating the proposed system in a therapeutic context, ensuring a pleasant and secure environment where the user handles control over his rehabilitation process.

Finally, the QUEST survey about the user's perception of the interface is summarized in Table 7, where the values were also assessed on a scale of 1 to 5, being 1 the lowest score.

Table 7. QUEST survey responses of the non-pathological participant.

Criteria	Total Valuation
Dimensions (size, height, length, width)	5
Weight	4
Adjustments (fixing, fastening)	3
Safety (secure)	5
Easy of use	5
Comfort	3
Effectiveness	4
Device Satisfaction	**4**

The game was compliant and had a positive perception of the subject. This can be stated because it was obtained a user satisfaction of 4 over 5. These results indicated a high level of adaptability of the user to the interface proposed. Additionally, the user remarked on aspects such as ease of use, safety, and effectiveness. In this sense, the interface and the proposed system seem to be a promising and potential tool for pathological patients. The user gave them feedback to understand that the game was easy to understand and use. However, according to the scenario analysis, it is necessary to add more interactive components for a long session. The methodology proposed for long therapy sessions is not viable since it was possible to observe that the user was losing attention in the game at the final gaming sessions. This same analysis was carried out in [21], where although the interface allows fast and entertaining learning, it was not enough in therapies of even 10 minutes.

5. CONCLUSIONS

The bibliographic review carried out and the study of basic concepts for game design allowed us to understand the feedback mechanisms in therapy and strategies for the implementation of serious games. Within these, it was possible to understand that strategies such as clear objectives, rewards, challenges, and performance evaluation are essential for designing interactive games in motor rehabilitation. Likewise, the game functionality with robotic devices requires sensing methods for movement detection, adaptability strategies, and a necessary skill for progress monitoring. Additionally, it was found that game design includes principles such as motor learning and neurosciences. This is where an enjoyable activity follows the therapeutic goal to improve adherence and physical therapy.

The present degree work presented the development of a serious game for motor recovery. This game proved to be an attractive tool potentially usable for ankle rehabilitation after stroke. The implementation of each of the strategies, such as calibration, tutorial, and database, allowed us to build a complete platform that includes all the criteria studied for therapy. *Jumping Guy: Ankle Rehabilitation Therapy with T-FLEX* is a serious game potentially usable in stroke patients since it complies with both therapeutic and entertainment components. The interactive design includes dynamic and eye-catching graphics. Moreover, the game motivates and challenges the user while meeting the therapeutic goal through controlled repetitions of the plantar and dorsal flexion movement.

The process of movement automation proposed in this game incorporates a vital component in motor rehabilitation and neurorehabilitation. As studied in previous chapters, neuroplasticity is a process dependent on experience and learning. Practice like the one carried out in this game leads to learning through repetition. That is to say, while the person seeks to achieve the most significant number of points and overcome oneself, the plastic capacity of the brain promotes the neural systems reorganization to recover the lost motor function. In this way, although the game was focused on stroke survivors, this could also be potentially effective in the ankle rehabilitation process for other nervous system pathologies like cerebral palsy. These cases, being related to a brain injury, require further neurological rehabilitation to promote neuroplasticity.

In terms of the feedback offered to the player, it is concluded that providing control over the learning environment is essential to promote motivation and enhance rehabilitation therapies. In this case, the positive and informative properties in the augmented feedback were focused on exceeding the user's performance without considering failure. This tactic avoids demotivating the player and conducts him to remain committed to the practice. Furthermore, the motivational properties with visual messages were functional through sporadically, short, and simple phrases to avoid information overload. It was corroborated that highlighting the user’s effort, motivates them to keep going in the therapy practice. However, although the audiovisual and motivational feedback system successfully engaged the participant, the game needs to include more elements to attract attention during long therapy periods.

Now, on a technical level, inertial sensors worked properly for the participant’s intention to move. However, other strategies as electromyography should be considered to involve motion detections that could be imperceptible by the inertial sensor. On the other hand, the TCP/IP sockets connection was enabled to transmit and process the information in a timely way and without delays. This type of connection was effective due to its superior degree of reliability in data transmission and its high speed of performance. Within the game, it was possible to reflect the participant’s movements simultaneously with those of the avatar on the screen when exceeding the threshold. However, this communication is completely dependent on the network. Therefore, in case it fails, the system will presumably do likewise. Following this, it is necessary to consider another type of device-game connection to prevent these possible failures.

