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MASTER EN INGENIERÍA BIOMÉDICA

MASTER'S THESIS

DESIGN AND IMPLEMENTATION OF A SERIOUS GAME FOR UPPER EXTREMITY REHABILITATION OF PATIENTS WITH SPINAL CORD INJURY

JUAN JOSÉ GARRIDO BASCARÁN

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Resumen

La lesión medular espinal es una alteración de la médula espinal normalmente causada por una enfermedad o un traumatismo. En España, ocurren 1000 nuevos casos nuevos al año y genera un gran gasto económico. Además, no tiene cura actualmente, solo puede ser tratada con rehabilitación. El objetivo principal de ésta es la reincorporación del paciente en la sociedad. Sin embargo, esta también es cara, larga y exhaustiva, demandando paciencia y motivación tanto a los pacientes como a la familia.

La rehabilitación de las extremidades superiores es muy importante para el desarrollo del paciente, ya que éstas son esenciales para completar actividades para la vida cotidiana. Como complemento a las terapias tradicionales, y a raíz de las nuevas tecnologías con la ayuda de la realidad virtual, otro tipo de terapias complementarias han aparecido.

Los robots de ayuda y los exoesqueletos han ido evolucionando y se usan para realizar rehabilitación tras un derrame cerebral o durante la enfermedad de Parkinson. Estas nuevas tecnologías son capaces de hacer las sesiones de entrenamiento mucho más atractivas y divertidas que la terapia tradicional.

Por todo esto, en esta Tesis se ha diseñado y desarrollado un sistema de rehabilitación para las extremidades superiores con la ayuda de los dispositivos Leap Motion y Novint Falcon. En dicho sistema se ha creado e implementado un juego serio con el software Unity3D para realizar la rehabilitación con éstos dispositivos.

Por un lado, el Leap Motion es un dispositivo que detecta la mano del usuario sin necesidad de colocar ningún senosr. De esta manera se evita cualquier tipo de dolor o herida. El juego se controla realizando movimientos fundamentales para la rehabilitación de las extremidades superiores: el cierre de la mano, el desplazamiento vertical y horizontal del brazo, y la pronación y supinación del mismo. Por otro lado, el Novint Falcon es un dispositivo háptico capaz de transmitir fuerzas al usuario, el cual realiza una fuerza hacia abajo constante. Dicha fuerza debe ser soportada por el usuario a la vez que realiza el juego.

Para comprobar la eficacia del sistema se han realizado una serie de pruebas de validación en las cuales pacientes y personas sanas han probado el juego serio. Los resultados de las mismas muestran que el juego es factible para ambos tipos de personas y que se consigue realizar una rehabilitación de las extremidades superiores más divertida y entretenida.

Abstract

Spinal cord injury is an alteration of the spinal cord usually caused by disease or trauma. In Spain, 1000 new cases occur each year and it generates a large economic expense. In addition, there is currently no cure, it can only be treated with rehabilitation. It main objective is the reincorporation of the patient into society. However, it is also expensive, long and exhaustive, demanding patience and motivation from both patients and family.

The rehabilitation of the upper extremities is very important for the development of the patient, since these are essential to complete activities for daily life. As a complement to traditional therapies, and as a result of new technologies with the help of virtual reality, other types of complementary therapies have appeared.

Assistive robots and exoskeletons have evolved and are used for rehabilitation after stroke or during Parkinson's disease. These new technologies are capable of making training sessions much more attractive and fun than traditional therapy.

For all these reasons, in this thesis a rehabilitation system for the upper extremities has been designed and developed with the help of Leap Motion and Novint Falcon devices. A serious game has been created and implemented with the Unity3D software to perform rehabilitation with these devices.

On the one hand, the Leap Motion is a device that detects the user's hand without placing any sensor. This avoids any kind of pain or injury. The game is controlled by making essential movements for the rehabilitation of the upper extremities: the closing of the hand, the vertical and horizontal displacement of the arm and the pronation and supination of the same. On the other hand, the Novint Falcon is a haptic device capable of transmitting forces to the user, which performs a constant downward force. Such force must be supported by the user while playing.

In order to test the effectiveness of the system, a series of validation tests have been completed in which patients and healthy people have played the serious game. The results of these tests show that the game is feasible for both types of people and that a more fun and entertaining rehabilitation of the upper extremities is achieved.

Keywords: Spinal cord injury, rehabilitation, upper extremities, serious game, Leap Motion.

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List of Acronyms

SCI: Spinal Cord Injury.

ASIA: American Spinal Injury Association.

AIS: American Spinal Injury Association Impairment Scale.

CNS: Central Nervous System.

ROM: Range Of Motion.

ADL: Activities of Daily Living.

VR: Virtual reality.

PD: Parkinson's Disease.

UE: Upper Extremity.

Chapter 1

Introduction and Objectives

1.1 Spinal Cord Injury

The spinal cord is one of the most important nerves of the Central Nervous System (CNS). It is placed in the middle of the spine and spreads from the lumbar region to the brainstem. The cord is just a continuous cylinder of central nervous tissue, but it functioning allows it to be split into different parts called segments (Watson et al., 2009). These are arranged in groups depending on the part of the back where they are placed.

The human spinal cord has 31 segments: 8 cervical situated in the neck (C1 to C8); 12 thoracic in the chest (T1 to T12); 5 lumbar located in the abdomen (L1 to L5); 5 sacral situated in the pelvis (S1 to S5); and 1 coccygeal segment placed in the tailbone (see Figure 1.1). From each of them, the spinal nerves emerge in pairs, driving the information to the different parts of the body (Cramer and Darby, 2005). The one which runs from the motor cortex of the brain to the body travels through the efferent fibers. Moreover, the afferent fibers lead the information of the sensory neurons to the sensory cortex. Also, the spinal cord is responsible for the coordination of the reflexes, since it contains the reflex arcs, the neural pathways that controls them.

Spinal Cord Injury (SCI) is an alteration of the Spinal Cord due to disease or trauma. This modification leads to an interruption of the communication between the body and the brain, causing an impairment in the life of the patient (Hospital Nacional de Parapléjicos, 2019b). The lesion affects motor and sensitive functionality below the injury (see Figure 1.1).

Depending on the level of injury, the patient will suffer from tetraplegia or paraplegia. The first one refers to impairment or loss of motor and/or sensory function in the cervical segments of the spinal cord. This type of lesion results in impairment of function in the arms as well as in the trunk, legs and pelvic organs. The second one refers to impairment or loss of motor and/or sensory function in the thoracic, lumbar or sacral segment of the spinal cord. Arm functioning is spared, but the

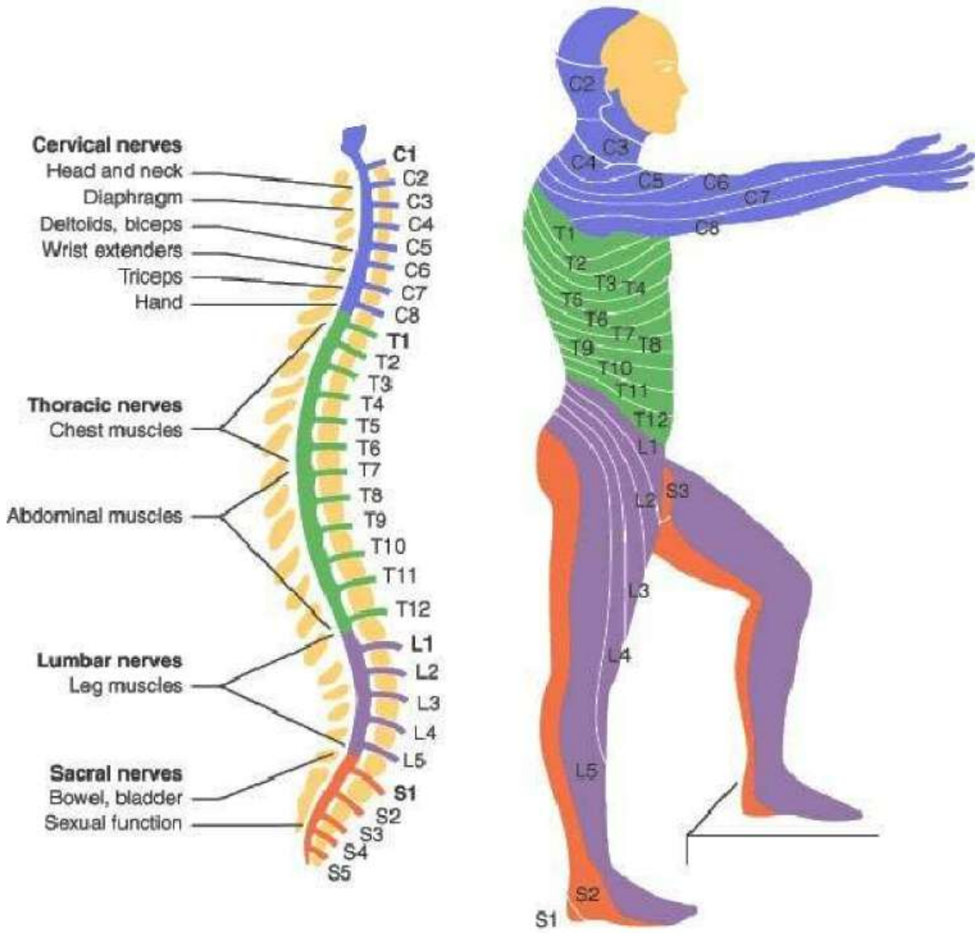

Figure 1.1: Spinal Cord (Singh, 2019).

trunk, legs and pelvic organs may be affected (American Spinal Injury Association, 2019). Apart from that, SCI can be classified as incomplete, if partial preservation of sensory and/or motor functions is found below the neurological level and includes the lowers sacral segment; or complete, when exist an absence of sensory and motor function in the lowest sacral segment (Waters et al., 1991). This classification is made by the American Spinal Injury Association (ASIA), which has an assessment protocol to classify the lesion. It name is AIS (ASIA Impairment Scale) and consists of a motor examination and a classification framework to quantify the severity of the SCI (see Table 1.1).

