UNIVERSIDAD POLITÉCNICA DE MADRID

ESCUELA TÉCNICA SUPERIOR
DE INGENIEROS DE TELECOMUNICACIÓN

MASTER THESIS

MÁSTER UNIVERSITARIO EN INGENIERÍA BIOMÉDICA

DESIGN AND IMPLEMENTATION OF A VIRTUAL REALITY PLATFORM FOR UPPER LIMB REHABILITATION WITH ELECTROMYOGRAPHY (EMG) MONITORING

DELIA SEPÚLVEDA MUÑOZ

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Tutor:
ANA DE LOS REYES GUZMÁN

Cotutor:
ÁLVARO GUIÉRREZ MARTÍN

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Abstract

The aim of this Master Thesis is to design and implement a virtual reality platform with electromyography monitoring, that will be used for upper limb rehabilitation in cervical spinal cord injury patients.

Spinal cord injury is a neurological disease that causes permanent changes in strength, sensation, and other body functions below the site of the injury. One of its possible consequences is the affectation of the upper limb function, limiting the patient's autonomy in the execution of activities of daily living.

Nowadays, robot aided and virtual reality environments are used usually in rehabilitation tasks due to their effectiveness. These technologies can be used as rehabilitation exercises complementary to the traditional ones. Combining these two types of rehabilitation, patients can receive more quantity of therapy.

The virtual reality platform is formed by a set of serious games, games designed for different purposes rather than pure entertainment, in this case, a rehabilitation purpose. Each of these games has different upper limb rehabilitation objectives, but all of them improve the coordination and muscle strength. With virtual reality, patients feel more motivated, adherence to treatment increments and the level of attention increases during the process of motor rehabilitation. Therefore, these therapies can improve motor learning and functional mobility in patients with motor impairments.

In the rehabilitation process designed, patients feel a haptic feedback for exercising the arm muscles strengthening. Haptic feedback consists of the use of a technological interface that interact with users through the sense of touch. Consequently, patients will feel a total immersion sensation in the game. They can feel different sizes and shapes, receiving a force feedback.

During the rehabilitation working, the electromyography signal of the upper limb muscles will be caught with eight sensors disposed in an armband. This signal is used to monitor the muscle contraction and the patient progress. The patient tracking is very important for offering objective information about the patient's

performance to the clinicians.

To accomplish this task, the game development platform Unity 3D will be used. The games must fulfill the real time specification for achieving a realistic experience. In addition, the execution frequency is important for achieving a continuity in the patient movement inside the virtual game. Therefore, the communication protocol between the different sensors and actuators is crucial in the development.

KEYWORDS

REHABILITATION, VIRTUAL REALITY, HAPTICS, SERIOUS GAMES, UPPER LIMB

Resumen

El objetivo de este Trabajo de Fin de Máster es diseñar e implementar una plataforma de realidad virtual con monitorización electromiográfica, el cual será utilizado para la rehabilitación del miembro superior en pacientes con lesión medular cervical.

La lesión medular es una enfermedad neurológica que causa cambios permanentes en la fuerza, la percepción de sensaciones y otras funciones corporales que se desarrollan por debajo del lugar de la lesión. Una de sus posibles consecuencias es la afectación de la función del miembro superior, limitando la autonomía del paciente en la ejecución de las actividades de la vida diaria.

Hoy en día, los dispositivos robóticos y los ambientes de realidad virtual se utilizan usualmente en tareas de rehabilitación debido a su eficacia. Estas tecnologías se pueden utilizar como ejercicios de rehabilitación complementarios a los tradicionales. Combinando estos dos tipos de rehabilitación, los pacientes pueden recibir más cantidad de terapia.

La plataforma de realidad virtual está formada por un conjunto de "'serious games"', juegos diseñados con otros fines diferentes al del puro entretenimiento, en este caso, rehabilitación. Cada uno de estos juegos tiene diferentes objetivos rehabilitadores, pero todos ellos mejoran la coordinación y la fuerza muscular. Con la realidad virtual, los pacientes se sienten más motivados, la adherencia al tratamiento aumenta y el nivel de atención se incrementa durante el proceso de rehabilitación motora. Por lo tanto, estas terapias pueden mejorar el aprendizaje motor y la movilidad funcional en pacientes con discapacidades motoras.

En el proceso de rehabilitación diseñado, los pacientes sienten una reacción háptica para ejercitar el fortalecimiento de los músculos del brazo. La retroalimentación háptica consiste en el uso de una interfaz tecnológica que interactúa con los usuarios a través del sentido del tacto. En consecuencia, los pacientes sentirán una sensación de inmersión total en el juego. Pueden sentir diferentes tamaños y formas, recibiendo una realimentación de fuerza.

Durante el trabajo de rehabilitación, la señal de electromiografía de los músculos de la extremidad superior se capturará con 8 sensores dispuestos en un brazalete. Esta señal se usa para monitorizar la contracción muscular y el progreso del paciente. El seguimiento del paciente es muy importante para ofrecer al personal clínico información objetiva sobre el desempeño del paciente.

Para lograr esta tarea, se usará la plataforma de desarrollo de juegos Unity 3D. Los juegos deben cumplir con las especificaciones de tiempo real para lograr una experiencia realista. Además, la frecuencia de ejecución es importante para lograr una continuidad en el movimiento del paciente dentro del juego virtual. Por lo tanto, el protocolo de comunicación entre los diferentes sensores y actuadores es crucial en el desarrollo.

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List of acronyms

SCI: Spinal Cord Injury.

VR: Virtual Reality.

CNS: Central Nervous System.

ASIA: American Spinal Injury Association.

UL: Upper Limb.

WHO: World Health Organization.

DOF: Degrees Of Freedom.

CSV: Comma Separated Value

EMG: Electromyography

IMU: Inertial Measurement Unit

CHAPTER

1

INTRODUCTION & OBJECTIVES

1.1 Context

Spinal Cord Injury (SCI) is one of the most important neurological diseases that produces deficiencies in the field of physical disability. Approximately each year about 1,000 new cases of SCI occur throughout Spain due to trauma, which is the mainly cause, half due to traffic accidents, the rest due to falls, blows, sport accidents or other injuries. Most of these people have permanent damages. It is observed that people with spinal cord injury have mainly difficulties and limitations in mobility (96.9% of cases), in self-care (81.1% of cases) and in carrying out tasks of domestic life (84.3% of cases) (Huete-García, 2012). This situation means that the majority of the population with SCI requires personal support and technical support to carry out these activities.

The health cost of these diseases is very high, the treatment of a patient who suffers a SCI in acute phase, the first 60 days, costs an average of €55,000 plus another €10,000 for the intensive care stay (González-Viejo, 2014). The inclusion of lower cost technologies is a key aspect for reducing the therapy cost. This shows that there is a great need for exciting new systems that utilize modern technology to improve the quality of life for SCI injured patients.

The use of new technologies in the rehabilitation field have been increased in the last years, because patients can increase the therapy. One of these new technologies that are raised is the use of *Virtual Reality (VR)* in rehabilitation therapies. There are evidence that VR, in combination with traditional rehabilitation, produces an acceleration in the rehabilitation process, also patients enjoy more the task performance (Dimbwadyo-Terrer et al., 2016c). This type of therapy can be used during the hospitalization period but also helps for continuing the therapy at home after the medical discharge. In this way, patients do not lose the progress in their rehabilitation.

Integrating gaming features into VR environments has been reported to enhance motivation in adults undergoing physical and occupational therapy. This is called *serious game*, which is a computer-based game with the goal of education and/or training in any form, as opposed to traditional computer games, which are primarily intended to entertain (Omelina et al., 2012). The health care sector is showing steadily increasing interest in serious games.

These computer systems have a significant impact on at least two aspects. The first one is to serve as a means to carry out exercises where the use of virtual environments generates support for conventional treatment procedures making them effective and efficient. The second is the storage and administration of information about patients, their pathological condition and their evolution during the rehabilitation process (Guzmán, 2016).

Therefore, by using game mechanics it is possible to create an engaging experience that simultaneously helps with rehabilitation.

1.2 Motivation and Objectives

The aim of this Thesis is to develop a low cost virtual reality platform for upper limb rehabilitation with electromyography monitoring providing force feedback to the patient. This work takes advantage of immersive VR systems and robotic haptic devices to enhance involvement and engagement of patients, to provide a congruent multi-sensory afferent feedback during motor exercises, and to benefit from the flexibility of virtual scenarios for adapting the motor exercises to the needs of the patient.

The platform will be validated as a proof of concept in the Hospital Nacional de Parapléjicos (Toledo). This rehabilitation platform could be used in a complementary way with the conventional therapy that patients receive.

To achieve this goal the following specific objectives were fixed:

- To study spinal cord motor and sensitive disorders.
- To explore the basis of virtual rehabilitation games and assistive robots.

- To design different software games.
- To integrate with sensors and actuators developing the communication protocol.
- To validate the rehabilitation platform in a proof of concept.

1.3 Thesis Organization

The Thesis chapters are organized as follows:

- An introduction of the spinal cord injuries is presented in Chapter 2, as well as the presentation of traditional and robotics rehabilitation, and the presentation of haptics devices.
- Chapter 3 integrates a commercially available haptic device, the Novint Falcon, into a virtual graphic and haptic interface, Unity 3D, with the inclusion of the myoelectric sensor Myo Gesture Control Bracelet.
- Chapter 4 presents the virtual model of the different serious games with the enabling technology presented in Chapter 3, creating a rehabilitation platform.
- Chapter 5 explains the clinical validation as a proof of concept.
- Finally, conclusions and discussions are addressed in Chapter 6.

CHAPTER

2

BACKGROUND

2.1 Spinal Cord Injuries

The **spinal cord** is a nerve cord that is protected by the spine and extends from the brainstem to the lumbar region (Guttmann, 1981). The spinal nerves appear along the spine, there are 31 pairs of spinal nerves and depending on the region of the spinal cord from which emerge, are named: cervical formed by 8 nerves located in the neck (C1-C8), thoracic 12 nerves located in the chest (T1-T12), lumbar 5 nerves located in the abdomen (L1-L5), sacral 5 nerves located in the pelvis (S1-S5) and 1nerve located in the tailbone called coccygeal (Castro Sierra and Bravo Payno, 1993) (see Figure 2.1).

The spinal cord is part of the *Central Nervous System (CNS)* and it is the main route of body information. The spinal cord does three types of functions: the afferent one, in which the brain receives information from the rest of the body, the efferent function, in which the brain sends governing movement orders, and reflexive actions, being a reflex a simple and uncontrolled response or a learned response. In reflexive actions the brain does not take action.

Spinal cord injury is an alteration of the spinal cord, as result from trauma (work accident, sports, random, traffic etc.), a disease (tumoural, infectious, vascular etc.) or a congenital disease (spina bifida etc.) (Institut-Guttmann, 2018).

When the marrow is damaged, the messages communication is interrupted from

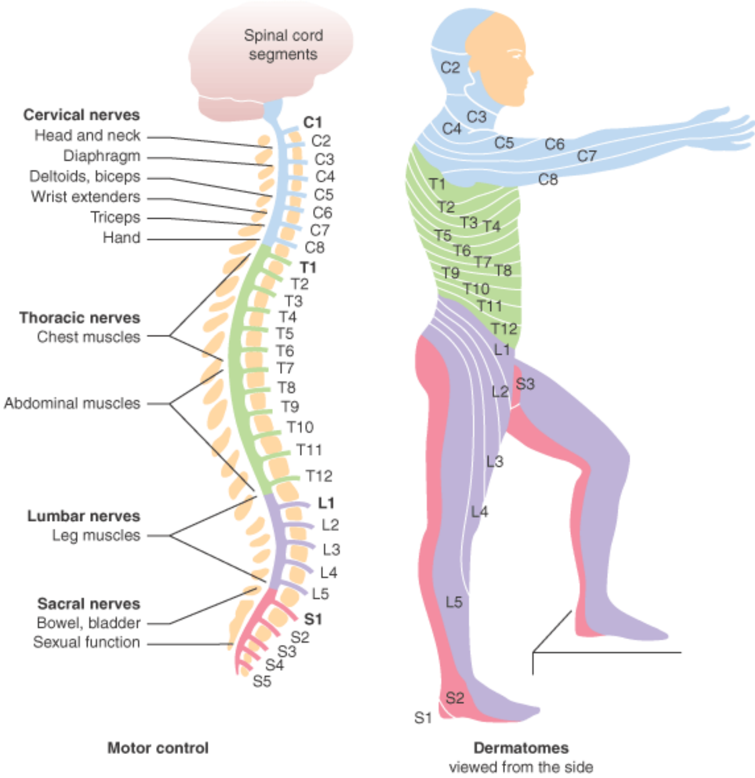


Figure 2.1: Spinal cord structure (Bone&Spine, 2018)

the point where the injury occurred. The interruption causes paralysis of voluntary mobility and absence of any sensation below the affected area. To know the region in which the injury is located is often the key to understand diagnosis and treatment. A person's level of injury is defined as the lowest level of full sensation and function (Hospital Nacional de Parapléjicos, 2018).

SCI is also classified by the degree of impairment. According to the *American Spinal Injury Association (ASIA)*, paraplegia occurs when the legs are affected by the spinal cord damage (in thoracic, lumbar, or sacral injuries), and tetraplegia occurs when all four limbs are affected (cervical damage). 50% of traumatic injuries occur at the cervical level causing a tetraplegia (Huete-García, 2012).

The motor and sensory supply of the *Upper Limb (UL)* is provided by the brachial plexus which is formed by the ventral rami of spinal nerves $C5-T1$. Table 2.1 shows the motor function of each cervical level from which there is functional capacity of the UL.

To classify the spinal cord injury the most use method is the ASIA assessment protocol (American Spinal Injury Association, 2018). It is based on neurological

Level	Motor function
C5, C6	Move shoulder, raise arm (deltoid); flex elbow (biceps)
C6	Externally rotate (supinate) the arm
C6, C7	Extend elbow and wrist (triceps and wrist extensors); pronate wrist
C7, T1	Flex wrist; supply small muscles of the hand

Table 2.1: Motor function of each cervical level

responses, touch and pinprick sensations tested in each dermatome, and strength of the muscles that control key motions on both sides of the body. Therefore, two sensory examinations take place, a motor examination and a classification framework to quantify the severity of the spinal cord injury. The classification is shown in Table 2.2.