The preliminary validation of this system constituted an important step that brought an approach to the future goal of creating a low-cost device that improves motivation towards ankle rehabilitation after stroke. The participation of the healthy subject allowed corroborating the usability of the game with T-FLEX as well as its functional strategies. Under this, it was concluded that the adaptability in time is one of the most useful strategies to analyze the user performance in each game session. On the other side, the information obtained by the user allowed to have feedback regarding the operation and structure of the proposed setup. In this sense, the system was comfortable, easy to use, and highly effective. Nevertheless, despite the system's high usability, validation on a single subject is not representative enough. Therefore, it is necessary to assess its response in healthy participants and stroke survivors to evaluate the impact of the strategy and corroborate what was found in this study.

All things considered, by comparing *Jumping Guy* with the other reports previously studied, it was encountered that the serious game brings together novel strategies to improve the rehabilitation experience. Likewise, the game meets the objectives of encouraging the user's motivation and commitment. The augmented and positive feedback through the serious game implemented in the present degree project seems to represent a tool that allows users to become self-sufficient in their therapeutic process. Despite this, the support and knowledge of healthcare professionals will inevitably be vital in this progression. In this way, the tool is considered as a secondary component that together with the ankle exoskeleton could favor both therapist and patient to improve the neuromotor rehabilitation process and the disposition towards it.

6. RECOMMENDATIONS AND FUTURE WORKS

7.1 Recommendations

To improve interactivity, a shorter time should be considered for each therapy session. Besides, when running the game, it is recommended to guarantee a decongested network to ensure an adequate connection between the device and the serious game.

7.2 Future works

In this serious game, it is expected to integrate more attractive tools that allow the user to be hooked during long therapies, in the short term. These tools include the integration of additional enemies, rewards, or obstacles for each level. Also, it is expected to finalize another modality of serious games for the ankle rehabilitation of stroke survivors. This is a 3D game whose execution is performed by measuring the angle of the non-paretic foot. In this way, the inclination of an object is conducted to comply with a visualized route. The modality responds to a robotic intervention based on mirror therapy, for which improvements in motor recovery of the lower extremities have been reported.

In the medium term, a statistical evaluation is expected with an adequate sample of pathological and healthy participants to carry out a completed study in which these strategies' impact is evaluated. In general terms, this study will be divided into three therapy approaches, which will be executed randomly in the participants. The first procedure would consist of automatically performing the orthosis without any kind of feedback; the second strategy would use the game modality exposed in this project, and the last strategy would incorporate the robotic intervention based on the mirror therapy. Variables as the kinematic and spatiotemporal performance at the ankle joint, spasticity level, range of motion, and muscular activity are planned to be evaluated. From this information, it is expected to perform a statistical analysis evaluating the viability and training effects.

In the long term, it is expected to generate a modern tool to distribute within the clinical collaborators of the T-FLEX project at an international level. This low-cost setup is projected to improve motivation towards ankle rehabilitation therapy and have the ability to engage users through telemedicine systems. Additionally, it is expected to combine this strategy with others, like haptic feedback, artificial intelligence, and even sensory stimulation therapy. The inclusion of a multiplayer strategy that includes other patients and the therapist is also expected to be studied. The idea would be to explore numerous sensory channels and provide an increasingly more complete and challenging experience.

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APPENDIX

Appendix 1

Visual Feedback Strategy based on Serious Games for Therapy with T-FLEX Ankle Exoskeleton

Angie Pino, Daniel Gomez-Vargas, Marcela Munera and Carlos A. Cifuentes

***Abstract*— Therapies with repetitive exercises can result in a lack of interest and motivation. Therefore, the inclusion of feedback strategies, such as serious games, evidences a significant improvement in those aspects. This paper presents the development and a preliminary validation with a healthy subject of a visual and interactive interface based on serious games for the rehabilitation of patients with ankle dysfunctions. The results show a high level of adaptation of the user to the interface and positive perception in this application.**

***Index terms* — serious games, ankle exoskeleton, gait rehabilitation, visual feedback, movement intention detection**

I. INTRODUCTION

Physical therapy aims to counteract stroke after-effects and provide independence to the survivor. However, different studies associated with the inclusion of robotic devices present promising results (e.g., ankle exoskeletons) in the motor recovery of the patient [1].

Specifically, the T-FLEX ankle exoskeleton improved motor recovery during 18 sessions of repetitive movements [2]. Nevertheless, the study exhibited a lack of interaction and patient attention in the session [2]. Considering the repetitive exercises can result in low motivation and tedious experience [3], the use of T-FLEX could have better results.