Economical and social impact

The Spinal Cord is one of the most vital parts of the central nervous system and a small injury can lead to severe disability (Dobkin and Selzer, 2008). In Spain, approximately 1000 new cases of Spinal Cord Injury (SCI) occur every year due to truma, half due to traffic accidents and the rest due to falls, blows, sports accidents or other traumas, such as diving accidents. To all these, we must add around 30% more of

Grade	Definition
A	Complete. No sensory or motor function is preserved in the sacral segments S4-S5.
B	Incomplete. Sensory but not motor function is preserved below the neurological level and includes the sacral segments S4-S4.
C	Incomplete. Motor function is preserved below the neurological level, and more then half of key muscles below the neurological level have a muscle grade less than 3 (grades 0-2).
D	Incomplete. Motor function is preserved below the neurological level, and at least half of key muscles below the neurological level a have a muscle grade greater than or equal to 3.
E	Normal. Sensory and motor functions are normal.

Table 1.1: ASIA scale (Association, 2019)

medical origin due to different diseases (arachnoiditis, plaque sclerosis, Pott's disease, tumours, etc.) and congenital causes such as myelomeningocele. Approximately the 80% of the total lessions occur from 16 to 45 years (Hospital Nacional de Parapléjicos, 2019a).

This kind of injury affects more men than women, with an usual relation of 4:1, and all of them have limitations and disabilities due to the lesion. The 96.6% of the cases have disabilities in mobility, 81.1% disabilities in self-care and 84.3% disabilities in the tasks of domestic life. Even the 10% of people with SCI have to remain in bed permanently (García and Velázquez, 2012).

Furthermore, lower cost technologies are needed in the treatment of patients with SCI in acute phase. This kind of diseases carry a high economic cost, reaching 55,000€ of average in the first 60 days, plus 10,000€ for the intensive care stay (Ángel González Viejo, 2014). Nowadays it is possible to develop new types of technologies to improve the quality of life of patients with SCI and also to reduce costs of rehabilitation.

1.2 Rehabilitation after cervical SCI (tetraplegia)

The definition of rehabilitation as provided by the World Health Organization (WHO) is "a set of interventions designed to reduce disability and optimize functioning in individuals with health conditions in interaction with their environment" (Organization, 2017). With 'health condition' WHO means disease (acute or chronic), injury, trauma or disorder. In addition, it may also include other circumstances such as genetic predisposition, congenital anomaly, stress, ageing or pregnancy.

Since SCI has no cure, rehabilitation is essential for a patient's reintegration into society. An interdisciplinary team with physiatrists, physiotherapists, occupational therapists, dietitians, psychologists, speech therapists and other specialists are necessary in the recovery of a patient (Nas et al., 2015). Furthermore, rehabilitation of this kind of injury is long, expensive and exhausting, demanding patience and motivation of the patients and relatives. It usually bring economic, biophysical and psychosocial problems.

Rehabilitation has to starts as soon as possible after the appearance of the injury to prevent disability and complications. According to the patients' ASIA scale and their social and medical status, the goals and the rehabilitation plan are made. It has to be personalized for each patient (Nas et al., 2015).

After hospital admission and the stabilization of the neurological state of the patient, the acute and subacute rehabilitation begins. In this period, the rehabilitation is made in order to prevent long term complications. Passive exercises are made and bags or pillows are used in positioning. The development of joint contractures and stiffness is the most important complication in this period. About the 66% of patients has at least one joint contracture within 1 year (Nas et al., 2015). For this reason, passive Range Of Motion (ROM) exercises should be performed by the patients.

However, traditional rehabilitation have certain problems too. The amount of therapy the patients receive is scarce and less motivating. New technologies, such as the use of robots or networks of sensors, are closely linked to the use of virtual applications. Concretely, Virtual Reality (VR) games are being implemented in rehabilitation therapies to fulfill the problem of traditional rehabilitation. This type of therapeutic modality is administered as a complement to traditional therapies. It makes patients enjoy performing the exercises while reducing the time of rehabilitation (Dimbwadyo-Terrer et al., 2016). It also provides the appropriate intensity and repetitions to facilitate motor learning. Also, the number of repetitions made by the patient is higher.

Another characteristic of this technology is that it allows the exercises to be performed at home, not just in the hospital. Thanks to that, the patients have always the opportunity to make the exercises and improve their state. This is really important because spinal cord injuries do not have a complete healing process. So in this way there is an approach of therapies to the home. This fact has a great importance because the main objective of the patients is to get back to the society. By the time the patient gets home it has to be as independent as possible and, if this were not possible, a continuation of therapies at home would help achieve this goal. He has to feel integrated in the society and know the importance of the family's role.

A huge variety of exercises for rehabilitation exits, depending on the different parts of the body. However, this Thesis is concretely focused on the rehabilitation of the upper extremity (UE) of the body.

Upper extremity rehabilitation

One of the most shattering and significant loss a person can suffer is the loss of UE function. Specially the use of the hands. Upper extremities are essential in completing elementary Activities of Daily Living (ADL) such as self-feeding, bathing, toileting or dressing (Rice et al., 2016). Mobility demands such as rolling, bridging and sit to lying down, crutch walking, wheeled mobility and transfer between surfaces can be completed with just one arm.

Patients with tetraplegia give a high priority to the rehabilitation of hand function, comparable to bladder and bowel dysfunction (Snoek et al., 2004). In the Hanson and Franklin study (Hanson and Franklin, 1976) the sexual function was compared to three other impairments in patients with SCI. The 76% of subjects gave the highest priority to UE function. Another studies highlighted that recover arm and hand functions would improve the quality of life of SCI patients (Anderson, 2004). These studies demonstrate the importance of UE rehabilitation for patients, as it gives them independence to live.

The treatment of tetraplegia of the UE is eclectic. It involves traditional rehabilitation interventions of task directed training in which patients perform many repetitions of movements relevant to ADL; UE surgery; and the use of orthosis. UE rehabilitation is divided in three phases: acute, subacute and reconstructive phase (Murphy and Chuinard, 1998). Prevent complications, the achievement of an optimized performance within the limits of neurological deficit and the creation of optimal conditions for the reconstructive phase are the objectives of the first two phases (Bedbrook, 1981; Curtin, 1994; Harvey, 1996; Keith and Lacey, 1991). The last phase consists of surgical operations and functional electrical simulation (FES) to improve the positioning and stabilization of the arm and the palmar grasping function (Johnstone et al., 1988; Peckham et al., 2001; Snoek et al., 2000; Triolo et al., 1996; Waters et al., 1996).

During the rehabilitation process in the adult CNS, spontaneous injury-induced structural reorganization, known as plasticity, can occur over a protracted time course. This contributes to functional recovery of the patient, in addition to compensatory behavioral strategies (Ding et al., 2005).

Concretely, plasticity is the brain's ability to create adaptive changes in morphological and network neuronal structure and function of nervous system. This includes changes in neuronal connectivity, neurogenesis and neurochemical (Sasmita et al., 2018). Adults SCI patients can recovery motor and sensory functions after the lesion, but not with axonal regeneration. This reconstruction of neural circuits is made by axonal or dendritic elongation connections in the thalamus, sensorimotor cortex, brain stem and spinal cord (Darian-Smith, 2009). Thus, functional exercise can improve neural plasticity to promote functional recovery after CNS injury (Liu et al., 2012).

Motivation of the patient, feedback and repetition are the three key elements in neurorehabilitation (Peñasco-Martín et al., 2010). Repetition is important for motor learning and for the cortical changes that cause it to take place. However, repetition has to be linked to a sensory feedback. On the other side, motivation of the patient is essential to perform repeatedly the required activities for neurorehabilitation. An excellent way to achieve this is through videogame therapy, and more concretely VR, so that treatment sessions are much more enjoyable and attractive (Holden, 2005).

1.3 Rehabilitation technologies

As observed, neuroplasticity of the adult brain can be impacted by activity-base therapy, and treatment intensity has significant effects on motor recovery. In addition, robotic-assisted therapy, always alongside traditional therapies, has potential to support recovery through motor practices of high intensity. (Krebs and Volpe, 2013; Reinkensmeyer and Boninger, 2012).