A = Complete injury.	No motor or sensory function is preserved in the sacral segments S4 or S5.
B = Sensory incomplete.	Sensory but not motor function is preserved below the level of injury, including the sacral segments.
C = Motor incomplete.	Motor function is preserved below the level of injury, and more than half of muscles tested below the level of injury have a muscle grade less than 3.
D = Motor incomplete.	Motor function is preserved below the level of injury and at least half of the key muscles below the neurological level have a muscle grade of 3 or more.
E = Normal.	No motor or sensory deficits, but deficits existed in the past.

Table 2.2: ASIA Impairment Scale

The level of injury is the segment located above the most affected rostral segment. The same injury can have different motor and sensory levels and differ in both hemibodies. The ASIA graduation (American Spinal Injury Association, 2018) allows to determine the severity of the injury by classifying them in:

- **Complete SCI.** Complete injuries occur when the spinal cord is fully severed, eliminating all functions below the injured area.

- **Incomplete SCI.** With incomplete injuries, the spinal cord is only partially severed, allowing the injured person to retain some function. Involves preservation of motor or sensory function below the level of injury in the spinal cord.

Incomplete spinal cord injuries are increasingly common, thanks in part to better treatment and increased knowledge about how to respond to a suspected spinal cord injury. These injuries now account for more than 60% of SCI (National Spinal Cord Injury Statistical Center, 2016).

Socioeconomic impact of spinal cord injuries

Cervical SCI is often a catastrophic condition requiring chronic care. Despite an enormous amount of research in SCI, the neurological prognosis for a patient with severe SCI remains dismal. Furthermore, the majority of patients with SCI are young, the greatest number of injuries occurs between the ages of 16 and 30 years, with approximately 80% of the injuries in the group of 16 to 45 years of age. The economic and societal impact is enormous, both to the immediate family and the society at large (Goel et al., 2016).

Life expectancy after such an injury is markedly reduced due to complications proportional to the severity of injury or remaining neurologic functions. SCI is associated with a risk of developing secondary conditions that can be debilitating and even life-threatening, such as, deep vein thrombosis, urinary tract infections, muscle spasms, osteoporosis, pressure ulcers, chronic pain, and respiratory complications (World Health Organization, 2018). Acute care, rehabilitation services and ongoing health maintenance are essential for prevention and management of these conditions.

The Impairment of UL is one of the most common sequels following neurological lesions (Murphy et al., 2006), the loss of arm and hand function is one of the most devastating consequences in tetraplegia (Lu et al., 2015). Small progresses in arm and hand function may lead to increased autonomy in daily activities (Hoffman et al., 2000), improving independence and quality of life. For this reason, improvement in UL function after cervical SCI is a top priority in individuals with tetraplegia (Kalsi-Ryan et al., 2012).

The economic cost associated with people with SCI in US is between 92 and 212 millions of euros according to the injury mechanism. The average yearly expenses in health care costs and living expenses, for people with low tetraplegia ($C5-8$) is €$659,000$ during the first year and €$97,000$ each subsequent year (National

Spinal Cord Injury Statistical Center, 2016). Estimates for Spain give an average hospitalization cost of between €60,000 and €100,000 during the first year of the injury (García-Altés et al., 2012).

The worldwide incidence of SCI lies between 10 and 83 per million inhabitants per year (Wyndaele and Wyndaele, 2006). In Spain, the global incidence (traumatic and medical) is estimated between 12-20 million per inhabitants, with 70-80% of traumatic causes. Inside these traumatic causes, half of them are because of traffic accidents, the rest due to falls, blows, sport accidents or other injuries (Huete-García, 2012).

2.2 Traditional Rehabilitation Methodologies

According to the *World Health Organization (WHO)* rehabilitation is a set of interventions designed to optimize functioning and reduce disability in individuals with health conditions in interaction with their environment. Health condition refers to disease (acute or chronic), disorder, injury or trauma (World Health Organization, 2017).

Nowadays, there is no complete cure for the SCI, so the rehabilitative treatments are approached from several perspectives (Mazaira et al., 1998). The objective for a person with SCI is to become as independent as possible in the performance of daily functions and activities. Short and long term functional targets are determined by the calculation of the patients' ASIA scale, taking into consideration medical and social status and the individualized rehabilitation plan. Factors such as injury level, age, weight, general health status, motivation and spasticity affect the ambulation potential (Nas et al., 2015).

The most important goal is realization of the independent mobilization for paraplegic patients during the chronic period. The aim of rehabilitation in this period is to prevent complications that may occur long term. Passive exercises should be done intensively to resolve contractures, muscle atrophy and pain during the acute period of hospitalization. Moreover, positioning of the joints is important in order to protect the articulatory structure and maintain the optimal muscle tone. Sand bags and pillows can be useful in positioning. Nonetheless, the most important expectations in the chronic phase are ensuring the maximum independence related to the level of the patients' injury, integration of the patient to society and teaching the importance of the family role (Nas et al., 2015).

The rehabilitation treatment after a SCI is approached from different areas, highlighting for this Thesis the treatment that patient receives on the upper limb.

Upper limb rehabilitation

This thesis is focused on recovery UL impairment. The recovery and rehabilitation of the arm and hand after SCI is often slow and difficult. The arm and hand are designed to perform very skilled movements which allow us to do daily living activities (Connolly et al., 2013). A study showed recovery of hand function was preferred to that of the bladder, bowel or even sexual function among persons with tetraplegia (Hanson and Franklin, 1976). The most important point in the acute period of rehabilitation in patients with complete paraplegia is to strength of the upper extremities to the maximal level.

Physical therapy is a key component of the rehabilitation process following SCI, and includes a variety of interventions that address multiple domains (Taylor-Schroeder et al., 2011). Physical therapy includes exercise programs geared toward muscle strengthening in UL. Inside the field of the physical therapy exists the neurological physical therapy, a field focused on working with individuals who have a neurological disorder or disease. These can include spinal cord injury, stroke, Alzheimer's disease, multiple sclerosis, and Parkinson's disease. Common impairments associated with neurologic conditions include impairments of vision, balance, ambulation, activities of daily living, movement, muscle strength and loss of functional independence.

Neurorehabilitation steps in to help the patient to recover, maximize their functional and cognitive abilities and to help them realize their personal goals. Early rehabilitation is important to prevent joint contractures, the loss of muscle strength and conservation of bone density (Nas et al., 2015).

In this type of rehabilitation there is two types of exercises, functional and non-functional (Hospital Medical School University of London, 2017).

- **Functional exercises (FS)** are based on improving how you perform normal activities throughout your day. UL functional tasks can be bilateral functional activities like throwing and catching a ball, unilateral reaching activities which are object directed, for example, picking up a cup. There are also unilateral reaching activities which are spatially directed, like taking hand in and out of pocket or dexterity exercises (including all grasp and manipulation activities) for example, writing. The aim is to make these movements easier and pain free.

- **Non-functional (NFS)** consisted of active or assisted-active or passive movements of all upper limbs articulations in all directions. These exercises did not reproduce motor functions similar to everyday use. Examples of this type of activities are: soft tissue mobilization, joint mobilization, facilitation of muscle activity/ movement, positioning, specific sensory input, splinting techniques, exercise to increase strength, balance and mobility incorporating UL activity. Task are performed with the help and supervision of the therapist.

On the one hand, NFS tasks are important when the main rehabilitation goal is to gain amplitude in a specific movement, rather than functionality. On the other hand, if therapy is focused on functional gain, particularly of fine movements, FS seems to be the choice (McCombe Waller and Whitall, 2004).

All these training works through mechanisms of experience-dependent plasticity, and there is now interest in enhancing the potential for plasticity to increase the efficacy of motor-skills training. During the rehab process, it is now clear that in addition to compensatory behavioral strategies, spontaneous injury-induced structural reorganization in the adult CNS can occur over a protracted time course, which at least partially contributes to functional recovery (Ding et al., 2005).

The process of plasticity consists of changes in the activation pattern either of structure or function that involves alteration of the strength of existing connections and sprouting of new neural connections. There is now considerable evidence that cortical representation of body parts is continuously modulated in response to activity, behavior, and skill acquisition. Reorganization of cortical representation occurs after CNS injuries such as stroke or spinal cord injuries, which may account for recovery of function after injury. Although it is likely that some of the reorganization after injury takes place in the cortex, plasticity changes may also occur in subcortical structures such as the thalamus, brainstem, and spinal cord (Kaas, 2001). Therefore, neuroplasticity is essential in the rehab process.

Three key elements in neurorehabilitation are repetition, feedback and patient motivation. Repetition is important for motor learning and for the cortical changes that originate them to occur, but it is not repetition alone that causes motor learning, but rather it must be linked to a sensory feedback about the result of each one of the realizations. On the other hand, to perform again and again the activities required for neurorehabilitation, it is essential the motivation of the subject (Peñasco-Martín et al., 2010). Some aims of the neuroplasticity is the process of learning and to create a learning the patient need to be focus on the therapy.

The traditional arm and hand therapies has some limitations like the difficulty to keep patients motivated, limited number of repetitions, therapy limited by availability of therapists and unclear feedback regarding progress and performance. All these limitations can be supplied by the use of robotics and VR games in the rehab therapies.

To change the traditional motor rehabilitation programs, the incorporation of VR games can make a difference in the therapies. Because integrating gaming features into VR environments has been reported to enhance motivation in adults undergoing physical and occupational therapy. In contrast with traditional programs, which can be tedious and monotonous due to traditional interventions, require simple and repetitive movements, resulting in low adherence to the treatments. The number of repetitions can be increased using a specific rehabilitation facilitated by robot-aided therapy, intensifying the rehabilitation care and augmenting the total hours of rehabilitation dedicated to the paretic limb. Intensifying the rehabilitation training program means improves the arm function (Oujamaa et al., 2009).

Also in rehabilitation, considerable amounts of practice are required to induce neuroplastic changes and functional recovery of neurological motor deficits. However, conventional therapies do not provide sufficient intensity for optimizing neuroplasticity because of practical limitations such as its time-consuming and labor-intensive nature, difficulty in transportation to special facilities, and need for insurance coverage (Dimbwadyo-Terrer et al., 2016a).

The majority of prescribed UL exercises in traditional therapy are of low intensity, range of motion or stretching exercises, rather than repetitive practice or strengthening exercises (Connell et al., 2014). Also, there is concern that the dose of UL rehabilitation is too low. Several studies have examined whether increasing the time spent on upper limb therapy makes a difference. One way of increasing dose is to implement a treatment program that patients can administer themselves.

All these limitations of the traditional rehab process can be solved by introducing the use of robot-aided and VR in the rehabilitation.

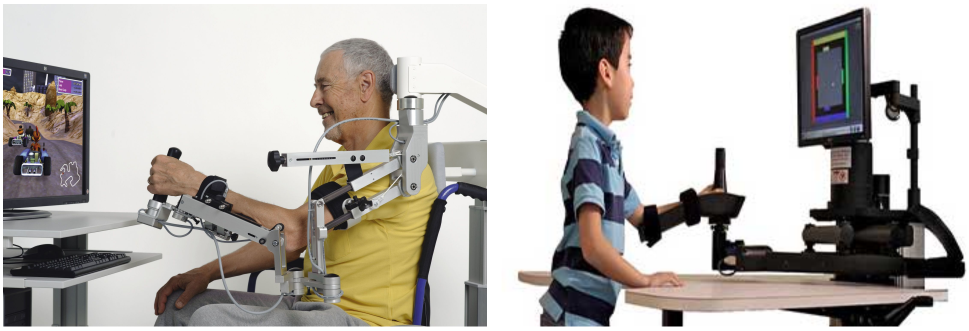
2.3 Rehabilitation based on Robots & Virtual Games

Robotic device seems to be the ideal sensorimotor support. The use of robotic technology in guiding highly specific training regimes might also allow a sufficient number of repetitions to be delivered in a motivating virtual environment (Colombo and Sanguineti, 2001). Therapy robots are machines or tools for rehabilitation therapists that allow patients to perform practice movements aided by the robot (Poli et al., 2013).

According to their mechanical characteristics ans structure, rehabilitation robots can be classified into two main groups (Lo and Xie, 2012):

- **Exoskeletons.** Exoskeletons have a structure which resembles the human upper limb, having robot joint axes that match the upper limb joint axes. Exoskeletons are designed to operate side by side with the human upper limb, and therefore can be attached to the upper limb at multiple locations. This can make it more difficult for the robot to adapt to different arm lengths. One example of this type of rehab robots is ArmeoSpring (see Figure 2.2(a)).

- **Operational machines/end-effectors.** End-effector robots hold the patient's hand or forearm at one point and generate forces at the interface. This type of robot is simpler, easier to fabricate and can be easily adjusted to fit different patient arm lengths. The range of motion that end-effector robots can generate for the upper limb tends to be limited therefore only a limited set of rehabilitation exercises can be produced by these robots. Examples of end-effector rehabilitation robots include the MIT-MANUS (see Figure 2.2(b)).



(a) Exoskeleton. ArmeoSpring (Hocoma, 2018) (b) End-Effector. MIT-MANUS (MIT, 2018)

Figure 2.2: Rehabilitation robots types

The motion type of assistance that can provide these robotics devices for UL rehabilitation can be: active, passive, haptic and coaching (Maciejasz et al., 2014).

- **Active device.** A device able to move limbs. Under such condition, this device requires active actuators which may increase the weight. It may also apply to subjects completely unable to move their limb.

- **Passive device.** A device unable to move limbs, but may resist the movement when exerted in the wrong direction. This type of device may only be used for rehabilitation of subjects able to move their limbs. It is usually lighter than active device since it possesses no actuators other than brakes ans springs.

- **Haptic device.** A device that interfaces with the user through the sense of touch. In most cases it provides some amount of resistive force, often also some other sensation like vibrations. It is sometimes also able to generate specific movements. However, the force it generates is usually small. Haptic devices are commonly used in rehabilitation settings with virtual environments.