Several studies evidenced increases in motivation, effort, and active engagement when included visual feedback strategies [4]. In the ankle joint, the inclusion of visual feedback improved patients' balance, which is related to the continuous visual information provided for stimulating the motor area of the brain [4]. Furthermore, interactive feedback strategies, or serious games applied in rehabilitation, proved to be solutions for discouragement in long-term therapies and efficient gait rehabilitation [5].

This paper presents the development of a visual and interactive interface based on serious games for the rehabilitation of patients with ankle dysfunctions in three parts: (1) serious game development, (2) user intention strategy, and (3) a preliminary validation.

II. MATERIALS AND METHODS

The proposed system for the visual feedback strategy (see Figure 1) includes (1) an ankle exoskeleton to assist the dorsi-plantarflexion movements, (2) a graphic interface based on serious-games to motivate the patient, and (3) an inertial sensor to detect the user's movement intention to control the avatar of the game.

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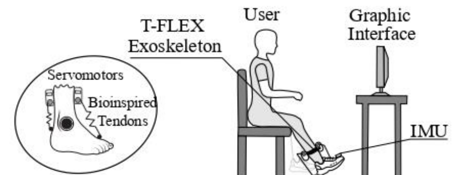

Fig. 1: System setup proposed for the visual feedback strategy

A. Visual Interface Design

The interface's virtual environment covers a retro type design based on the open-source game Jumping Guy (see Figure 2). The game incorporates a calibration stage to assess the user's movement intention, which could be adjusted to increase the difficulty [3]. Moreover, the interface has a tutorial that shows and explains the functionalities and the playing mode looking for easy user adaptation.

The game's goal consists of jumping to avoid enemies through the movement intention explained in the next section. The game has three levels with different characteristics (i.e., the frequency of enemies and graphic design). The first level induces a dorsi-plantarflexion every 3 *s*, the second every 2 *s*, and the third every 1.5 *s*. The selected frequencies intend to increase the therapy's intensity and counteract the adaptation period in repetitive exercises [2].

The interface provides feedback for both preserving the motivation and indicating the user's progress and achievement. Finally, a database store the information acquired in the session to compare the session with previous results, as well as encouraging the patient to perform the therapy [3], [5]. The interface and functionalities were developed in Unity (Unity Technologies, Denmark).

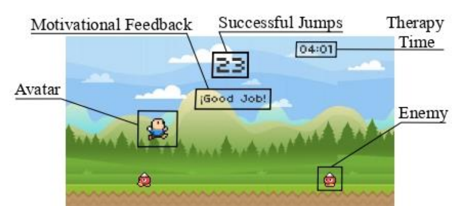

Fig. 2: Interface design based on serious-games for ankle rehabilitation.

B. User movement intention

An inertial sensor (100 Hz, BNO055, Bosch, Germany), located on the paretic foot tip, estimates the user movement intention. Initially, a 4th-order Butterworth low-pass filter (cutoff of 6 Hz) removes the noise from the angular velocity along the sagittal plane. In the calibration stage, the user performs five movements to define the threshold value. Once in the game, the filtered data is compared in real-time with the threshold value calculated in the calibration stage. This way, the avatar jumps, and the exoskeleton executes a repetition when the angular velocity is larger than the threshold. The user intention module runs in the Robotic Operating System (ROS) on a Raspberry Pi 3.

C. Preliminary Validation

The experimental protocol intends to assess the healthy subject's usability and adaption (i.e., female, 20 years old, without cognitive and motor-related pathologies) to the graphical interface using the T-FLEX exoskeleton [1]. For that, the participant accomplished the three levels of the game in two conditions: (1) wearing and (1) without using the device. The participant executed each level with both conditions for 5 minutes, and rested for 5 minutes between trials. For the wearing state, T-FLEX performed a dorsi-plantarflexion repetition after detecting the user movement intention. This repetition was executed concerning the user's range of motion and with a frequency of 1 Hz between movements. In the user adaptation context, the interface registered different parameters of the interaction for each level in both conditions, such as the success rate, the movement detected to trigger the device, and the time response to jump the obstacle. Lastly, the participant completed a QUEST survey to measure the user's perception to the setup proposed.