Two of the most important points of neurorehabilitation are repetition and motivation (Peñasco-Martín et al., 2010). Robotic devices can offer a consistent, subject-specific and prolonged training in an entertaining and safe environment. Therefore, the use of robots in UE rehabilitation has increased in recent years (Singh et al., 2018). Two main categories of UE robotic systems exist:

- **Exoskeletons**. Exoskeletons are wearable devices that work as a duo with the user. They are used in rehabilitation to reinforce and restore human performance. They can be attached in various locations in order to adapt to the upper extremities. One example of an exoskeleton used in UE rehabilitation is the ArmeoSpring (see Figure 1.2).
- **End-effector robots**. End-effector systems hold the forearm or the hand of the patient. They usually use footplates or handles to generate a motion of the limb in space and no alignment between patient and robot joints is required. An example of an end-effect rehabilitation robot is the InMotion ARM (see Figure 1.3).

This electromechanical devices used in the UE rehabilitation can be also divided depending on the type of assistance that they can provide: active, passive, haptic and coaching (Maciejasz et al., 2014).

- **Active device**. Devices that have at least one actuator. They give active motion assistance, so patients can move the upper-extremity. The device can

Figure 1.2: Exoskeleton rehabilitation robot ArmeoSpring (Hocoma, 2019).

Figure 1.3: End-effector rehabilitation robot InMotion ARM (Bionik, 2019).

provide movement assistance if necessary in the exercises. However, for an exercise to be considered active, the patient must exert some kind of effort.

- **Passive device**. Devices only providing resistive force. This means that they will oppose the patient's movement during the exercise. Therefore, this type of device can only be used by patients who are able to move their limbs.
- **Haptic device**. This device is able to interact with the user through the sense of touch. Depending on the type of actuator they have, haptic devices can be classified as active or passive too. However, since its main function is to provide the patient a haptic sensation, and not to move or resist the patient's UEs, these are classified differently.
- **Coaching device**. This kind of devices do not generate forces to the patients but another feedback. The sensors that these devices have, allow the interaction of patients with VR games and telerehabilitation. Even devices that provide video-based motion recognition are included in this category, despite no mechanical part is in contact with the patient.

The possibilities offered by rehabilitation robots are considerable. Their versatility and personalization allow a great variety of exercises. In addition, they offer support to therapists during these exercises. The type of exercise done by these robots has a different type of classification (Basteris et al., 2014):

- **Assistive**. Patient's voluntary activity is required during the entire movement. Robots can assist either providing weight support or providing forces aiming at task completion.
- **Active**. The robot is being used as a measurement device, without providing force to subject's limb.
- **Passive**. Robot performs the movement without any account of subject's activity.
- **Passive-mirrored**. This is for bimanual robots, when the unimpaired limb is used to control the passive movement of the affected side.
- **Active-assistive**. Assistance towards task completion is supplied only when the subject has not been able to perform actively. At this stage, the subject experiences passive movement of the limb.
- **Corrective**. Subject is stopped by the robot when errors (e.g. distance from a desired position) overcome a predefined value and then asked to perform actively again.
- **Path guidance**. Robot guides the subject when deviating from pre-defined trajectory.
- **Resistive**. Robot provides force opposing the movement.

Many of the robots used for exercises are accompanied by VR. It has important advantages over traditional rehabilitation. The possibility of controlling precisely and repeatedly each session; the capability to adapt the interfaces and the motor limitations of the user; the recreation of secure virtual environments to practice abilities that would be dangerous in real life; and the possibility to develop telerehabilitation platforms where doctors and therapists can follow remotely the evolution of the patient are just few of the advantages offered by VR (Rizzo and Kim, 2005).

Patient movements in VR are similar to the ones made in real life. These are suitable for neurorehabilitation despite the fact that there are some differences due to the difference in perception. This variation causes slower and less precise movements (Viau et al., 2004; Subramanian et al., 2007; Knaut et al., 2009). Also, neurohabilitation through VR may induce cortical reorganization, which plays a fundamental role in the recovery of motor capacity (Holden, 2005; You et al., 2005). These two advantages added to the fact that the skills acquired during virtual training will be useful in real life (Holden, 2005; Rose et al., 1997; Sveistrup, 2004; Fidopiastis et al., 2006), make VR an excellent tool for neurorehabilitation.

VR technologies have create a path in the introduction of videogames in therapy. This kind of games differ from the the traditional ones in that their primary purpose is not entertainment, but to educate or train. They are called serious games. The medical sector is very interested in the use of this new games since they accentuate motivation in patients. Not only children, adults are more enthusiastic when they perform occupational and physical therapy (Omelina et al., 2012).

This kind of therapy is always a complement of the traditional one. In addition, it offers certain advantages like the entire control of the environment and the recording of information. Firstly, having the information of the body of the patient and his movement is essential to perform the therapy correctly. Secondly, all that information can be recorded and stored in order to check and analyze the evolution of the patient. All this improvements makes doctors and the medical community to be interested in these technological advances. In fact, fields of medicine other than SCI have been working with this type of technology for years.

Previous studies

Several researches have studied the benefits of robotics systems, videogames devices and VR in the rehabilitation as opposed to traditional rehabilitation. Usually, the diseases studied were related to cognitive impairment, as Parkinson's Disease (PD) and strokes. The implementation of this type of rehabilitation in spinal cord injury began later in comparison to this diseases.

A recent research analyzed a number of publications in order to confirm an improvement in motor skills thanks to games used in rehabilitation called *Exergames* (Garcia-Agundez et al., 2019). They studied the reliability and safety of two devices used in videogames, the Kinect (see Figure 1.4), created by Microsoft; and the Wii Balance Board (see Figure 1.5), developed by Nintendo. The first one has a group of cameras that can detect the body of the user in order to play games with the whole body. The second one is a board that can measure the pressure that is applied to it.

Figure 1.4: Kinect device (IGN, 2015).

Figure 1.5: Wii Balance Board (GooHoo, 2019).

Recent research suggest too that cognitive training can improve and stabilize cognitive function in patients with PD (Petrelli et al., 2014; Leung et al., 2015; Folkerts et al., 2017). Also, several clinical studies indicate that memory and executive functions in PD patients are improved with cognitive training. On the other hand, a combined therapy with this training and a physical one seems to be a good option too (Hindle et al., 2013; Rahe et al., 2015). Since video games require the user to perform physical and cognitive movements at the same time, they have become a very useful tool in rehabilitation. They are usually mentioned as significant advantages over alternative rehabilitation methods (Göbel et al., 2010).

In Spain, the *Hospital Nacional de Parapléjicos* in Toledo has a project in progress for patients with SCI that uses serious games for rehabilitation called *RehabHand*. They use the device called Leap Motion (see Figure 1.6) that allows the user to interact with the virtual world with his hands. The rehabilitation that is done in the project is focused on the UE. The different games are designed to rehabilitate different movements of the hand and arm. Games that perform flexion exercises of the fingers; rotation of the wrist and the arm; and horizontal and vertical movement of this parts are some examples.

Figure 1.6: Leap Motion Device (Leap Motion, 2019a).

1.4 Motivation and Objectives

The aim of this Thesis is to develop a low cost VR serious game for UE rehabilitation that can be used by any patient. Thanks to the Leap Motion, the user can make the rehabilitation without placing any sensor in the body and without grabbing anything. The patient will not suffer during the exercise and no matter the shape of his hand, he will be able to finish the rehabilitation.

The serious game will be implemented alongside the ones created and developed by the *Hospital Nacional de Parapléjicos* in Toledo in the *RehabHand* project. They are used in a complementary way with the conventional therapy the patients receive there. The project is treatment oriented and has a therapeutic purpose. A group of objectives were fixed in order to achieve this goal:

- To study spinal cord motor and sensitive disorders.
- To explore the basis of virtual rehabilitation games.
- To create a painless and low cost rehabilitation modality.
- To design and develop a serious game for UE rehabilitation.
- To validate the serious game developed in a proof of concept.

1.5 Thesis Organization

The Thesis is organized as follows:

- Chapter 2 covers all information related to the technologies used in the Thesis: the Unity software and the devices Leap Motion and Novint Falcon.

- The explanation and the presentation of the serious game is made in Chapter 3, as well as it connection with the devices presented in Chapter 2.
- Chapter 4 explains the clinical validation as a proof of concept.
- The conclusions and discussions are finally embodied in Chapter 5.

Chapter 2

Enabling Technologies

This Chapter is going to provide all the information related with the software and devices used in this Thesis. The main objective is the creation of a rehabilitation system with low cost and useful for any kind of lesion. Centered in the UE rehabilitation, there are devices like exoskeletons or gloves in the market that are used for that purpose (see Figure 2.1). However, this kind of instruments can hurt the patients depending on their specific SCI. If they have their hands with a determined stance, caused by their lesion, and the device forces them to maintain a certain posture, pain will not allow rehabilitation to be performed.

Figure 2.1: Saebo glove (Saebo Glove, 2019).