- **Coaching device.** A device that neither assists nor resists movement. However, it is able to track the movement and provide feedback related to the performance of the subject. As haptic devices, coaching devices are also commonly used in rehabilitation settings with virtual environments. For example, Microsoft Kinect (Microsoft, 2018).

Robotic UL rehabilitation therapy has been gaining traction in the rehabilitation field as technology advances. It is used to supplement or facilitate rehabilitation by assisting in the repetitive labor-intensive manual therapy that are normally administered by therapists. It decreases the time demands on therapists as the robotic devices can help move the patient's limbs during exercises, thereby increasing the amount of therapy for each patient and increasing the number of patients undergoing therapy simultaneously. The exercises provided by these UL rehab robots can be classified as (Basteris et al., 2014):

- **Assistive.** Subject'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 it is used as a measurement device, without providing force to subject's limb. An exercise in which subjects actively move their limb, although some assistance of the device may be provided. Such type of the exercise may be performed using any of the above listed types of devices.

- **Passive.** Robot performs the movement without any account of subject's activity. An exercise in which the subject remains passive, while a device moves the limb. This type of exercise requires an active device.

- **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.

The combination of robotics with virtual reality has many advantages for intervention, such as enabling the grading of activities, obtaining precise performance measures, providing a safe environment, and being enjoyable and motivating. Research has shown that by actively engaging stroke patients in repetitive tasks, the brain is able to rewire neurological pathways of motor functions, and the patient relearns movement of hand (Merians et al., 2006). Also, these technologies increase the range of possible tasks, partly automating and quantifying therapy procedures, improving patient motivation using real-time task evaluation and reward.

In the medical field physical therapists are already seeing the positive effects of having innovative ways to get their patients moving. Studies have shown that patients using immersive VR as a therapy tool reported less pain due to being distracted by the technology (Hoffman et al., 2000). Use of robotics and VR has emerged in an effort to promote task-oriented and repetitive movement training of motor skills while using a variety of stimulating environments. Other possible benefits of VR include rapid transition between tasks and unlimited affordances, stimulation of cognitive networks and increased activation in secondary motor areas (Dimbwadyo-Terrer et al., 2016b).

VR is a new approach in UL rehabilitation that is gaining popularity. VR provides a unique medium suited to the achievement of several requirements for effective rehabilitation intervention. Specifically, therapy can be provided within a functional, purposeful and motivating context (Sveistrup, 2004). VR offers a major sensory feedback while the subjects are immersed in a VR environment witnessing their own body in movement. The difficulty of the arm function exercises can be modulated according to the performance, the subject's motivation is greater because of the playful aspect of the training.

Robotics combined with VR based rehabilitation will find use as adjunctive therapy, rather than replacement for hands-on therapy. In other words, technological solutions provide a way of providing massed practice, but hands-on therapy is crucial for turning benefits into functional gains (Zariffa et al., 2012). According to (Laver et al., 2017), there is evidence that the use of VR and interactive video gaming may be beneficial in improving UL function and activities of daily living function when used as an adjunct to usual care or when compared with the same dose of conventional therapy. The literature supports the use of VR gaming rehab therapy as equivalent to traditional therapies or as successful augmentation to those therapies (Yates et al., 2016).

Clinical evidences

It is necessary to highlight existing research that use robotics and VR for rehabilitation. In these studies patients experiment an improvement in their motor functionality as well as more involvement in their rehab task.

A clinical study demonstrated the effectiveness of the VR system Toyra (INDRA, 2018) on UL function in tetraplegic people (Dimbwadyo-Terrer et al., 2016a). The study showed the effects of physical and occupational therapy combined with VR program. VR added to occupational therapy, in comparison with the only application of occupational therapy, produce similar results in the UL function. Moreover, the gaming aspects incorporated by VR in conventional rehabilitation appear to promote patient motivation and hence adherence to the treatment.

The NeReBot, a three DoF wire based robot (Masiero et al., 2007), robot allows for repetitive basic movements of the shoulder and elbow by eliminating the gravity effect. The patients actively move their arm towards various points, predetermined at the beginning of each session. The experimental group undergoes 20 hours of robot-aided therapy on top of classic rehabilitation training. The very early intensification leads to a better proximal voluntary hand function compared to the control group.

A different study investigated the viability of Novint Falcon (Novint Falcon, 2018) native applications for rehabilitation at home (Chortis et al., 2008). The games included with the Falcon were used by a patient group while a control group was subject to relaxation. The games were chosen that would motivate the participants to use their arm in order to perform sufficient repetition of UL movements. Performance measures were collected to indicate whether the games were set at a level suitable to the abilities of the participants and that with continued practice they had the potential to show some improvement. The patients show improvements that are not due exclusively to a greater familiarity with the games, since the improvement continues with respect to the remaining scheduled sessions. This suggests that there was also an improvement in motor ability.

Another clinical trial was made utilizing the VR activity station from SenseGraphics (Björkdahl et al., 2008). The user stood in the real world and looked into a virtual world generated in the computer. Patient was now able to reach into a virtual space and interact with 3D objects through a haptic device positioned in the line of sight. It was used for the rehabilitation of a group of 29 patients. The intervention studies show that the subjects made improvements in the kinematic variables measured with the VR system. Adherence to the programme was excellent and may have been facilitated by the novel technique of VR that would enhance their capacity for better UL function.

Rehabilitation based on robotics and VR has particular success among stroke survivors. With up to 75% of stroke patients suffering from mobility problems, studies have found that those using virtual reality games for rehabilitation were 4.9 times more likely to improve their upper body strength compared to using standard therapy (LiveScience, 2018). While a high number of VR systems have been used and have shown promising results in patients with stroke, as far as we know, experiences with people with SCI are scarce. So, there is a big opportunity to create specific designs for these patients.

Nowadays there exist different commercial rehabilitation stations which uses massive products like Nintendo Wii or Xbox Kinect. These product are become popular in the last years, but the main disadvantage of these type of games is that the patient only receive a visual feedback from the therapy. It is demonstrated that the use of force feedback increase the outcome of the therapy. This feedback is usually provided by assistance robots which are expensive one. Therefore, there exists a need for obtaining low cost solution for the upper limb rehabilitation focus on robotic and virtual reality.

2.4 Haptic Feedback

Haptics is the science of applying touch sensation and control to interaction with computer applications. Haptics offers an additional dimension to VR and is essential to the immersiveness of those environments. In everyday life, the importance of the sense of touch is eminent. In addition, the haptic perception plays a major role in every learning process (der Meijden and Schijven, 2009).

There are two main systems that together constitute haptics modality, the cutaneous and the kinaesthetic inputs. The **cutaneous** input is measured by sensors on the skin and the **kinaesthetic** input comes from internal sensory organs (Tiest and Kappers, 2009).

There are two main categories of haptic interfaces: admittance type and impedance type (Carignan and Cleary, 2000). **Admittance** type of haptic systems measure the force exerted by the human user and vary the position of the master device,

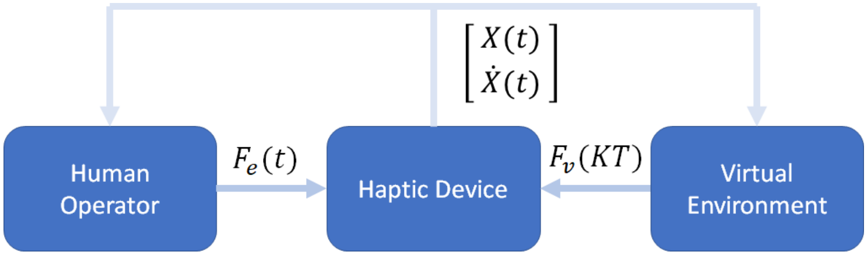


Figure 2.3: Components of a haptic system

according to the relationship of Equation 2.1 where Xh is the position of the haptic device, Fh is the force measured by the haptic device and Y is the admittance of the environment.

$$Xh = Y.Fh \tag{2.1}$$

On the contrary, haptic systems of impedance type measure the position of the haptic device imposed by the user and vary the amount of force applied in response, see Equation 2.2 where Xh is the position of the haptic device, Fh is the force measured by the haptic device and Z is the impedance of the environment.

$$Fh = Z.Xh \tag{2.2}$$

In this case, the haptic system is of impedance type. Because a measure of the position is produced and then the force is obtained through computational methods.

The haptic feedback consists of allowing the human operator to perceive tactile sensations related to the mechanical characteristics of the virtual environment. The haptic sensation allows the human operator that is displacing a virtual object to perceive a reaction force of the moving object. Nevertheless, the haptic feedback must be such that the human operator of the haptic device perceives the virtual world with the maximum fidelity. This requirement is called haptic transparency problem. Nonetheless, it is very difficult to completely eliminate the haptic distortion that exists between the perception and what it should be perceived because of the nonlinearities of actuators and sensors resolution (Monasterio-Huelin and Gutiérrez, 2017).

The haptic instability is typical of a low sampling rate, and can be perceived as oscillations in the end of the haptic device. It is important to note that the haptic perception requires a frequency between 500 Hz and 1 kHz.

Figure 2.3 shows the different components of a haptic system and their relationship, where $Fe(t)$ and $FV(kT)$ represent variable forces with respect to the continuous and discrete time, respectively and $X(t)$, $\dot{X}(t)$ represent the position and velocity of the end of the haptic system or robot.

This force Feedback is the simulations of physical attributes. It is mainly a form of kinaesthetic feedback and is commonly used to simulate a sense of weight to objects, the perceived weight of an object reflects its density and structure. Some devices use motors to manipulate the movement of a peripheral held by the user. The addition of vibro-tactile feedback creates a more realistic environment for users, enabling them to experience how a virtual object moves and responds to interaction.

Its importance has triggered the commercialisation of haptic devices useful for many different application fields. Nowadays, different commercial products can be bought at reasonable prices. A well-known commercial haptic device is the Novint Falcon (see Figure 2.4(a)). It is mainly oriented for gaming applications but it presents some advantages described in Chapter 3 that makes its use desirable for the present Thesis. Another example of extended haptic devices is the PHANTOM (see Figure 2.4(b)) line of haptics. It is portable, 6 *degrees of freedom (DOF)* haptic device from Sensable Technologies. The Virtuose 6D device (see Figure 2.4(c)) is the only product on the market combining a high force feedback in the 6 DOF with a large workspace. It is used as a co-manipulation medical robot and in rehabilitation applications. Finally another device to highlight is Delta3 (see Figure 2.4(d)), this desktop haptic robot has 3 DOF, it is designed for research and engineering experimentation. Taking into account the characteristics and price of these device the most suitable for this purpose is the Novint Falcon.

Among the many functions of haptics, medical use is one of its most interesting. Haptic technology has already been investigated for its application in different fields of medicine. Haptic machines are useful tools for robot-mediated therapy aimed to neuro-rehabilitation, and they could complement and integrate the activities of physical therapists (D'Elia et al., 2016). In combination with a visual display, haptics technology can be used to train people for tasks requiring hand-eye coordination. Some studies with patients show that the effects of VR and haptic technology using computer games achieve a positive change of attitude in the users (Broeren et al., 2009). Also, the use of proprioceptive feedback is demonstrate that is better that only the use of the visual one. A training with an enhancement of an appropriate proprioceptive input early after an SCI might serve as an intervention to prevent neuronal dysfunction (Dietz, 2012). Also, the introduction of a multisensory feedback indicates in different studies that VR systems with an haptic interface can function as a rehabilitation tool for motor impairment and assessment tool for visuospatial neglection (Broeren et al., 2009).

(a) Novint Falcon (Novint Falcon, 2018)

(b) PHANTOM OMNI (Sensable, 2016)

(c) Virtuose 6D (Haption, 2018)

(d) Delta3 (Dimension, 2018)

Figure 2.4: Desktop haptic devices.

CHAPTER

3

ENABLING TECHNOLOGIES

THIS Chapter provides a first approximation to the objective of this Thesis: a low cost, open source, reliable platform designed for UL rehabilitation. The platform is composed by a virtual environment uses for the implementation of the three serious games and two devices, and haptic device for providing force feedback and a monitoring device for providing information about muscle contraction (see Figure 3.1).

The haptic device used is the Novint Falcon, which will be described in Section 3.1. The EMG monitoring device used is Myo armband, its mainly characteristics will be described in Section 3.2. This device is used because of one main advantage: its wireless connection with the computer. The software used for integrating all these technologies is Unity 3D, due to its dominance in video games development. It will be characterize in Section 3.3.

3.1 Novint Falcon

The Novint Falcon (see Figure 3.2) is a desktop haptic robot device with 3 DOF. It is used to simulate touch in a virtual world, allowing you to feel virtual objects or other physical forces. The Novint Falcon is only able to provide kinaesthetic feedback. The device consists of three motorized arms attached to an interchangeable end-effector (Virtual Reality Society, 2018). The Novint Falcon was built for game control

Figure 3.1: Schematic illustration of the rehabilitation platform, using a Novint Falcon, a Myo armband and a virtual environment.

Figure 3.2: Novint Falcon device (Novint Falcon, 2016)

by providing touch output for the hands. But apart from gaming applications the Falcon can also be used for professional purposes, such as telerobotic applications or training simulations.

It is a device that only costs some hundreds euros, but the Falcon is a rather remarkably capable machine, especially compared to its multi-thousand euro competitors. It uses a bog-standard USB 2.0 interface, has 10x10x10 cm^3 of 3D touch space and can exert up to 9 Newtons of force. The device can simulate the feeling of objects to a sub-millimeter precision and refreshed 1000 times per second, making the experience very smooth (Novint Falcon, 2018).

The Novint Falcon can be used to assist, resist or support the patient. However, a drawback of the consumer oriented approach is that the Novint Falcon is not strong enough to help people with severe motor handicaps or spasticity (Palsbo et al., 2011).