III. Results and Discussion

The participant exhibited high success rates for the condition without the device (i.e., 98.9% in the first level, 98.0% in the second level, and 96.5% in the third). The inclusion of T-FLEX showed no significant difference in those rates, obtaining values between 94% and 96%. This way, the increase in the repetition frequency (i.e., the game level) led to a higher probability of failures for jumping the obstacle.

Figure 3 shows the participant's response during the first level in terms of the user response to avoid the obstacle (i.e., ideal, late, early, or failure in the jump). The blue elements represent the trial without the device, and the orange indicates the condition using T-FLEX. Concerning the condition using T-FLEX, the response time presented more alterations related to early and late executions (i.e., 0.15 *s* before and 0.34 *s* late of the ideal jump, respectively). Nevertheless, the response was enough to jump the obstacle.

In short, the participant accomplished the three levels in both conditions with a high success rate. Therefore, the results indicate a high level of adaptability of the user to the interface proposed. Likewise, the preliminary results show an improvement in comparison with other studies, where the success rate, in the condition using a robotic device, was close to 70% [6]. Nevertheless, this study has one participant.

[1]The Research Ethics Committee of the Colombian School of Engineering Julio Garavito approved this protocol. The researchers informed the participant about the scope and purpose of the experiment, obtaining her written consent before the study

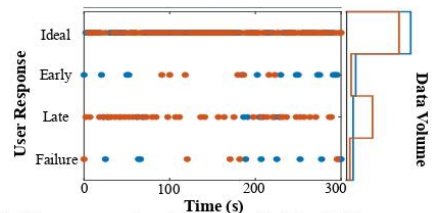

Fig. 3: User progression during the first level. The orange color represents the trial with T-FLEX, and the blue color shows no device condition. The right graph exhibits the data volume for each state.

Consequently, an experimental validation with a group of participants is necessary to verify these results.

For the user perception about the interface, Table I resumes the user's QUEST responses after the protocol. The values are assessed on a scale of 0 to 5, being 0 the lowest score. The device satisfaction was 4 of 5, which evidence an appropriate interaction of the user with the interface proposed. The participant remarked aspects such as ease of use, safety, and effectiveness.

TABLE I: QUEST survey responses

QUEST item	Level of Satisfaction
Dimensions (size, height, length,width)	5
Weight	4
Adjustments (fixing,fastening)	3
Safety (secure)	5
Ease of use	5
Comfort	3
Effectiveness	4
Device satisfaction	**4**

IV. Conclusions and Future Works

This paper presented the development of a visual and interactive interface intended to be used in therapies of people with ankle dysfunctions. The results showed a high adaptation of the user to the interface and positive perception in the preliminary validation. Likewise, the system worked properly and did not evidence to be unsafe. However, the experiment showed is only an initial trial with one subject. Hence a validation with a significant group is necessary to verify these promising results. The future works should be focused on assessing of the interface in patients with ankle dysfunctions in a rehabilitation scenario to determine the effectiveness and improvements in motor recovery.

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Appendix 2

Informed Consent (in Spanish)

I,____, identified with identification card number _________________, declare that I have read and understood this document and that my questions have been answered satisfactorily; therefore, I give my informed consent to participate in the research called "Development of a Serious Game for Ankle Rehabilitation with T-FLEX". I agree that my name, age and other anthropometric data will be stored. I authorize the recording of sessions only for academic use. I know I can withdraw from the experiment at any time.

Participating Subject:
Name: ______________________________
Address: ____________________________
Phone: ______________________________
Signature: __________________ Identification Card: _________________

Researcher's statement
I certify that I have explained to this person the nature and purpose of the investigation and that this person understands what his participation is, the possible risks and benefits involved. All the questions this person have been answered appropriately. Likewise, I have read and adequately explained the parts of informed consent. I am stating my signature.

Researcher:
Name: ______________________________Identification Card: _______________
Researcher's Signature: ________________________

Date (yyyy/mm/dd): ____________________

Appendix 3

Ankle exoskeleton validation and audiovisual feedback strategies survey (in Spanish)

Name: _______________________.
Evaluation date: ________________.
Age: ______. Gender: ___________.
Pathology: ____________________.
Time with the device: ___________.

The objective of this survey is to evaluate the game experience, adaptability, and satisfaction. The survey is subdivided into three parts: gaming experience, adaptability, and level of satisfaction.

General guidelines for completing the survey:

- Please answer ALL questions. We must know your perception of the device to make the necessary adjustments.

- For each question in which you declare that you are not very satisfied or very disagreed, please explain your arguments in the comments section.