This reason leads us to work with the Leap Motion device, since it can detect the position of the hands of the patient at any time without the need for anything placed on them. A second device is going to be used to provide another type of rehabilitation to the patients, the Novint Falcon. Moreover, in order to create the serious game and integrate these two devices, the software Unity has been used because of its advantages in the creation of videogames and the large community of developers it has.

2.1 Leap Motion

Leap Motion (see Figure 2.2) is a device for hand tracking that is comprised by two cameras and three infrared LEDs (Colgan, 2019). It emits infrared light with a wavelength of 850 nanometers, outside the visible light spectrum. The wide angle lenses that the device has, permits a large interaction space of eight cubic feet, with an inverted pyramid shape. The range of view is 60 cm above the device, and it is limited by LED propagation through space. It becomes much harder to infer the hand position in 3D beyond a certain distance.

Figure 2.2: Leap Motion Insides (Leap Motion, 2019b).

All the information gathered by the sensors is then processed by the software. It starts compensating the background objects and the ambient environmental lighting of the images, in order to reconstruct a 3D representation of the device vision field. After this, it is possible to track the fingers and the hands of the user and infer the positions of occluded objects (Colgan, 2019).

Leap Motion was first created for entertainment and educational purposes, but it can be used in medicine too. It has a low price, around 80 €, and his small size makes it easy to carry. In addition, no glove or accessory is required to use it, reducing any chance of harm to the patient. Also, there are research groups and companies that have developed software for other clinical purposes, like medical imaging, hand tremors, sight disorders and hearing loss (Colgan, 2015b). Companies like Evolv (Evolv, 2019) are using the Leap Motion for rehabilitation purposes as well (Colgan, 2015a).

Other devices as Kinect can detect the full body of the user and its range of vision is larger. However, this device is not able to obtain the position of the hands as precisely as the Leap Motion (Ren et al., 2013). Another device called KAI (see Figure 2.3) can detect hand gestures and very precise movements with the hand (Vicara, 2019). It is placed on the hand and tracks the movement that hand does to perform an action. Nevertheless, Leap Motion is able to do that too without touching the user.

Figure 2.3: KAI device (Vicara, 2019).

These three devices can be part of an UE rehabilitation in a serious game. However, Leap Motion offers better attributes to perform the activity. Besides being small and cheap, it can obtain all the information of the actual position of the hands easily. In addition, it can be programmed to learn gestures made by the user and apply them in the serious games. It is easy to set up and it can be used at home without problems. All these features have been taken into account when chosing the Leap Motion as a device for this Thesis.

2.2 Novint Falcon

Novint's Falcon Haptic Device (see Figure 2.4) is a robotic 3D haptic controller, marketed as a videogame controller. It is comprised by three motorized arms attached to an interchangeable end-effector granting three Degrees of Freedom (DOF). The computer keeps tracks of the position and updates the three motors at a speed of 1kHz to have a realistic sense of touch (House, 2019).

Despite the fact that his first purpose was entertainment, it has been proven to be very useful in other fields, like medicine. It is used in virtual surgeries, where doctors can practice the operation they have to do in the future, minimizing the risks (Knight, 2007). Thanks to the device, they can feel the body of the patient and prevent mistakes. Furthermore, thanks to the haptic feedback, the device is used in rehabilitation with serious games. The patients feel the interaction with the virtual world, encouraging them to continue with the game and improving the results of the rehabilitation.

Figure 2.4: Novint Falcon (Society, 2017).

Other haptic devices similar to the Novint Falcon exist in the market. Force Dimension (Dimension, 2019a) company has a variety of 3D haptic devices as the Delta.3 or the Omega.3 (see Figure 2.5). These two devices are similar to the Falcon, all of them offer an haptic feedback with three DOF. Nevertheless, the price of this products rises to 20000 €. Compared to the price of the Falcon, around 300 €, these devices are outside the scope of the objectives of this Thesis. As afforementioned in Chapter 1, the idea of this thesis is to create a type of rehabilitation that is affordable for all patients.

Taking this into consideration, even though knowing that Force Dimension devices are more precise, the Novint Falcon offers less precision but at a much lower price. In fact, the seious game to be developped in this Thesis does not need so much precision, so the Novint Falcon is the perfect device for this Thesis.

Figure 2.5: Force Dimension devices. Delta.3 (left) and Omega.3 (right) (Dimension, 2019b).

2.3 Unity

Unity is a real-time 3D game development platform (Unity, 2019). It contains a cross-platform editor software with which the serious game has been created. This tool have two main parts, the virtual world and the code. In the first one all the visual parts of the game are designed and created, like the scenario or the characters. The second one controls and links all the different parts of the game, establishing the behaviour and rules of the world and the objects. All the scripts are written in C# and they are attached to these objects to give them those properties that define them. Every project in Unity is created by scenes, which are a blank canvas where the virtual world is built (see Figure 2.6). This scenes are linked between them and are used to develop the different scenarios of the game.

The previously mentioned devices are connected with unity in different ways. The Leap Motion is supported by Unity, which have assets of connection between them. On the other hand, the Novint Falcon libraries are programmed using C++ and the games using C# as said before. This creates an incompatibility that has to be resolved with the implementation of Chai3d. It is an open source cross-platform simulation framework. It has been created for computer haptics, visualization and interactive real-time simulation (Chai3D, 2019).

Communication protocol

The communication between the Unity software and the devices is fundamental to create an accurate and reliable serious game. If the information between them is

Figure 2.6: Example of a Unity scene.

fast and correct, the game experience would be smooth and enjoyable. It is really important to create a good game experience. The users need to feel that they are in control and the game does what they want to do. Doing this, the users will enjoy the game and the rehabilitation will be done correctly.

The Leap Motion only sends information. This device searches with its cameras for a hand and tries to put a virtual hand on it. If this objective is achieved, the Leap Motion follows its movements and transfer them to the virtual hand in Unity. Thanks to this, the Leap Motion can send all the information in order to be processed and to create the controls of the serious game. The diagram of communication is shown in Figure 2.7

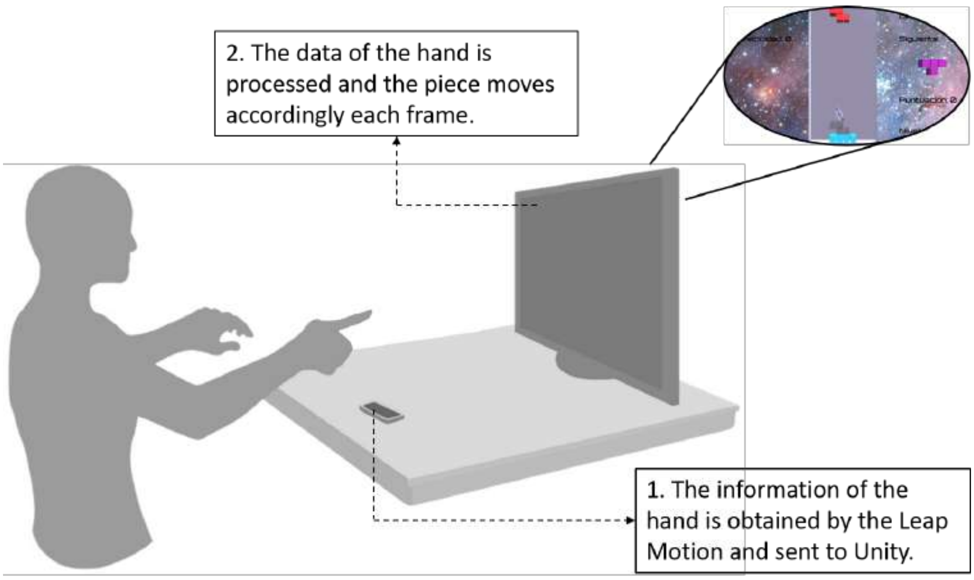

Figure 2.7: Leap Motion functioning diagram.

On the other hand, the Falcon receives and sends data. Chai3D is used as a communication bridge between Unity and the Falcon. It has been necessary to develop and implement a code for it. Unity acts as a controller of Chai3D, where the Falcon is connected. When the game starts, Unity opens a game in Chai3D and the Falcon connects to it. Unity controls the forces and movements sent to Chai3D, it implements them in the game made by this latter and the Falcon interacts with them. The resultant forces are sent back to Unity, which will process them and make the relevant changes in the Tetris according to this forces. The diagram of communication is shown in Figure 2.8

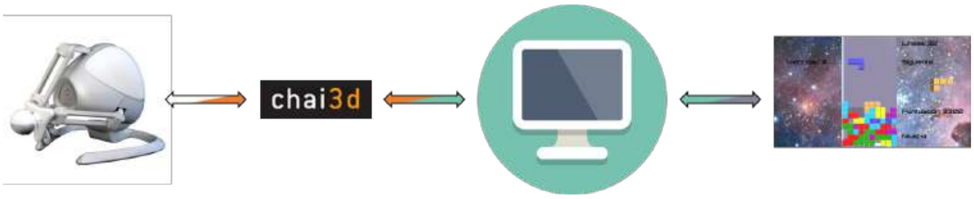

Figure 2.8: Novint Falcon functioning diagram.