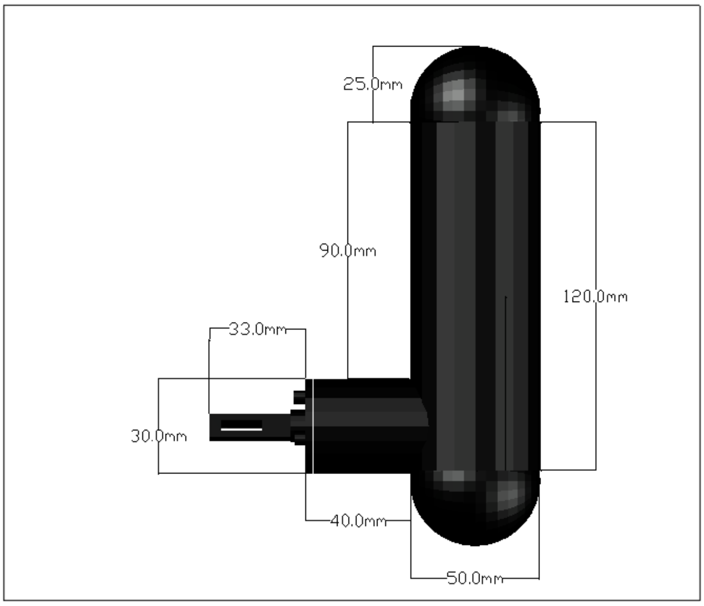


Figure 3.3: HandGrip for tenodesis grasp

While the falcon is an interesting device, its limited work space of 10 m^3 put it at a disadvantage when comparing to other interaction devices such as Nintendo Wii, Playstation Eyetoy or Microsoft Kinect that allow much freer movements. However, these devices have not got haptic feedback.

Due to its low cost and the features that offers, the Novint Falcon can be an excellent tool used with a rehabilitation purpose. There exist some studies, as defined in Chapter 2, that confirm their benefits in the rehabilitation process. Novint Falcon can be used as an end-effector robotic device for upper limb rehabilitation. The main advantage of the end-effector system is that it adapts to patients with different body sizes.

To use this device with a rehabilitation purpose the standard grip, which is a ball grip, need to be changed. This spherical end-effector is difficult to use for patients with neuromotor disabilities, because a fine pinch is necessary to perform the grasp (Curtin, 1999). So, it is necessary to change it. After some discussions with occupational therapists, it results that the best type of grip for these patients is to design a cylinder grip for a better hand-grasp.

The design for the prototype was made for building in a 3D printer (see Figure 3.3). It was made taking into account an average of the principle hand measurements, like the distance from the palm of the hand till the end of the fingers.

In a first test was made with the designed attached to the Novint Falcon. While

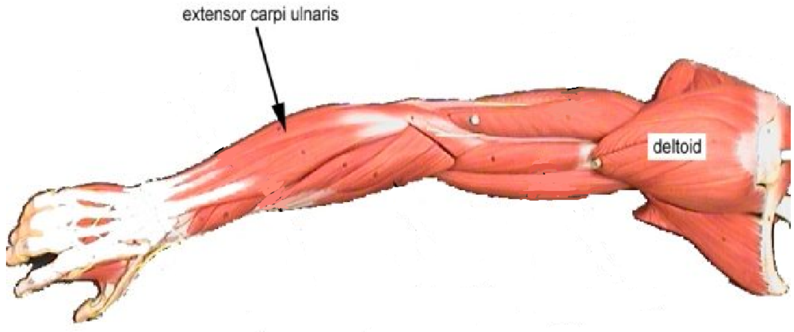


Figure 3.4: Muscles activated by Novint Falcon, adapted from (Carlsbad, 2017)

performing the test, and EMG recording system was located in the main arm muscles. The test showed that using the Novint Falcon to give force feedback activates the Anterior Deltoid muscle, which flexes and medially rotates the arm, and the Extensor Carpi Ulnaris muscle, which extends and adducts the hand at the wrist joint (see Figure 3.4). This was demonstrated by applying varying degrees of haptic feedback in an exercise where participants would press down on a vibrating cube (Nagaraj and Constantinescu, 2009). Therefore, it is concluded that by using the Novint Falcon the shoulder and the forearm will be activated.

A common interface is created to monitor the trajectory made by the patients during therapy. Therefore, therapists can analyze the smoothness of the movements performed. To achieve this, the information about the position in the three Cartesian coordinates are collected in a *Comma Separated Value (CSV)* files and stored on a local level.

3.2 Myo Gesture Control Bracelet

The Myo armband (see Figure 3.5) is a wearable gesture and motion control device working with EMG sensors to measure electrical pulses in the arm, converting them to simple signals able to be fed into a computer to control all manner of odds and ends. It is a gesture control accessory that allows people to control all manner of devices and software as it senses movements in their arm. While muscles expand and contract, the armband sends signals wirelessly to other devices.

Myo armband costs around 200€, which is a competitive price for a device with

Figure 3.5: Myo Gesture Control Bracelet (ThalmicLabs, 2018b)

its characteristics. It uses a Bluetooth 4.0 low energy connection, it has a proprietary muscle activity *electromyography (EMG)* sensor, 9-axis *inertial measurement unit (IMU)*, a rechargeable lithium-ion battery with one full day use out of single charge and haptic feedback which provide short, medium or long vibrations (ThalmicLabs, 2018a).

Deeping into the sensors the device has 8 medical grade stainless steel EMG sensors and highly sensitive nine-axis IMU, containing three-axis gyroscope, three-axis accelerometer, three-axis magnetometer. Thanks to this 9-axis IMU, Myo armband also senses the motion, orientation and rotation of the forearm. With all these sensor the tracking of the patient will be very exhaustive.

This device has a lot of possibilities, for example, the Myo armband can be used to control a prosthetic, with the Modular Prosthetic Limb, developed by the Johns Hopkins Applied Physics Laboratory (Johns Hopkins Applied Physics Laboratory, 2018). The prosthesis use the bracelet to pick up electrical signals from his residual limb muscles. Those signals are transmitted via Bluetooth to a computer inside the prosthetic arm. The computer processes the information and sends it back to the prosthetic to drive motors inside the device. Therefore, this bracelet is a very useful device for tracking the patient movement and muscle contraction during the performance of the rehabilitation games.

In this Thesis, the device is used for obtaining a correct patient monitorization during the performance of the rehabilitation games. It is very important store data about the patient performance because the therapist must follow the rehabilitation process and see the patient improvements. By using this bracelet, the muscle contraction as well as all the arm kinematics can be stored for a posterior data analysis. Therefore the values of the progress in the exercises can be easy stored and used in future examination and evaluation.

For the rehabilitation platform of this Thesis, the chosen positioning for Myo armband is highly dependent of the muscle activation by means of using the Novint Falon. Regarding that most of the movement to implement in the platform, are related with the shoulder, the best site to put the bracelet is the upper zone of the arm. In this way, the data obtained will be more precise related to the patient performance.

Data is only collected on a local level, it is done using CSV files. Data obtained from the therapy session is stored in two different files one with the EMG information and another one with the IMU data. The EMG data is streamed at 200 Hz and the IMU data is streamed at 50 Hz by Bluetooth to the computer.

The EMG Raw Data is obtained as a 8-bit value from -128 to 127 for each sensor representing activation. However, it does not translate to millivolts (mV). Around 0 is relaxed muscle.

On the other hand, the spatial data informs about the orientation and movement of the user's arm. This data is provided by the on board 9-axis inertial measurement unit. The Myo SDK provides several kinds of spatial data:

- **Orientation data** which indicates in which way the Myo armband is pointed in terms of roll, pitch, and yaw.
- **Acceleration vector data** which represents the acceleration the Myo armband is undergoing at any given time.
- **Angular velocity data** provided by the gyroscope, provided in vector format.

The rehabilitation platform implemented also provides the possibility to visualize in real time the data obtaining from one of the EMG sensor, to follow the muscle strength that the patient performs during each game. This can be a good option when the therapist is helping the patient.

3.3 Unity 3D

Unity is a cross-platform game engine developed by Unity Technologies, which is primarily used to develop both 3D and 2D video games and simulations for computers, consoles, and mobile devices (Unity3D, 2018).

In Unity the games are compound of scenes. They contain the environments of the whole game. In each scene, you place your background, obstacles, and decorations, essentially designing and building the game in pieces. Every element in the scene is an object, which has certain properties and behavior. The behavior is associated with each object through scripts.

The programming language used for create scripts uses of C# or JavaScript. These script will determinate the games behavior. In order to activate the scripts, these must be associated with one object presented in the game scene.

Unity enables to create VR environments, this involves using computer-based programs where a person can experience being in a three-dimensional environment and interact with that environment during a game.

Communication Protocol

To develop the rehabilitation platform it is necessary to create a communication protocol between Unity and the other two devices used, the Novint Falcon and Myo armband. The communication is made using sockets because their libraries are coded in different languages. The games are programmed using C#, the Novint Falcon and Myo Armband libraries are programming using C++.

A socket is one of the most fundamental technologies of computer network programming. Sockets allow software applications to communicate using standard mechanisms built into network hardware and operating systems. A socket represents a single connection between two pieces of software. In this way data can be sent or received within a node on a computer network. The rehabilitation platform implements the following sockets:

- Between the **Novint Falcon** and the games it is necessary a bidirectional communication. From the Falcon the end effector position is obtained which is translated to the virtual environment. From the games it is necessary send to the Falcon the force feedback information. To do this, the information is send in a 'string' format, in both cases the data of the three spatial coordinates is sent. Once the information is received, it is transformed into 'float' format.
- Between the **Myo Bracelet** and the computer, the communication established is in one direction only. The platform only needs to read the EMG sensor information to print it in a graph during the performance. In this case, data transmitted has only one value corresponding with the value of one of the EMG sensors. It is also transmitted in a 'string' format and then changed to a 'float' one.

The communication frequency between these devices is very important. Because user needs to perceive a continuity in the images, this is achieved with a frequency of

30Hz and for obtaining haptic stability without oscillations in the end of the haptic device it is necessary a sampling rate greather than 500 Hz. In this case the frequency obtained is around 650 Hz hence, both requirements are fulfilled.

Game modules

The entire platform is form by different modules implemented in Unity. These modules are used in all the games with different variation between them. This a good way to create a modular design which can be applied to create the same environment but with different tasks.

The game modules are the following:

Virtual end-effector

The first step to create the rehabilitation platform is the end-effector virtualization. This script creates the socket between the platform Unity 3D and the device Novint Falcon. Therefore, it is in charged of transmitting and receiving the information between them.

To study the movement of the virtual object, it is necessary to establish a relationship between the Cartesian coordinates of the end of the haptic device and the coordinates of the virtual object. This module updates the position of the end-effector every frame in the scene. This is very important for obtaining a good visualization in the game. It is necessary to avoid vibrations of the image or irreal movements.

Myo EMG graph

At the beginning of the therapy the connection between Unity 3D and Myo bracelet is produced. To perform this task, as commented above, it is necessary establish a socket connection. In this case, every frame is shown in the graph, which is updated with the information received from the EMG sensor.

Collision detection

This is the key of these rehabilitation games. The collision detection between the end-effector and the game objectives must be done in all the games. To develop this a *Rigidbody* component is required to be added to an object in Unity, this will put its motion under the control of Unity's physics engine. In this way, a *Rigidbody* object will be pulled downward by gravity and will react to collisions with incoming objects. It is also required to provide a *Collider* component in both objects, the virtual end-effector and the objectives. Once this components are added to the objects, Unity has available a detection function, which is fired when two objects with these characteristics are in contact.

Timer

All the games need a timer to restrict the therapy duration. Therefore, patients are focused on the task because they has only a certain time to perform it.

The timer is implemented by using a coroutine which is in charge of decreasing the total time available every second. When the time is finished, the game is over and the final result is shown.

Concerning the design, some of the visual aspect included in games are extracted from the *Asset Store* of Unity 3D. In this store users and professionals can add their work which can be used by others. In this case, models like trees or plants are obtained by this store. This models are obtained freely from the store.

CHAPTER

4

REHABILITATION PLATFORM IMPLEMENTATION

To offer variety in the rehabilitation process, three serious games with different characteristics have been implemented. In this Chapter, exhaustive information about these serious games is presented. The force feedback implementation of each game, as well as their therapeutic objectives will be shown.

To create a completed platform, different menus focused on patients are developed. The configuration of the games attributes is essential to fit the games according with the needs of each patient.

4.1 Design guideline

Rehabilitation is a very different environment for games and, as such, special design consideration should be made. The design needs to ensure that the game aspect does not compromise the rehabilitation effort.

In these types of games, the task to develop must be adjustable and personalized for each patient, because they must not create stress. In rehabilitation, exercises are necessarily simple. They need to be easy to repeat in order to ensure that the movement is correct and beneficial for the patient. Furthermore, each exercise needs to have very clear goals and limitations. To promote plasticity exercises, serious games need to encourage a constant repetition of movements. Objectives must be achievable, performing simple movements and with a rehabilitation purpose. With all of these considerations the patient is involved in the learning process (Schouten et al., 2014).

Virtual sessions were designed along therapeutic guidelines for SCI interdisciplinary rehabilitation. The system offered visual, auditory and haptic feedback during the sessions, to increase the engagement, to facilitate the comprehension of exercises and to deliver a clear sense of progress.

One of these design considerations should be to ensure that the instructions for setting up the game as well as the good performance of the exercises should be clear to both physiotherapists and patients. Additionally, it should be made clear how the haptic and monitoring devices are used, this includes the setup of both devices and the positioning of the patient during the performance (Ma et al., 2014).

In total, the following observations have been made and compiled into a list of concrete design guidelines to develop these serious games for rehabilitation purposes.

- **Accuracy:** The end-effector used for the purposes of the study, should be very accurate because is going to be analysed to evaluate the performance and progress of the patient.

- **Low-Cost solution:** The gaming devices that are to be employed for monitoring and providing haptic feedback need to be low-cost to reduce the therapy cost.

- **Real-time feedback:** The rehabilitation platform should realize the potential of real-time haptic feedback to the patient.

- **Customized games:** The designed games should have adjustable levels of difficulty which must be selected by the clinician.

- **Automated system calibration:** The system should incorporate an automatic or semi-automatic calibration system that will match the range of movement of the patient with the range of movement required by the virtual game player.

- **Reward system:** A motivating and encouraging feedback system increases entertainment and thus the engagement and involvement of the player with the game and reduces the risk of abandonment of the game and physiotherapeutic treatment.