1. Video game Survey:

This survey aims to understand the user experience with a serious game. Check the box that best describes your experience with the robot, being 0 totally at odds and 5 agree.

Criteria	Weight	Metrics	Weight	Attributes	Weight	Valuation
Learning	0,15	Efficacy	0,4	Completing the session is easy	0,6	
				The session duration is appropriate	0,3	
		Ease of Learning	0,3	Activity is predictive	0,4	
				The video game is familiar to you	0,35	
				The videogame is consistent	0,25	
		Help	0,2	Easy to read	0,35	
				The video game is useful for the rehab session	0,3	
				The game adapts to your context	0,2	
				It is consistent with the therapy quality and quantity	0,15	
		Documentation/Tutorials	0,1	Access to documentation or tutorials	1	
Operability	0,3	Ease of Use	0,3	Fast response by the video game	0,2	
				Visible and easy-to-identify options	0,15	
				Allows selection for operation parameters	0,1	
				Simple and clear language	0,3	
				The location of the information makes it easier to use	0,25	
		Ease of Navigation	0,25	Scrolling between menus is easy	0,4	
				Friendly navigation	0,3	
				Links and labeling are useful	0,3	
		Fault Tolerance	0,2	Error messages are relevant	0,2	
				Minimize recovery times	0,25	
				Makes it easier correction to continue	0,3	
				Detects and alerts input errors	0,25	

		Accessibility	0,2	No hardware/software limitations	0,4	
				Download or access speed is appropriate	0,6	
		Understandability	0,15	Interface functions are understandable	0,25	
				The explanation of entry and exit requirements is clear	0,35	
				Easy to understand the sequence	0,15	
				Easy to advance to the goal	0,1	
				The functions are obvious	0,15	
Attractiveness	0,2	Interface Attractiveness	0,8	The video game is aesthetically pleasing	0,3	
				The presentation is consistent	0,25	
				The texts and graphics combinations are sufficient	0,3	
				The color/background combination is visually pleasing	0,15	
		Customization	0,2	The video game fits my profile	1	
Communication	0,1	Message forms	1	The messages aesthetics are appropriate	0,35	
				Messages are integrated into the video game	0,15	
				Messages are adequate	0,25	
				The number of messages is appropriate	0,25	
Satisfaction	0,25	Reliability	0,7	The navigation inside the video game seems reliable to me	0,25	
				It is possible to complete the goals comfortably and safely	0,3	
				The visual presentation is simple and pleasing	0,2	
				I trust the frequent use of the video game	0,25	
		Acceptability	0,3	The information required is appropriate	0,6	
				The required functions and capabilities are appropriate	0,4	

2. Adaptation Survey

This survey aims to know the experience and adaptation between the user and the robot. Check the box that best describes your experience with the robot, being 1 is totally at odds and 5 agree.

1	2	3	4	5
Strongly disagree	Disagree	Neutral	Agree	Strongly agree

Questions	1	2	3	4	5	Guest reviews
The overall robot performance is quite good in the game						
The synchronization between my movements and those of the video game is quite precise						
You felt that you are in control throughout the session						
The robot response time to any stimulus is fast						
Training to use the device is not complicated						
The adaptation to the orthosis is fast						
The device is comfortable to perform rehabilitation therapy						
The use of the device does not cause any pain						

3. Satisfaction Survey (QUEST)

The purpose of this survey is to evaluate your satisfaction with the device. The survey consists of 8 questions. For each of the questions, mark your satisfaction level (how pleased you are with the device) using the following scale from 1 to 5.

1	2	3	4	5
Strongly disagree	Disagree	Neutral	Agree	Strongly agree

How satisfied are you with?	1	2	3	4	5	Guest reviews
The dimensions of the system (stem, width, length)?						
The weight of the device?						
The ease of device deployment?						
The ease of use (have it on) the device?						
The usability of the device?						
The effectiveness of the device according to its operation?						
The convenience of the device?						

The security of the device and the possibility that the system does not hurt you?						

Below you will find the list of the same 8 questions about satisfaction. Please select the THREE questions that are most important to you by checking them with an x in the THREE boxes of your choice:

1. Dimensions.
2. Weight.
3. Ease of implementation.
4. Ease of use of the device.
5. Device usability.
6. Device effectiveness.
7. Comfort of the device.
8. Device security.

Results

- **Game experience and adaptability test**

Total number	
Device qualifier	

- **Quest**

  The three most important questions of satisfaction are:
  ____
  ____
  ____