Chapter 3

Serious Game Implementation

3.1 Design

The developed serious game is a version of the videogame called Tetris, in which a series of pieces, called tetrominoes, fall over the screen. The objective is to avoid that the set of pieces reach the top of the screen. To achieve this, the player has to make rows. When they are created all the blocks of that row disappear and the pieces above fall (see Figure 3.1). All the tetrominoes can be rotated to better suit each other. As the rows are destroyed the score rises and the pieces fall faster.

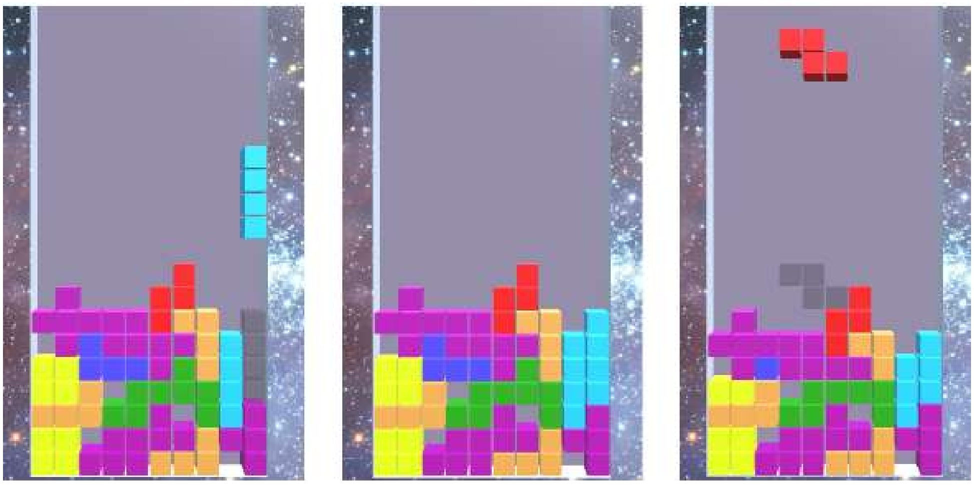

Figure 3.1: Row elimination.

The game has four possible actions: move to the right or to the left; rotate clockwise or counterclockwise; make the piece fall a little faster; or let the piece fall directly to the bottom. In order to adapt the game to the rehabilitation, the actions were transformed into movements of the UE of the body. As the entire code of the game has been made from scratch, any modifications or improvements that the game may need can easily be made in the future.

Leap Motion Control
Leap motion has been used to provide the rehabilitation of the next movements: horizontal displacement of the UE; pronation and supination of the forearm; and the closing of the hand. To make the correct pronation-supination movement of the forearm, the exercise has to be done with the arm flexed 90º. If not, a shoulder rotation may exist. It is very important to carry out the exercises correctly so that the rehabilitation is done successfully.

Every spinal cord injury is different, there are no two alike. Each patient is a unique case to study. In addition, most injuries are not parallel. In other words, the lesion usually affects the right and left parts of the body in a different way. To deal with this situation, a calibration of the game has been developed (see Figure 3.2). In order for the piece to rotate, the patient has to perform a pronation or supination of the arm. The degree of rotation that the patient has to achieve in order to make the turn is possible to be calibrated.

Figure 3.2: Leap Motion calibration.

This is also made because there are patients who at first can only reach a small degree of rotation and others who can reach a higher one. The calibration eliminates differences and achieves a personalized rehabilitation for each patient. In addition, as the rehabilitation progresses, the maximum pronation and supination limits will also change. Thanks to the calibration, the game will not be left behind the patient's progress. A calibration has also been made to the close of the patient fist. In this way we solve the same problems mentioned above.

The game has been developed to be played with both left and right hand. Thanks to this, it is possible to rehabilitate both parts of the UE. The movement made with the Leap Motion is based on the current position and rotation of the hand as well as the movement of the fingers:

- The movement from left to right of the piece is made with the actual movement to that directions of the hand. The piece follows the position of the hand at any time (see Figure 3.3). With this exercise the patient has to keep is hand and arm high and move it side to side.

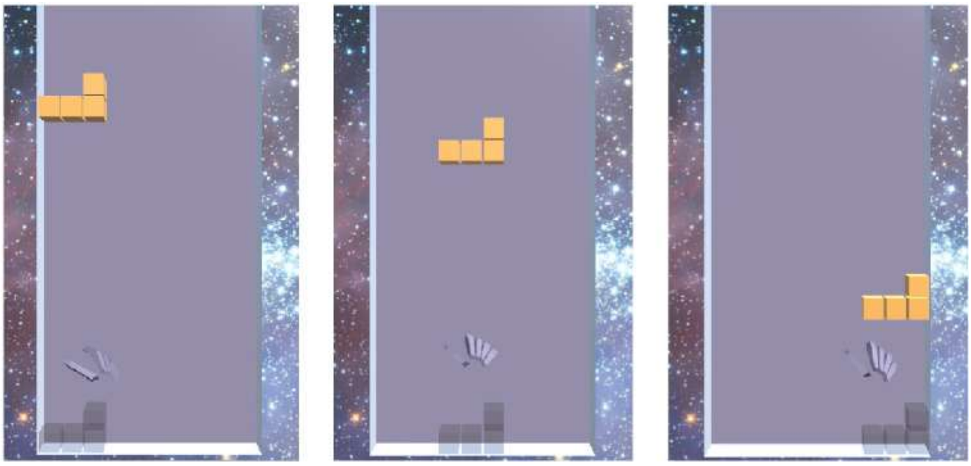

Figure 3.3: Horizontal movement of the piece alongside the horizontal displacement of the hand.

- Rotations of the pieces are made according to the actual rotation of the hand. When the turn of the hand exceeds a certain angle, in one way or another, the piece rotates depending on the direction of the hand (see Figure 3.4). This exercise rehabilitates the pronation and supination of the hand.

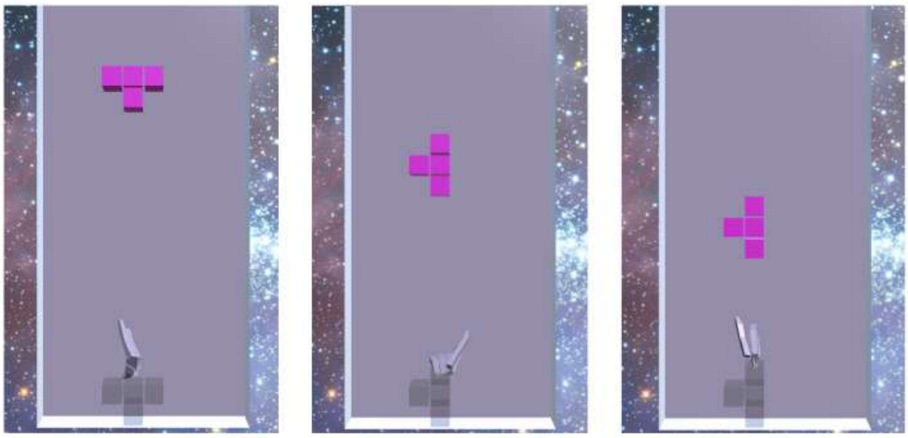

Figure 3.4: Rotation of the piece alongside the rotation of hand.

- To make the piece fall faster than normal, the hand has to go down from the reference position. The speed can be increased up to twice times (see Figure 3.5. This exercise is similar to the first one, where the patient has to maintain the hand and arm raised.

Figure 3.5: Fall at higher speed of the piece in relation to the vertical position of the hand.

- Finally, the fast fall of the pieces is made with a gesture. By the time the hand closes, the piece fall to the bottom (see Figure 3.6). Thanks to this movement, the patient can rehabilitate the closing of the hand repeatedly.

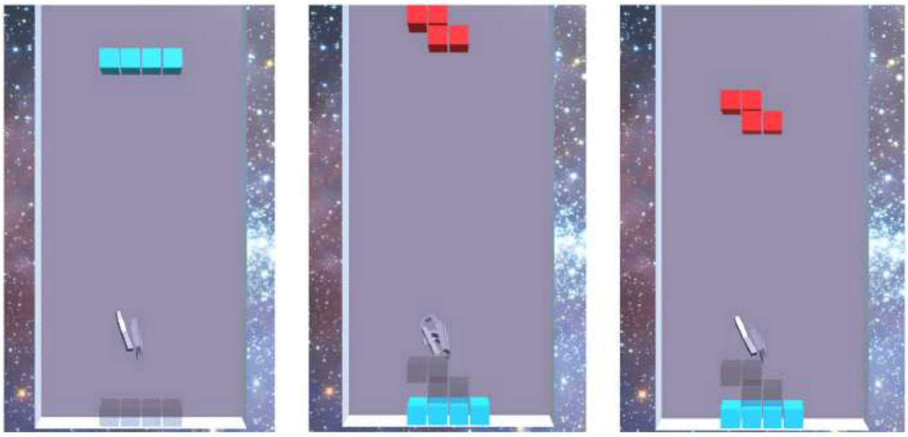

Figure 3.6: Total drop of the piece according to the closing of the hand.