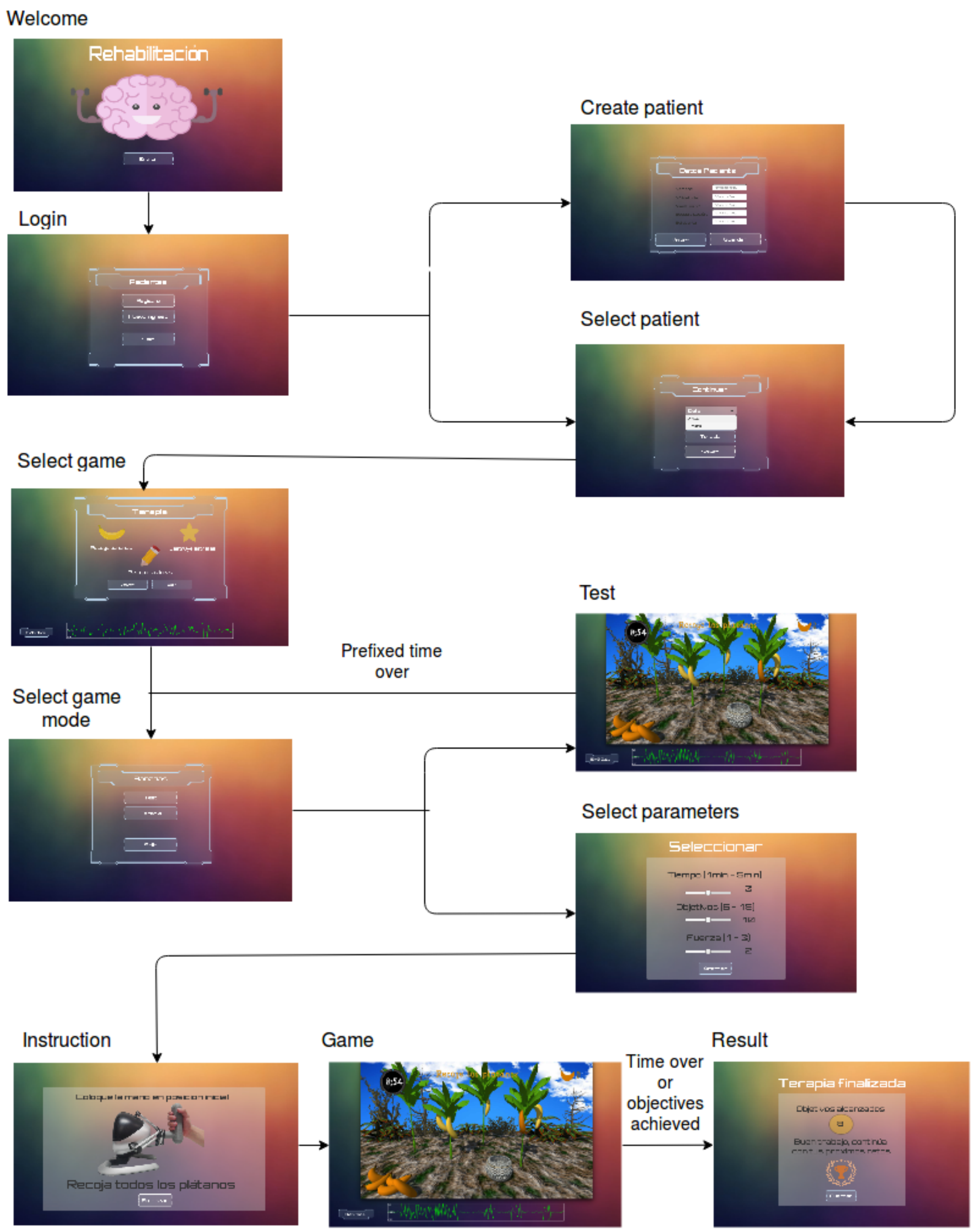


Figure 4.1: Scenes interaction

4.2 Scenes

The game is formed by various scenes, which interact between them for offering a completed rehabilitation experience (see Figure 4.1). The Novint Falcon is used as the input device during gameplay, the end-effector will be used for moving inside the virtual environment. Outside the gameplay, the Mouse and Keyboard can be used for controlling home and configuration menus.

The scenes have a simple design and only a couple of buttons to execute the actions. An essential point in the design is to consider the option of going back at any moment and remake the selections. For this reason, there is always a back button in the menus. The connection path between scenes need to be easy to remember. The action which will take place after the click must be clear to avoid undesired behaviors. To accomplish these tasks, the instructions in the scenes must be clear to abstain from wasting time in the configuration process. In the next subsections the most remarkable scenes will be detailed.

4.2.1 Creation and monitoring of profiles

One request from clinicians to these rehabilitation games is to create a patient center design and not a game center one. In these therapies, it is necessary to give importance to patients and their recovery and not only the games. Serious games are tools for the rehabilitation but patients are the most important. Therefore, the first task that the physiotherapist must do is to select the patient profile.

If this is the first time the patient goes to therapy, a new profile must be created. This task is performed by the therapist and can be made before the therapy session. To create a new profile, some parameters are needed to characterize the patient. The required data are the name, the medical record number, the level of the injury in terms of ASIA classification, the etiology of the injury and the clinician who solicited the treatment (see Figure 4.2). These parameters are important for clinicians to control patients and providing a personal therapy session according to their characteristics.

These profiles are stored in separated files. Patients profiles contain all the therapy progress made. The storage of data is made at the end of each game, the information acquired during the game performance like the game played, the game parameters selected by the therapist and the score obtained will be saved. Therefore, all the results obtained during the task are associated with the patient and stored in one file. In this way, the clinicians can follow the evolution of each patient visualizing these data after each therapy session.

Figure 4.2: Necessary information of a new patient

4.2.2 Game setting

Once the profile is selected, it is time to configure the game according to the patient characteristics. Games have the option to make a preview of the scene implemented in a test game mode. With the test mode patients obtain a clear instructions of the exercise and can become familiar with the game environment. Thus, when patients go to perform the therapy they have all the knowledge about the rehabilitation exercise. The test is limited in time and has a reduced number of objectives. With the information obtained during the test performance and the profile of the patient the configuration of the game by the therapist is easier.

An important utility of the platform is the game setting, the therapist can modify the individual exercises. Three parameters can be selected: the exercise time, the number of objectives and the force feedback to apply (see Figure 4.3). The ranges of the value had been set by the clinicians and by observing similar platforms like Virtual Rehab (VirtualRehab, 018s).

Having a dynamic adaptation of the scenarios and challenges of a game to the individual skills of a patient, may result useful to maintain the user's attention in the rehabilitation process and to increase the gameplay. This type of customization is expected to improve the usability of the solutions.

After the configuration phase, to start the gameplay mode it is necessary to setup the device. The setup is required to prevent the device to provide force feedback to the patient at the beginning of the game, which can be uncomfortable. Also, with this procedure the system is calibrated. The setup need to be as easy as possible, it consists of moving the end-effector to the center of the Range of Motion (ROM), putting the end-effector close to the Novint Falcon icon.

Figure 4.3: Configuration scene

4.2.3 Game Design

In the design phase, the interface of the games is a very important part, it must be clear and it must highlight the main element, which are the end-effector and the objectives to be achieved. Apart from these two main elements there are other informative elements that should also appear in the scene. All the games have the same informative elements distribution, this creates a uniformity in the platform. There are three key informative elements that are always presented in the scene, these are the timer, the score and the description of the exercise. The EMG activity is an optional information that can be presented or not in the scene, this information is more relevant if the physiotherapist is during the game performance (see Figure 4.4). This EMG activity shows the signal capture of one of the sensor in real time, the sensor chosen to be on the screen is the one that is placed in the muscle group of interest.

The exercise description is essential because patients must know which is the task to perform during the game. The score and timer are motivational elements to encourage patient to finish the task.

4.2.4 Final result

A final scene must emphasize the final summary of the patient score. In this scene the patient can visualize the objectives achieved during the game. The goal of this scene is to obtain a patient motivation showing positive messages and encouraging them to continue with their rehabilitation process (see Figure 4.5).

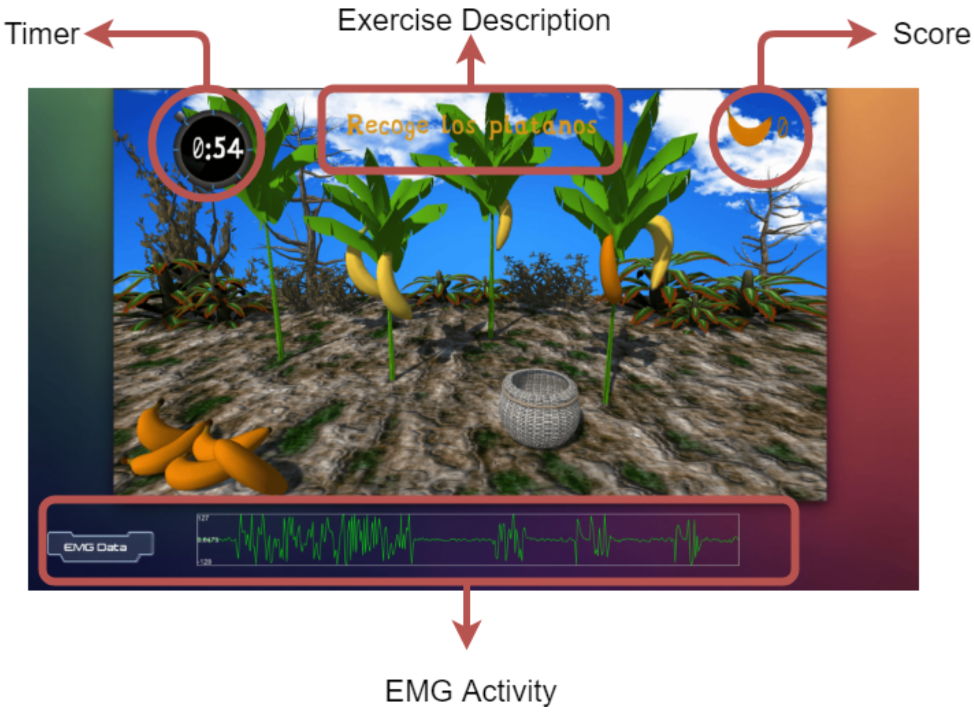


Figure 4.4: Elements distribution in game scenes

Figure 4.5: Final result scene

4.3 Serious games description

The rehabilitation platform is formed by three serious games, the goal of all of them is to reach the number of objectives selected by the therapist. To achieve this goal the time is restricted, if the patient does not achieve the objectives in the available time the game will finish. To help patients in developing this task, the movement made with the end-effector will be visualized in the virtual environment.

All serious games follow the same coordinate reference, y axis allows to go up and down with the end-effector, x axis corresponds to the movement from right to left, and z is the depth coordinate that allows a forward movement and back. In Figure 4.6 a cube with the origin of coordinates is represented.

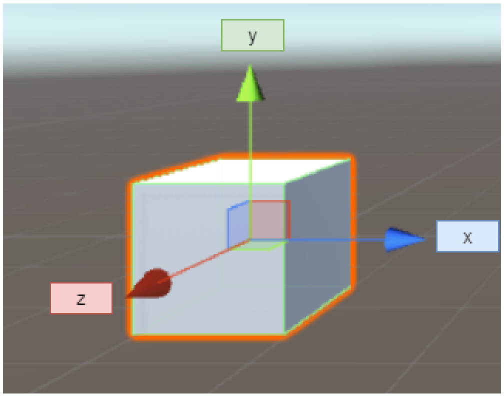


Figure 4.6: Coordinates origin

A summary of the main characteristic of each game can be visualized in Table 4.1. The behavior and characteristics of each of the serious game is introduced in subsequent sections.

Game	Exercise type	Force type	Therapeutic objective
Following the path	Path guidance	Hooke's law	Accuracy
Picking bananas	Resistive	Viscosity	Accuracy, Strength
Destroying stars	Resistive	Hooke's law	Accuracy, Strength

Table 4.1: Summary with the main characteristics of each game

4.3.1 Following the path

The end-effector in the scene is representing a pencil. When the user moves it, the pencil will draw a trajectory in the scene. The visualization of the trajectory helps users in the development of the task. In this game there is not a selection of the number of the objectives. The path will be the same in all configurations. Users must try going by the path without going out of the edges. When users go out of the trajectory, a sound is produced to enhance their attention. The goal of the game is to pass through all the lines. When the user complete a segment it changes its color to a darker one (see Figure 4.7).

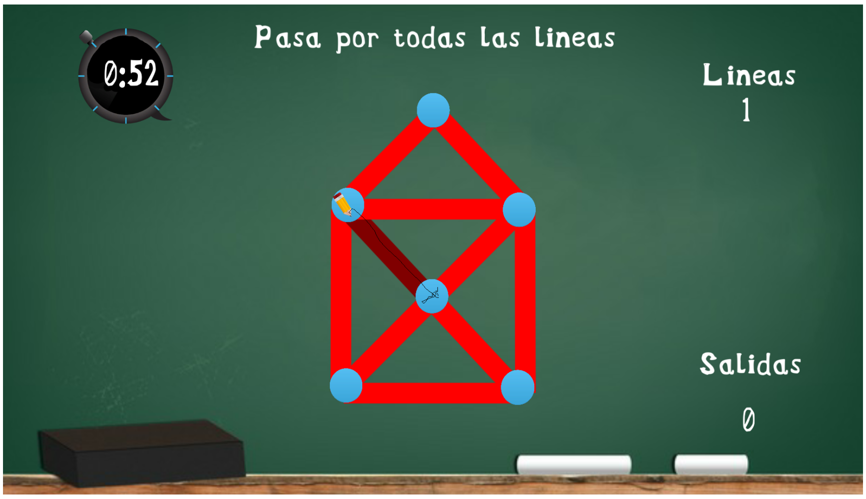


Figure 4.7: Following the path game interface, one segment has been completed

The user starts the game with the pencil situated in the center of the scene and must move it till the adjacent circles. The game needs to detected a collision of the pencil with two adjacent circles to count one line. When this occurs, the line goes dark and the score is incremented (*Lineas*). Moreover, a second score appears in the scene, it corresponds to the number of times that the user went out of the trajectory (*Salidas*). This information is useful to check the progression of the user (see Figure 4.8).