As can be seen, this four movements perform an important role in the UE rehabilitation of the patient. The possibility of having all of them in a single game makes this a complete rehabilitation, being also more motivating and fun. An overview of the movements can be seen in the Table 3.1

Novint Falcon control

The Novint Falcon has been implemented to make another kind of rehabilitation. In this case, the piece falls with a high speed and the Novint Falcon exerts downwards force to the grip. In order for the piece to stop falling at such a high speed, the patient has to push the grip upwards, as if holding it. When the grip is in the neutral position, the piece will stop falling so fast. This rehabilitation modality is still under

Hand gesture	Movement	Tetris effect
	Supination	Right turn
	Pronation	Left turn
	Closure	Fast fall
	Hand down	Increase speed

Table 3.1: Hand movements that control the game.

development, it potential is being analyzed.

- The movement from left to right is made with the grip of the Falcon. The patient just have to move it to one side or another and the piece will follow that movement. The complexity of this exercise is that the patient has to hold the weight and the force of the grip while moving it.
- To rotate the piece, as the grip can't rotate, the patient has to pull the control to himself. The aim of this this kind of movement is the same as the one mentioned before.

With the Falcon, another kind of rehabilitation is made. This choice makes the patient train strength to gain muscle mass. In this way the patient can recover the strength in the arms.

3.2 Structure

The game has two main scenes, the menu (see Figure 3.7) and the actual game. The first one is used to control all the functionalities of the game. All the design is centered in the patient because he is the most important part of the rehabilitation. After the initial screen, the patient can choose his profile or, if it is the first time he uses the platform, register as a new patient. The registration saves the name of the patient, the medical records, the kind of lesion, the etiology and the applicant for rehabilitation. All this information is saved in a file into the computer. This file will be filled with all the information of the patient in each game: the maximum level which he has reached, the number of lines made or the final score.

In addition, the Leap Motion is able to provide all the information related to the hand that is performing the rehabilitation. The Hospital has requested that the following information must be provided for this game at any frame: the level of the game, the current frames per second, the frame identificator, the number of hands in that frame, the number of tools, whether the hand is right or left, the confidence of the hand, the grab strength of the hand and the degree of inclination of the hand. The game generates another file with all this information. The progress of each patient can only be revised by the doctor by introducing a particular password. In this way, as the rehabilitation progresses, the patient's progress can be followed.

Once the patient has been registered, he can access the menu of the game. From here it is possible to play the serious game, see the controls (see Figure 3.8) and make the calibration of the devices.

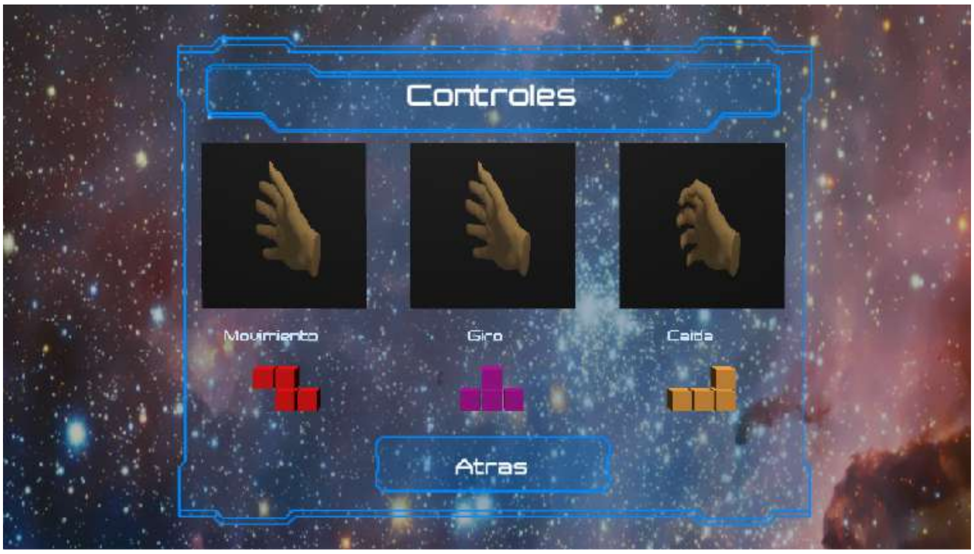

Figure 3.8: Controls of the serious game.

The calibration is different for each device. On the one hand, the Leap Motion controls the game with the pronosupination of the arm and the closing of the hand. This parameters can be calibrated in this screen to meet the needs of the patient, and they can be changed at any time. Thanks to this, if the patient improves his range of motion the values can be updated. The rehabilitation will always be adapted to the level of the patient and the game experience will always be the best.

In the actual state, the Falcon device provides force to the patient in the game. To meet also the needs of each patient, this force can be changed too. As the patient develops strength and get used to the game, the strength may be increased.

All the scenes have a *"back"* button which brings you back to the previous screen.

In this way, if at any time the user gets lost in the menu or wants to make a previous change, it is always possible to go back. The whole menu is controlled with the mouse and the keyboard. It is connected with the second scene, the serious game.

This second scene is controlled with the devices explained in Chapter 3 and not with the mouse. However, it is possible to return to the menu if the *escape* key is pressed during the game. This scene is comprised by the box where the pieces fall and a group of markers that show the state of the game:

- *"Lineas"*: Displays how many rows has been eliminated in this game.
- *"Siguiente"*: Show the piece that will appear after the current one when it falls.
- *"Puntuacion"*: Displays the score of the current game. Every time a row is eliminated 100 points will be added to the score. However, if the player manages to make four lines at the same time (play called *Tetris*) the score will be 500. This reward is intended to encourage the patient to continue playing and to achieve a higher score with fewer lines.
- *"Nivel"*: Displays the level of the current game. Every 10 rows eliminated the level rises by one point. The speed of fall of the piece also changes with the level. Each level up leads to an increase of the falling speed.
- *"Velocidad"*: Displays the manual increase of speed. This is done by lowering the hand from the reference position. Three speed levels exist, the standard one and two increments.

The game ends when the top of the game box is reached with pieces. When this occurs, the whole box is filled with white cubes and the score appears in the middle of the screen. If any key is pressed, the game returns to the menu screen.

According to the information provided by the hospital, they already have a Tetris in 3d which they are unable to play. According to their information, both their interface and their gameplay is unplayable. Not only is it impossible to perform any kind of rehabilitation, but it is not possible to play in a normal way.

For this reason, this two scenes have been made with simplicity in mind. An attempt has been made to create an easy to use and simple platform. The interface is clear, understandable and has no unnecessary buttons or options. It has all the basic functionalities needed to be a rehabilitation platform. The game does not present any extra elements also, in order not to overload the patient during the rehabilitation. In this way, the patient is able to focus his attention on the game and on the rehabilitation to perform it correctly.

In addition, the serious game has been adapted as much as possible to follow the standards and design of the Hospital. All files originated by the game are identical to those used in the Hospital. This avoids confusion and future format changes. Furthermore, all the code has been commented and explained so that its modification by the Hospital staff will be as simple as possible. The installation and start up of the game is identical to the one used in the Hospital, so there is no need for a user or technical manual.

3.3 Code development

The serious game code has been completely developed from scratch. No template or recycled code has been used for the realization of this project. No guide has been used for the creation of the game, only the inspiration of the original Tetris game. It has been tried to be as close as possible to this title.

Unity presents two main functions that are always present in all scripts pasted to objects. The first is Start, where all the variables and processes to be used throughout the game are initialized. The second is Update, which is a loop that runs uninterruptedly until the object is destroyed. This is where the control of the game takes place.

Every time the loop starts, a number of functions are always executed in the same order. First, if the necessary time has passed, the piece drops one level. After this, the hand information provided by the Leap Motion is collected and processed. According to the parameters of fall, turn or closure, the functions that control the movements of the current piece are activated one by one. For the control of the Falcon, the procedure is the same, only that instead of processing the information of the hand, position the end-effector of the Falcon is processed.

As it can be observed, the sending of information by the devices is constant. This is necessary in order to achieve the correct functioning of the whole system and offer a good game experience.