This game is implement in 2D because the depth of the scene can cause trajectory disturbance in patients. The movements allowed are only in x and y axis. The movement in z axis is limit to only 1 cm using two walls implemented with force feedback which users cannot cross. The ROM is of 5 cm in x axis and of 7.5 cm in y axis. The path of the trajectory has a width of 0.5 cm.

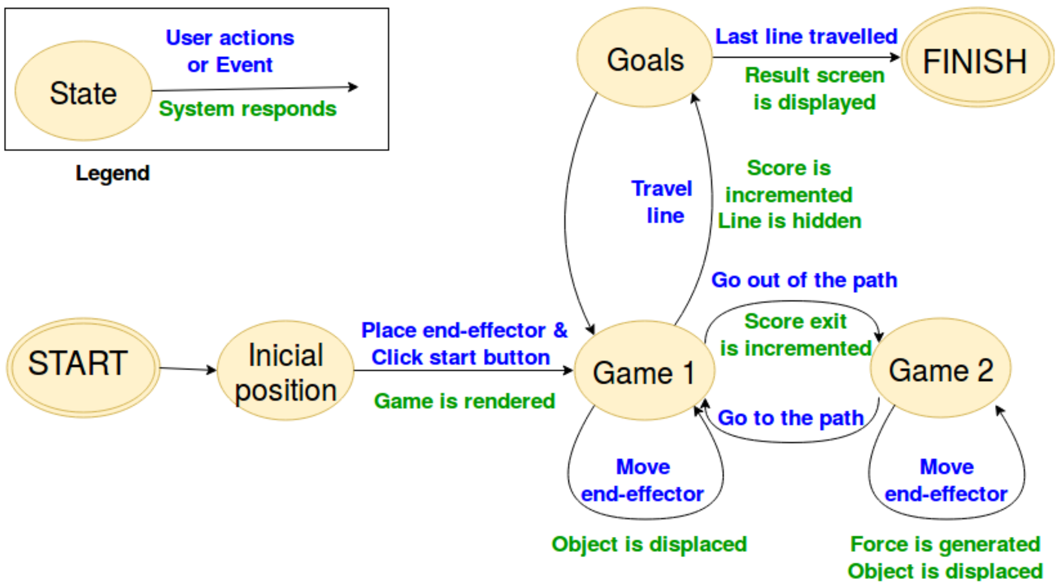


Figure 4.8: State transition networks (STN) for Following the path game

Therapeutic objective

This rehabilitation game is based on a path guidance exercise. The therapeutic objective is to improve the precision in the UL movement made by the patient and to recover fine motor control. This training modality using robot-mediated therapy is a combination of assistive and active exercise. When the patient is moving the end-effector freely by the path, the active mode is working because during this process patient feels no force. However, if the patient goes out of the prefix path, the assistive modality is acting. Therefore the haptic robot assists by providing force feedback opposing to the movement of the patient. In both modalities, the patient voluntary activity is required during the entire exercise.

In this training, the trajectory performed by the patient acquire relevant importance. For this reason, the trajectory made by the patient will be collected and the movement smoothness must be analyzed.

The assistive force applied in the path guidance exercises can be convergent or divergent. In the convergent field, the assistive force pushes the patient's hand to the correct path. On the other hand, diverging force field pushes the hand away from the path, constantly requiring the user to correct it. The diverging force requires moving the UL in an unstable environments and with motor variability. This situation can lead to undesired therapy outcomes for more impaired patients, or did not represent the optimal therapy approach (Tropea et al., 2013). In consequence, the force applied in this rehabilitation game will be convergent.

This force feedback is implemented by using the Hooke's law (see Equation 4.1). Hooke's law is a principle of physics that states that the force (F) needed to extend or compress a spring by some distance (d) scales linearly with respect to that distance. k, is a constant factor characteristic of the spring, its stiffness (Westergaard, 1952). The force will be implemented in the edges of the path, so, patients will feel these edges like walls that they cannot cross (see Figure 4.9).

$$F = -kd \tag{4.1}$$

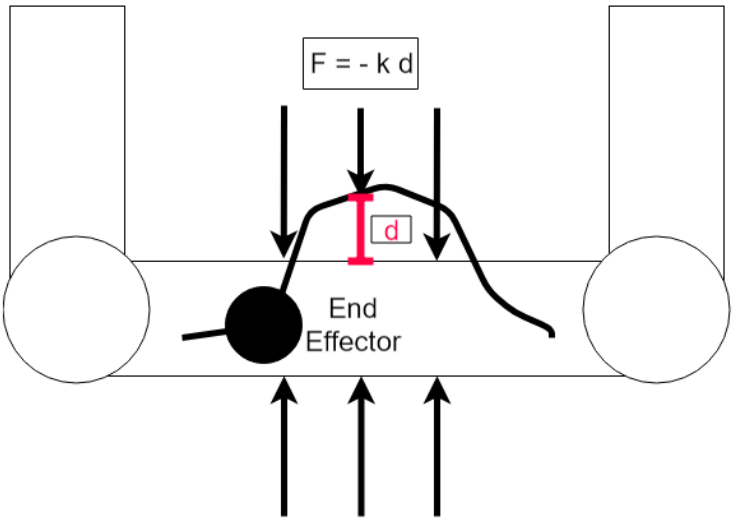


Figure 4.9: Force applied in Following the path game

4.3.2 Picking bananas

The end-effector in the virtual environment is visualized as a basket and the objectives to achieve are bananas. The goal of the game is to pick up the total number of bananas with the basket (see Figure 4.10). Therefore, users need to move the end-effector in a precise way to capture the bananas. The game finishes when all the bananas have fallen from the trees.

Four banana trees appear in the scene with the total number of objectives selected in the game setting menu. In this way, the playability of the game increases. Bananas

Figure 4.10: Picking bananas game interface

are going to fall from the trees in a random way, preventing users from knowing in advance the position to which they have to move the end effector.

Depending on the number of objectives and the time selected, the frequency of falling changes to obtain a proportional distribution. When one banana is going to fall, it changes its color and a sound is produced. These visual and auditory feedbacks help users to identify toward which place they need to move the end-effector. The fall is produced due to the bananas lost their joint with the tree and acquire the property of gravity. When users catch a banana with the basket, it disappears and another sound is produced to inform about the achievement. Moreover, the score is incremented and visualized in the screen. If all the objectives have fallen, the game ends and the final result screen is visualized (see Figure 4.11).

The force feedback will be increased with the number of bananas captured, but if the number is high this can tire users, then the option to release the basket weight appears. Every five bananas collected, the user can perform the release of weight in a corner of the screen. In this way, the basket will be empty again and the force feedback will be zero till a new banana is captured.

This game is implemented in 3D, although the movement in y axis is not considered because the game pretends to achieve a movement only in two directions left-right and forward-back. Consequently, users only are free to move in x and z axis. For helping users during the performance, a virtual board exists in the y axis equal to zero. This board holds users' hands and facilitates resting during performance. This force feedback contributes to compensate the gravity force. The virtual board is the floor of the terrain in the scene.

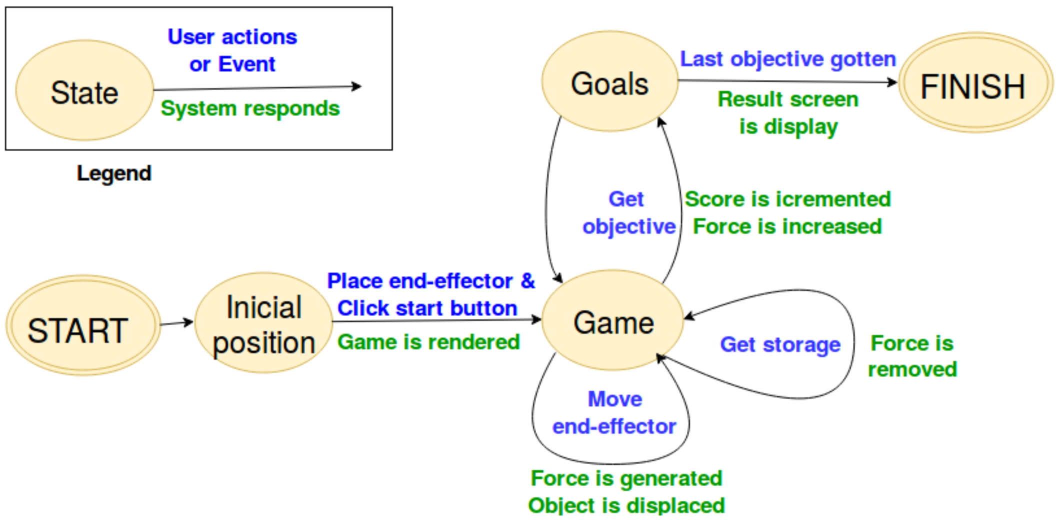


Figure 4.11: State transition networks (STN) for Picking bananas game

The trees are disposed in the floor using a distance of 6 cm in the x and in the z axis are set in a range of 4 cm. With this distribution, users have enough space to move the final effector in the total ROM offered by the haptic device.

Therapeutic objective

The rehabilitation exercise implemented in this serious game is a resistive one, that means that the haptic robot makes the movement more difficult by opposing the movement received from the patient. Progressive resistance exercise appears to be a safe and efficacious intervention for many patients with muscle force deficits. In this exercises the number of repetitions should be small for avoiding fatigue, rest between exercises should be sufficient for recovery, and the resistance should be modulated to increase it as the ability increases.

This rehabilitation game is convenient to practice precise movements too. SCI patients usually try to compensate the UL movement executing compensation movements with the trunk, these actions cause movements without precision in the end-effector. In this exercise, patients need to finish their movements with maximal precision to capture objectives. Therefore, this rehabilitation exercise also provides a recovery to perform precise movements of the UL.

The force feedback implemented is a viscosity resistance, the force is proportional to the velocity and opposes to end-effector movement (see Equation 4.2). This force will increase according to the number of objectives collected.

$$F = -b\dot{x} \tag{4.2}$$

In this exercise, an isotonic muscle contraction is produced, this muscle contraction implies the shortening and lengthening of muscle fibers. Depending on the amount of force working against an individual's body, one of two kinds of isotonic contractions will take place: concentric and eccentric contractions. Concentric contractions occur when muscles shorten while its tension is greater than the force opposing it. On the other hand, eccentric contractions occur when muscles extend in length (Muscle Physiology, 2006).

Isotonic exercise promotes the development of muscle endurance, muscle tone and muscle strength. These movements have also been shown to improve ligament and tendon strength. To avoid the fatigue that this type of exercise usually causes, the force is only applied when patient performs a movement with the end-effector.

4.3.3 Destroying stars

The virtual visualization of the end-effector is a rocket and the objectives are stars. The aim of this game is to destroy all the stars that appear in the scene (see Figure4.12). To achieve it, the user needs to move the end-effector of the Novint Falcon till the star position. The game finishes when the total number of objectives are achieved or the time is up.

Figure 4.12: Destroying stars interface, one star has been destroyed

At the begging the objectives selected in the game setting menu appears in the scene and the end-effector appears in center. The stars have different sizes to force user go away from the center, the bigger ones are easier to catch than the others.

During the game, if a collision is detected between the rocket and one of the available stars, this star will be destroyed and will disappear of the scene. When the user destroys a star, a sound is produced and the score available in the screen increments. This help users to follow their own progress during the performance. After destroying a star, the user must come back to the center of the screen before another destruction. The collision detection will not be available until the user reaches the center of the scene. To make this case clearer, once a star is destroyed the Earth that is placed in the center acquires a colorful appearance. When the collision of the rocket with the Earth has occurred, the user can go again for another star and the Earth becomes transparent (see Figure 4.13). This behavior is put into practice to avoid the circular movement that SCI people usually do with a trunk compensation. The game promotes to obtain a straight trajectory.

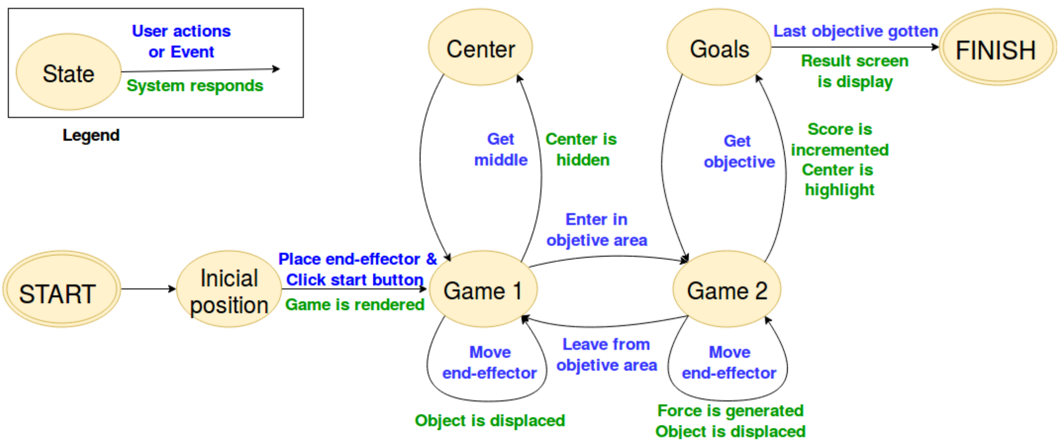


Figure 4.13: State transition networks (STN) for Destroying stars game

This game is designed in 2D, because it focus on following this straight trajectory, rejecting the depth of the scene. Therefore, the allowed movements are in the y axis and in x, but not in z axis. To avoid this movement, but obtaining the maximum ROM of the haptic device, two walls are created using a force feedback. These walls limit the user end-effector movement with a range of 2 cm in the z axis. Including these restrictions, the permitted movements are up-down and left-right.

The center of the stars are disposed in a circumference with a radius of 4.5 cm and centered in x and y equal to zero. Consequently the ROM of the haptic device is fully covered, allowing a ROM of -5 cm to 5cm in both axis.

Therapeutic objective

The exercise implemented in this game is resistive, the robot provides force opposing the movement. Thus, its goal is to obtain the strengthening of the UL muscles. In addition, with this game the linearity of the movement can be checked. Patients with UL lesion usually try to compensate movements performing curved trajectories when they try to catch an objective which is in a straight direction.

In this case, there is a zone without force in the middle of the game circle, but when the patient is close to the targets, the force applied increases. The force begins to act in a radius of 2.5 cm. This force is only applied in a zone and not all the time, to avoid muscle fatigue. The force applied follows the Hooke's law (see Equation 4.1). Therefore, the force, scales linearly with respect to the distance that the end-effector is introduced into the force area (see Figure 4.14).

As in the picking bananas game, because the force depends on the movement and the position, the muscle contraction is isotonic. A shortening and lengthening of the muscle fibers occur during the game performance.

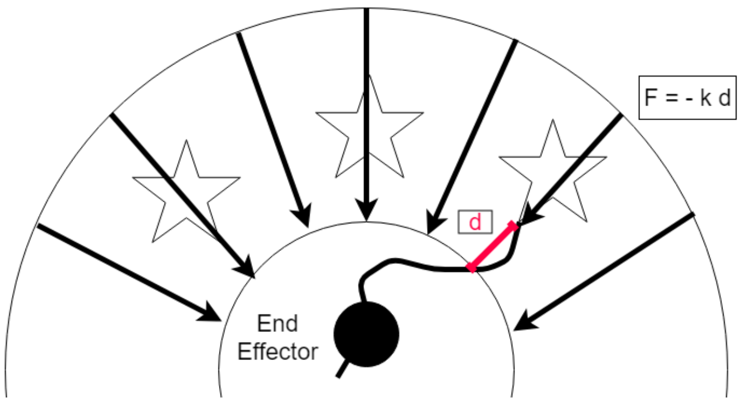


Figure 4.14: Force applied in Destroying stars game

CHAPTER

5

CLINICAL VALIDATION AS A PROOF OF CONCEPT

To test the three serious games and to check the usability of the platform, a proof of concept was made in the Biomechanics and Technical Aids Department of the Hospital Nacional de Parapléjicos in Toledo (Spain). The study was carried out for obtaining data which supports the feasibility of the platform developed and to examine that SCI patients have the ability to manipulate the applications in a successful way. These data are the key of the platform, the objective information obtained about the patient is useful for controlling the progress made during the therapy.

In this study, healthy subjects and patients with incomplete cervical SCI have participated. During the experiments, the hand trajectory from the Novint Falcon effector device and the EMG signals obtained from the Myo armband were recorded from each participant and all along the performance of each game. Data obtained have been analyzed and the results extracted from each group are shown in subsequent sections, as well as, the difference between them.

5.1 Participants

In the platform validation eight people have participated, four healthy subjects and four cervical SCI patients, obtaining paired groups. All 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 UL including shoulder and wrist movement allowed. In Table 5.1 the clinical characteristics from all SCI patients are provided.

Patient	Age	Sex	Injury Level	ASIA
1	19	M	C4	C
2	18	M	C4	C D
3	45	F	C5	D
4	20	M	C6	C

Table 5.1: SCI patients characteristics

5.2 Intervention

The study was performed during two days, with two sessions per day. Therefore, the study is formed by data obtained from four different session. In all sessions, participants performed the test before to start with the serious games, this methodology was used for obtained clear results. In this way, participants had a previous knowledge of the games and the result obtained does not show the variability of the learning process.

The three games were performed in all sessions, always in the same order and with the same characteristics to avoid including variability into the study. First, the Picking bananas game was performed with 2 minutes of time and 15 objectives selected. Secondly, the Destroying stars game with 2 minutes of time and 16 objectives selected. Finally, Following the path serious game was performed with also 2 minutes of time. In all rehabilitation games the force selected was at a value of 2, the middle of the force available. This parameter selection was chosen, because in all tests, participants showed skills to perform the task with this configuration.

The study was carried out only taking data from one of the arm of the participants. In the SCI group, the arm with less mobility was selected. 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. In the healthy group, all subjects performed the experiment with their right hand because all of them are right-handed. The end-effector of the Novint Falcon is held with the hand to treat and the Myo armband is placed in the same arm with the electrodes located on the muscle group of interests.

5.3 Processing and analysis

In this study, knowing the trajectory smoothness is interesting. Movement smoothness is a quality related to the continuity or non-intermittency of a movement, independent of its amplitude and duration. Smooth and well-coordinated movements are a characteristic feature of a healthy, and trained human motor behavior (Rohrer et al., 2002). However, SCI patients goal-directed reaching movements are saccadic. These movements become smoother with motor recovery, because muscle properties contribute to movement smoothness. The smoothness showed the strongest ability to discriminate movement quality between healthy subjects and SCI patients (de los Reyes-Guzmán, 2015). Measurement of smoothness may provide a meaningful, objective quantification of motor performance that could be used to augment clinical evaluations.

Consequently, movement smoothness has been used as a measure of motor performance of both groups healthy and SCI. Smoothness measures have been obtained using the number of peaks method, which relies on the fact that the speed profile of smooth movements are single peaked, while unsmooth movements have higher number of speed peaks. Therefore, fewer peaks in speed represent fewer periods of acceleration and deceleration, making a smoother movement.

This measure counts the number of local maxima (peaks) of the signal in a given speed profile $v(t)$, where $| \cdot |$ represents the cardinality of a set (see Equation 5.1).

$$NP \cong \left| \left\{ v\left(t\right), \ \ \frac{dv\left(t\right)}{dt} = 0 \ \ and \ \ \frac{d^2v\left(t\right)}{dt^2} < 0 \right| \right\} \tag{5.1}$$

To perform this study the mathematical tool Matlab has been used. The first step to accomplish the smoothness analysis is to obtain the speed profile of the movements. The speed profile can be obtained from the position data obtained by the haptic robot. These data are stored in files during the performance of each game. Due to the ROM of each game, only the two axes of interest have been analyzed because of the limited variability of the other one.

To compare these two data sets of each participant group, a statistical hypothesis test is performed. With this test data can be compared and the statistical inference obtained. In this test, a hypothesis is proposed for the statistical relationship between the two data sets, and this is compared as an alternative to an idealized null hypothesis that proposes no relationship between the two data sets. The comparison is deemed statistically significant if the relationship between the data sets would be an unlikely realization of the null hypothesis according to a threshold probability, the significance level (Gibbons and Chakraborti, 2011). In this case, the Mann-Whitney U test have been chosen for testing the difference between two independent groups with a significance level of 5%. The Mann-Whitney U test is a non-parametric test that can be used to determine whether two independent samples were selected from populations having the same distribution. This test have been selected because when the samples are small, a nonparametric test is appropriate. Moreover, this test is use for independent groups which is the case of healthy and SCI patients.

In addition, the mean speed, peak speed, and duration of the exercises were applied to the kinematic data collected during the movements.

5.4 Results

The result of the smoothness analysis for each game and for each axis of interest will be shown in this section. The results obtained in the analysis of the trajectory smoothness show difference between healthy and SCI patients. In all cases, SCI patients execute an elevated number of peak in the speed profile, more than the healthy subjects. This is due to SCI patients have less control of their UL. The results obtained confirm the hypothesis of the smoothness analysis, because a big number of peaks indicates less smooth in the trajectory.

5.4.1 Following the path

In Table 5.2 the duration of each exercise, which is the time spent to achieve all the objectives, the maximum of the speed profile in the interest axes, and the maximum peak in speed profile are exposed. These data have been obtained calculating the average of each measure in healthy and SCI groups.

	Duration (s)	**Max** x (m/s)	**Max** y (m/s)	**Mean** x (m/s)	**Mean** y (m/s)
Healthy	28.55 ± 7.91	0.255	0.556	0.063 ± 0.008	0.070 ± 0.018
SCI	49.52 ± 13.33	0.406	0.270	0.058 ± 0.015	0.058 ± 0.020

Table 5.2: Result of Following the path game

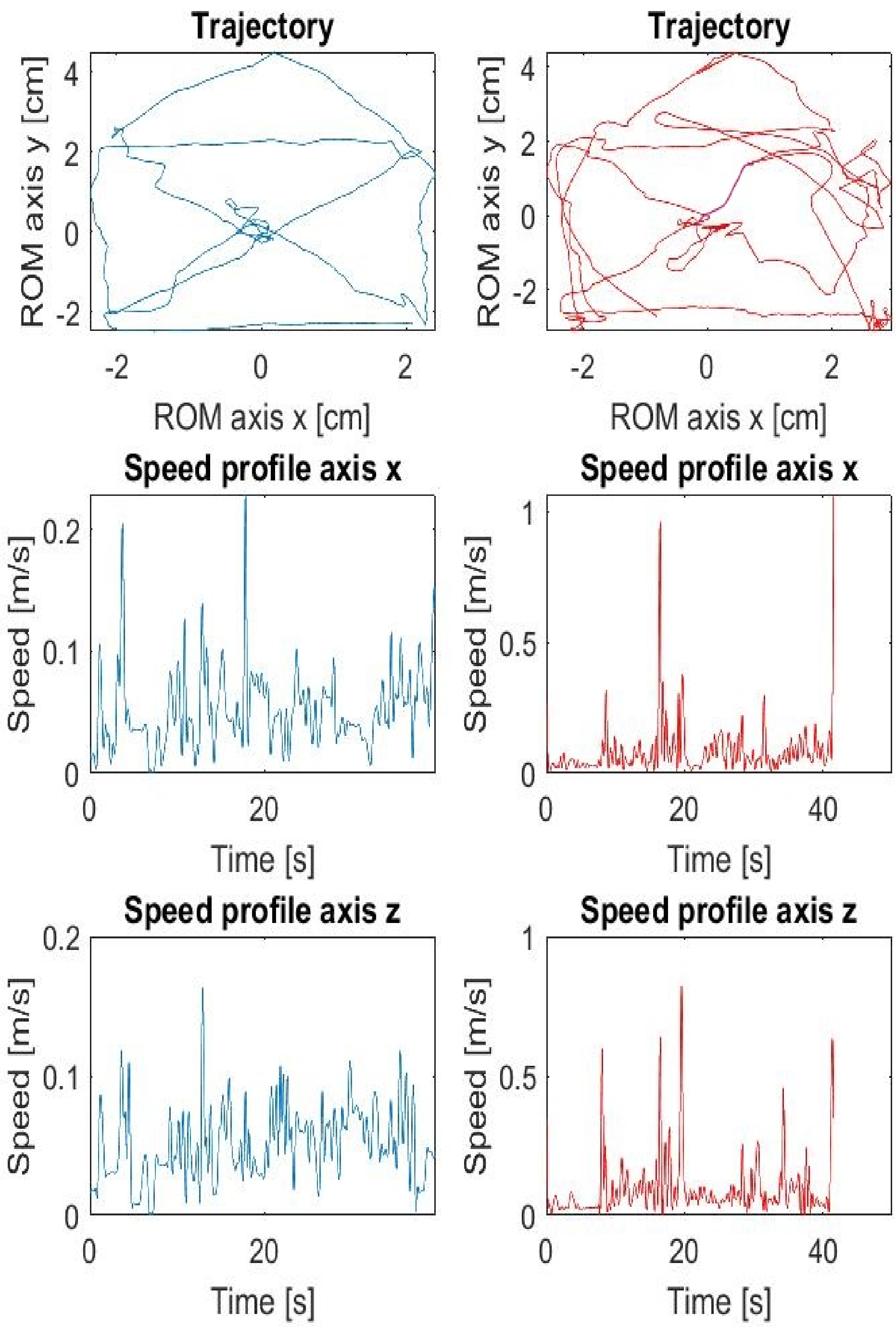
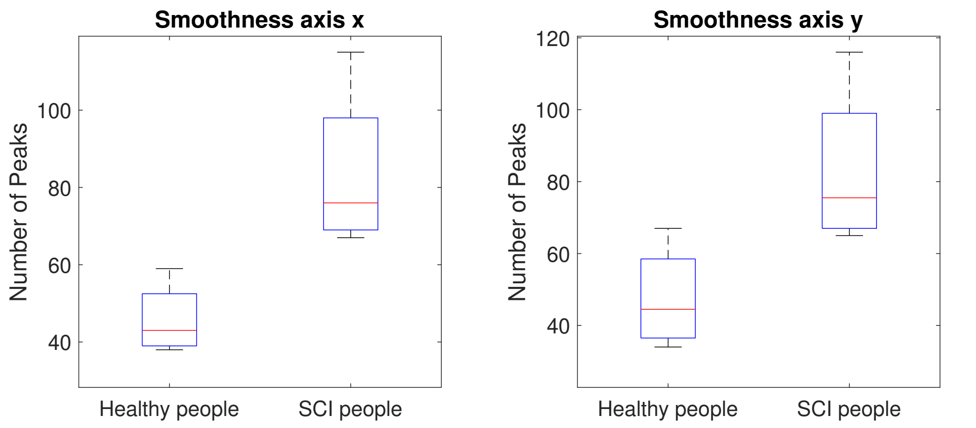


Figure 5.1: Healthy (blue) and SCI (red) participants results of trajectory performed and speed profile of x and y axes from Following the path game



(a) Box plot of the number of peaks in axis x (b) Box plot of the number of peaks in axis y

Figure 5.2: Box plots of the smoothness achieved in healthy and SCI groups from Following the path game

In this game, the time spent in the performance of the task is significantly different, healthy people spend $28.55s$ and SCI people $49.52s$ on average. This indicates that patients need to perform the movement slowly for avoiding to go out of the edges. The trajectory and speed profile of x and y axis from a healthy and SCI patients can be seen in Figure 5.1.

This serious game has one special consideration, the number of times that a user goes out of the path. This is important for knowing the effectiveness of the performance of the exercise. The analysis shows that healthy subjects go out of the path an average of 2.75 times and SCI patients 13.75 times. SCI patients go out of the path five times more than healthy subjects. This increases the number of corrections of the hand movement due to the force feedback applied.