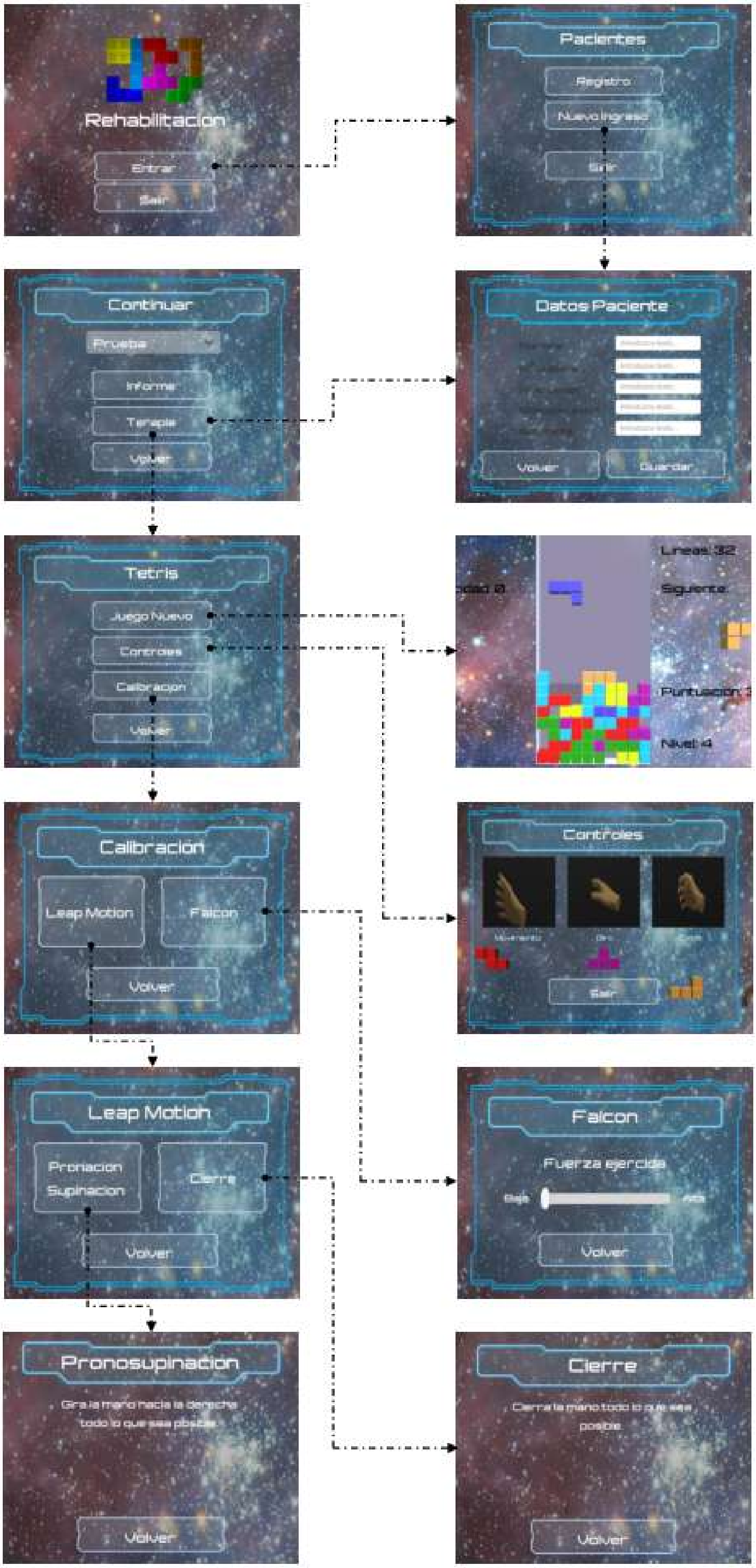

Figure 3.7: Flux diagram of the different screens of the menu.

Chapter 4

Clinical Validation as a Proof of Concept

To validate, test and check the usability of the serious game, a proof of concept was made. As the serious game is going to be introduced in the Hospital Nacional de Parapléjicos project, tests has been made there, in Toledo. The Biomechanics and Techincal Aids group is in charge of developing the project, so the tests have been carried out in it department. The study was carried out for obtaining data which supports the feasibility of the platform developed, and also to examine that SCI patients have the ability to manipulate the applications in a successful way by means of Leap Motion and Novint Falcon.

The subjects have performed a set of repetitions with the serious game during the morning of a day. Only one experimental session has been conducted. In order to be able to observe the evolution of the subjects with each repetition of the game, a record of the first and the last repetition has been made. Measuring the performance of these repetitions, the validity of the serious game will be analyzed and conclusions will be obtained.

In this study, healthy subjects and patients with incomplete cervical SCI have participated. Since two different test groups have been involved, greater data variability can be obtained.

4.1 Participants

In the validation 7 people have participated, five healthy subjects and two cervical SCI patients. The SCI patients have an incomplete lesion in the motor and sensitive aspect. Therefore, these patients have motor and sensory function preserved below the level of the lesion. All patients involved in the study need to have control of their UE including shoulder and wrist movement allowed. In the table 4.1 the clinical characteristics from all SCI patients are provided.

Subject	Age	Sex	Injury Level	AIS Scale	UEMS [1]
H1	40	F	-	-	25
H2	28	F	-	-	25
H3	21	M	-	-	25
H4	24	F	-	-	25
H5	20	F	-	-	25
P1	38	M	C2	D	21
P2	22	M	C6	D	23

Table 4.1: Functional characteristics of the sample analyzed.

4.2 Intervention

The experimental sessions were made within the same day for each participant, with only one experimental session with several repetitions of the serious game developed.

In the SCI group, the arm with less mobility was selected for performing the experimental session. It was the same member in which they were receiving traditional rehabilitation in physiotherapy sessions and the one in which they wanted to improve their skills. Thanks to this it will also be possible to observe the differences between the rehabilitation carried out with the serious game and that carried out with the traditional one. In the healthy group, all subjects performed the experiment with their right hand because all of them are right-handed.

The virtual application by means of Leap Motion has to be manipulated with the elbow in 90º of flexion with the aim of avoiding the movement of external-internal rotation and obtaining a successful pronation and supination movement of the forearm. This is very important for correct test results and for patients to carry out rehabilitation properly.

4.3 Results

Serious game
The results of the validation made with the serious game are presented in the table 4.2. This table contains the number of times the game has been played(repetitions) by healthy people and patients and the information related to the first and the last game he has played. The number of rows eliminated, the maximum level reached and the total time of play is the information subtracted from the game.

[1] Muscle Force (0-5 points) for each muscle group related to the upper extremity analyzed.

Patient	Repetitions	First game			Last game		
		Lines	Level	Time	Lines	Level	Time
H1	5	6	1	4’29”	32	4	17’3”
H2	4	3	1	6’45”	26	3	15’21”
H3	3	9	1	7’53”	17	2	9’7”
H4	4	1	1	4’21”	24	3	15’45”
H5	6	4	1	4’56”	17	2	13’44”
P1	6	0	1	1’57”	27	3	10’49”
P2	2	9	1	9’27”	23	3	15’28”

Table 4.2: Results of the validation test.

The information shows that there is an improvement in the total rows eliminated, the maximum level reached and the total time of play. This indicates that both patients and healthy users need to adapt to the game system. It may be complicated the first time, but as the number of sessions increases, the results improve considerably. In addition, it can be observed that there is not much difference between the results of the patients and the results of the healthy group (see Table 4.3). In fact, there are patients who have achieved a greater number of eliminated rows and have endured playing longer than some people in the healthy group. This indicates that the serious game developed works for both cases, with healthy people and in presence of neurological pathology. Furthermore, the patients are the most favoured, as they have performed a large number of rehabilitation movements in a single game.

		Healthy (n=5)	Patients (n=2)
Repetitions		4.4	4
First game	Lines	4.6	4.5
	Level	1	1
	Time	5’41”	5’42”
Last game	Lines	23.2	25
	Level	2.8	3
	Time	14’78”	15’28”

Table 4.3: Validation test results mean.

Usability Questionnaire

After the validation tests, both patients and healthy people filled out a questionnaire to provide feedback about the experience. It is anonymous and it is an excellent tool to obtain an opinion about the platform and thus improve it in the future. The questionnaire provided uses a 5-point Likert scale being 1 strongly disagree, 5 strongly agree and 3 neutral. Two questionnaires have been developed, one for the healthy people (see Table 4.4) and another one for the patients (see Table 4.5).

Both of them share almost the same questions, with the exception of three. The

Question	Score					
	Mean (± s.d.)	H1	H2	H3	H4	H5
Q1. The game has been enjoyable.	4.2	4	4	4	5	4
Q2. Understanding how the game works was easy.	4.6	5	3	5	5	5
Q3. The game has reacted well to the controls.	3	4	2	3	3	3
Q4. You would be comfortable to do this kind of exercise at home.	4.8	5	5	4	5	5
Q5. The game has motivated you to continue with the exercises.	4.2	5	4	3	5	4
Q6. The exercises carried out are useful on a day-to-day basis.	4.4	4	4	4	5	5
Q7. Would you play the game in your free time?	4.2	5	4	3	5	4
Q8. Does your arm feel tired after the games?	2.6	3	2	2	3	3

Table 4.4: Results of the healthy people questionnaire.

healthy group questionnaire have the question "The exercises carried out are useful on a day-to-day basis", that wants to make the healthy people question themselves if the serious game really rehabilitates daily movements. The patient questionnaire have the questions "Would you use this game as a complement to traditional therapy?" and "The game is appropriate for someone with your level of injury". These two questions are key to the Thesis as patients have to want to use the platform in their day-to-day life alongside traditional therapy. The rest of the questions are mainly focused on the user and their interaction with the platform.

Above all the questions, it should be noted that most of the subjects have scored the "You would be comfortable to do this kind of exercise at home." question with the highest score. This, added to the rest of the answers, shows that the serious game has been satisfactory for the subjects.

4.4 Conclusion

According to the results, rehabilitation for the upper extremities with the serious game is feasible. It seems even ready to be played by both patients and healthy people.

The information from the game sessions shows that as the number of game sessions increases, the results improve considerably. In addition, there are no notable differences between the results of the study groups. This supports the idea that the

Question	**Score**		
	Mean (± s.d.)	P1	P2
Q1. The game has been enjoyable.	4	4	4
Q2. Understanding how the game works was easy.	4	4	4
Q3. The game has reacted well to the controls.	3.5	3	4
Q4. You would be comfortable to do this kind of exercise at home.	4	4	4
Q5. The game has motivated you to continue with the exercises.	4	4	4
Q6. Would you use this game as a complement to traditional therapy?	5	5	5
Q7. The game is appropriate for someone with your level of injury.	4	4	4
Q8. Would you play the game in your free time?	4	4	4
Q9. Does your arm feel tired after the games?	2.5	2	3

Table 4.5: Results of the patients questionnaire.

game seems playable for both of them.

The objective data obtained from the questionnaires show a high affinity of the subjects to the serious game. The vast majority have found the game easy to understand and fun, and would continue to play it. Healthy people remarked that they would play the game at home, which is very important. Thanks to this, rehabilitation could be brought home in a simple way. Also, patients remarked that they would play the game as a complement to traditional therapy, and that they think this therapy is useful for people with the same level of injury. These results show that the game is really useful for patients and that they themselves would be happy to continue using it in rehabilitation.

However, according to the feedback provided, sometimes when some gestures are made, the game is not able to recognize them properly and it make another ones. This is not a problem of the game, but the Leap Motion. The detection system of the device is not as good as expected, because of its low price.

On the other hand, it should also be noted that most of the subjects have shown that they have ended up tired after the test. This is not a problem, because it means that the arm is working at the same time that it is playing. Serious game is not only playful, but also work is executed with the upper limb.

In conclusion, the serious game has been able to amuse the subjects while simultaneously performing a large number of repetitions of the rehabilitation movements.

Chapter 5

Conclusion and Future Work

5.1 Conclusions

New technologies have made their way into the field of rehabilitation in recent years. This therapeutic modality presents several advantages: a follow-up of the patient's treatment over time, a constant tracking of the patient's movements during exercises, a greater motivation of the patient in rehabilitation and an increase in the number of repetitions during rehabilitation, are only some of the advantages that this technology offers. Virtual reality and aid robots make rehabilitation much more attractive. However, these technologies are expensive, and not all hospitals and people can afford them.

This thesis is born from the sum of this need and the amount of benefits offered by these new technologies. For this reason, a serious game for rehabilitation for the upper extremity has been designed and developed with the help of the Leap Motion. This device is capable of detecting the patient's hands without any sensor attached to it and, therefore, without causing any injury or possible damage. In addition to the game, a patient tracking system has been developed, where they can be registered by doctors and monitor their rehabilitation. Thanks to the developed platform, patients can enjoy at the same time they do the rehabilitation. Therefore, the time they spend doing the exercises increases, while at the same time they monitor their improvement over time. All these advantages make this platform a great complement to the traditional rehabilitation methods. In addition, the Novint Falcon has been implemented into the game too. This haptic device is capable of providing strength to the user while playing. This is another type of rehabilitation that has been carried out which will be completed and tested in the future.

The interface and the serious game have been developed to meet the requirements for an adequate SCI rehabilitation. It has been created from scratch with the video game software Unity 3D. This allows any changes that need to be made in the future to be simple. In addition, since each spinal cord injury is different for each patient, the game is customizable. A calibration has been introduced into it, also taking into account that the patient's needs will change as the rehabilitation progresses. The serious game is also going to be included within the RehabHand prototype developed in the Hospital Nacional de Parapléjicos in the context of a research Project. The capability of the game to work with the supination and pronation of the arm, as well as the closing of the hand, make it a very useful tool for rehabilitation.

In order to validate the usability of the platform with SCI patients, a proof of concept has been performed. A number of tests have been performed on both patients and healthy people. These have consisted of testing the game several times in order to obtain feedback. According to the results of the questionnaire given to the patients and the results of the tests with the serious game, the game seems to be feasible for its use. The information obtained shows that both patients and healthy people present an improvement in play, which leads to an increase in rehabilitation. Not forgetting that all this is linked to a general good gaming experience. Both groups have been comfortable while playing and would bring rehabilitation home.

However, an important limitation of this study has been that the serious game by means of Novint Falcon couldn't be tested in SCI patients yet. The results in relation to the proofs performed in patients will be presented in future works.

In summary, an innovative rehabilitation platform for the upper extremity of the body has been developed in this Master's Thesis. Its low price, its customization and its virtual reality environment make it an excellent complement to traditional rehabilitation. Moreover it does not harm the patient and encourages him to continue with the rehabilitation in an enjoyable way.

5.2 Future work

This Thesis opens futures lines of work to improve the rehabilitation platform.

- As it could be seen in the results of the validation, the game does not respond as well as it should. An improvement of the software of the game or changing the Leap Motion for a better device could bring a better game experience for the users.
- The results shown in the proof of concept are encouraging. However, the number of people who have made the tests is scarce. A larger study of the rehabilitation platform would help to improve it and to be adapted in the future to a larger number of people.
- The communication protocol between the Novint Falcon and Unity is already working. This device is a haptic tool that could bring another kind of rehabilitation. However, it has not been tested yet. If a more in-depth study of this device were done and tests with patients were made, this device could be

a great complementary tool for rehabilitation with the serious game developed in this thesis.

- Currently, the platform only shows progress to the doctor. If tables and graphs were created to show the patient's progress, they could motivate the patient to continue with rehabilitation.
- The platform is in Spanish to meet the needs of the Hospital. It could be a great breakthrough to translate it into English and other languages to bring rehabilitation to a larger number of people.
- The serious game is playable for both hands. However, calibration is only performed to collect values for one hand. If the hand is changed, you need to perform the calibration again. Implementing a database that would store the information for each hand would be a great improvement to the system.

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Appendices

Appendix A

Impact

A.1 Introduction

In Spain, 1000 new cases of Spinal Cord Injury occur every year. This type of injury radically changes the lives of the people who suffer it, thus having a great impact on their day to day. Rehabilitation is a key factor for their physical and mental recovery, whose objective is the reincorporation of patients into society. This thesis has attempted to make the rehabilitation process more enjoyable and fun, as well as tracking the patient's progress. For this purpose, a platform has been developed with a serious game for the rehabilitation of the patient's upper extremities.

A.2 Impacts

The different impacts of this Master's Thesis have been categorized in different groups:

- Ethical impact: this impact is controlled as the Hospital Nacional de Parapléjicos in Toledo has passed the ethics and clinical research committee of the hospital complex in Toledo before doing the tests. With this, the approval to do the study has been obtained. In addition, the patients had to sign the corresponding informed consent to do the tests and they have been informed properly of all the procedures in which they were involved.

- Economical impact: this project has developed a low cost platform for the upper extremity rehabilitation. Also, the simplicity of use of the system would allow several patients to perform rehabilitation at the same time, so the therapist could reduce the general treatment time. Because of that, it will reduce the general costs of rehabilitation.

- Social impact: the rehabilitation provided by the system developed in this Master's Thesis is enjoyable and fun. In addition, it motivates patients to perform more repetitions of the upper extremities. Therefore, patients will have an impact on their day-to-day life, as they will be able to improve their condition faster and in a more pleasant way.

- Environmental impact: there is no environmental impact due to the development of this Master Thesis.

- Legal impact: all the activities performed during this Thesis are in framework of the "Ley de Investigación biomédica" 14/2007 (BOE 159, 4th July 2007). Therefore the legal impact of this project falls within this framework not causing any further impacts. On top of that, the data obtained from each participant is protected by the Spanish Law "Ley Orgánica" 15/1993 for Personal Data Protection law of 13th December (BOE 298, 14th December 1996, pages 43088-43099). All researches and engineers in charge of the experiments are protected by the Spanish Law 54/2003 of 12th April, which deals with the regulatory framework for Labour Risk Prevention.

A.3 Conclusion

In summary, this master's thesis presents a great impact for people with spinal cord injury and for hospitals. A platform for upper extremity rehabilitation has been developed that amuses patients while improving their physical condition. This platform is also low-cost and reduces working time for occupational therapists.

Appendix B

Budget

The Master's Thesis has been developed in the Control and Robotics laboratory (RoboLabo) in the Universidad Politécnica de Madrid. The validation test has been made in the Hospital Nacional de Prapléjicos from Toledo. An approximate budget has been made taking into account the resources, both material and human, that have been used.

- **Human resources costs.**
  The salary of all the people involved in this project is being considered: associated engineer, software engineer and engineering student. Table B.1 show all the content.

- **Material equipment costs.**
  The material equipment used in this Thesis, software an technical equipment, is displayed in Table B.2.

	Working hours	**Cost per hour (€)**	**Total costs (€)**
Associated engineer	30	40.00	1200.00
Software engineer	100	25.00	2500.00
Engineering student	900	16.00	14400.00
Total			**18100.00**

Table B.1: Human resources costs.

	Cost (€)	**Time used (month)**	**Lifetime (years)**	**Total cost (€)**
Leap Motion	100.00	4	2	100.00
Novint Falcon	300.00	4	2	300.00
Personal Computer	1500.00	4	5	1500.00
Total				**1900.00**

Table B.2: Material resources costs.