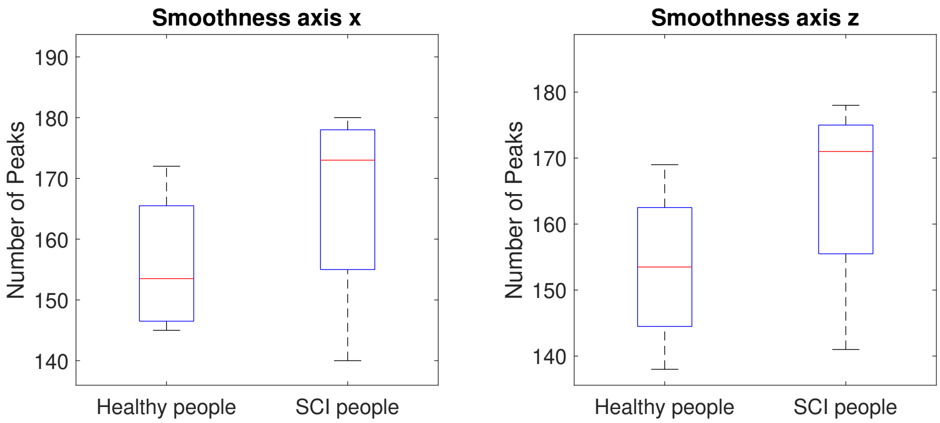
In this case, the number of peaks in the speed profile is very different in both groups. Although in SCI patients there are some variability, the maximum number of peaks obtained is highest than in healthy subjects. The overlap of the box plot is almost nonexistent in the y axis (see Figure 5.2(b)), and without overlap in the analysis of the speed profile of the x axis (see Figure 5.2(a)). This shows a big difference in the smoothness of the trajectory between the two groups.

5.4.2 Picking Bananas

This is the most complicated game for analyzing the trajectory, due to the aleatory of the movements. However, some annotations can be made. In Table 5.3 it can be observed that the average of the speed profile is higher in SCI patients than in healthy subjects. This is because SCI patients made quick movement trying to catch the objectives. The trajectory and speed profile of x and z axis from one participant of the two groups can be see in Figure 5.4.

	Duration (s)	**Max x** (m/s)	**Max y** (m/s)	**Mean x** (m/s)	**Mean y** (m/s)
Healthy	120	1.646	1.467	0.060 ± 0.013	0.047 ± 0.013
SCI	120	0.696	1.227	0.141 ± 0.653	0.091 ± 0.220

Table 5.3: Result of Picking bananas game



(a) Box plot of the number of peaks in axis x (b) Box plot of the number of peaks in axis z

Figure 5.3: Box plots of the smoothness achieved in healthy and SCI groups from Picking bananas game

The number of peaks obtained in the analysis show that SCI patients perform more accelerations and decelerations in the speed profile showing a big number of peaks and consequence less smoothness. However, some of the SCI patients can achieve smoothness movements obtaining the same number of peaks than healthy subjects (see Figure 5.3). Also it can be appreciated that the number of peaks is more elevated in this serious game than in others, because the time spent in the exercise is longer. In this case, the game for all participants lasted two minutes.

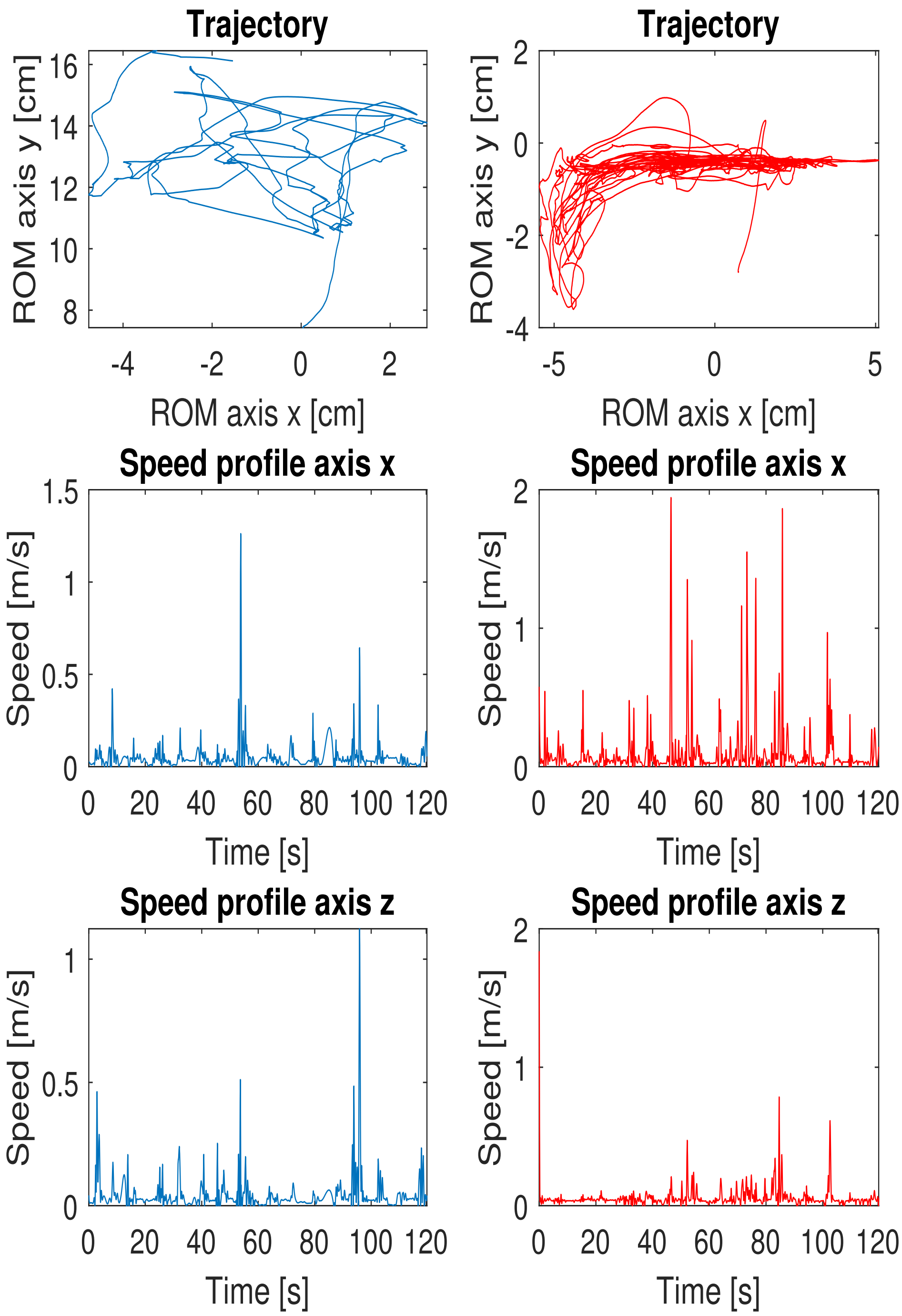


Figure 5.4: Healthy (blue) and SCI (red) participant result of trajectory performed and speed profile of x and z axes from Picking bananas game

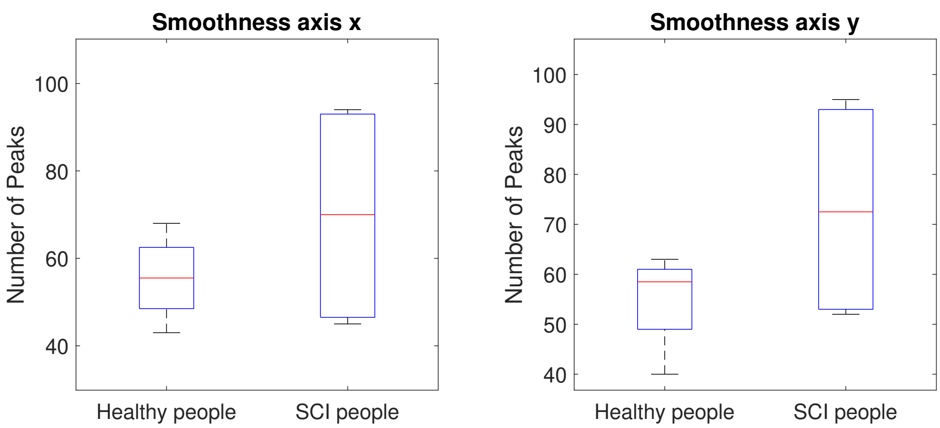
5.4.3 Destroying stars

Analyzing the result obtained in the performance of this game (see Table 5.4), it can be observed that SCI patients spent a long time for achieving the 16 objectives. SCI patients have an average of $41.78s$ and healthy subjects utilize $34.66s$ on average.

	Duration (s)	**Max** x (m/s)	**Max** y (m/s)	**Mean** x (m/s)	**Mean** y (m/s)
Healthy	34.66 ± 7.91	1.232	1.317	0.160 ± 0.082	0.158 ± 0.054
SCI	41.78 ± 15.83	0.878	0.898	0.140 ± 0.056	0.137 ± 0.054

Table 5.4: Result of Destroying stars game

The duration of the exercise can affect in the smoothness of the movement because the fact of carrying out the task more slowly produces segmentation of the movement and more peaks in the speed profile appeared. Also, the average speed in both group is different, healthy group has an speed average of $0.15m/s$ and the patient group $0.13m/s$. Obtaining the maximum peak of speed with higher values in healthy subjects than in SCI patients. Therefore, SCI patients develop this task in a longer time and with less speed causing a movement without smoothness. Moreover, the trajectory is less straight in SCI patients than in healthy people.



(a) Box plot of the number of peaks in axis x (b) Box plot of the number of peaks in axis y

Figure 5.5: Box plots of the smoothness achieved in healthy and SCI groups from Destroying stars game

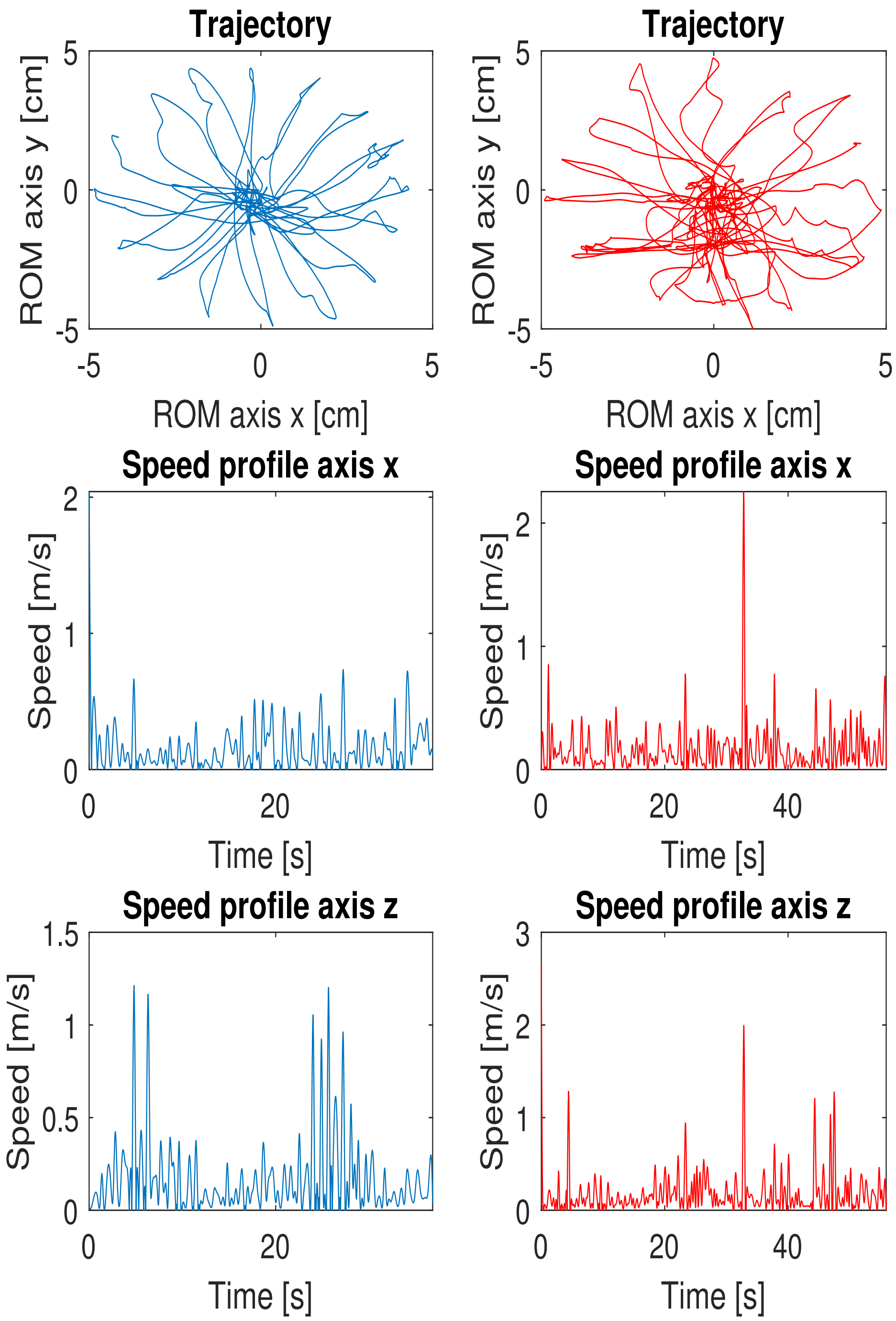


Figure 5.6: Healthy (blue) and SCI (red) participant result of trajectory performed and speed profile of x and y axes from Destroying stars game

In Figure 5.5, it can be appreciated that the group of healthy subjects shows less number of peaks than the other group. The two groups overlap, due to some SCI patients that can perform a smoothness trajectory obtaining the same number of peaks than healthy subjects. Also, the dispersion in SCI patients is bigger than in healthy subjects. The number of peaks obtained in x and y axis indicates that there are not variability between movements along these axes. The trajectory and speed profile of x and z axis can be seen in Figure 5.6.

After the execution of the statistical test to the result of the smoothness analysis showed above, the null hypothesis is confirmed, obtaining that the two groups are equal. However, in the case of the speed profile of the x axis in Following the path game, the null hypothesis is rejected obtaining that the two groups are different. This is the only case where the box plots do not overlap. The similarity between healthy subjects and SCI patients can be due to the lower number of participants in the study. With this few sample it is not possible to discern between the two groups, because the isolated cases contribute to increase the variability of the groups.

	Healthy subjects		
Game	**Axis x**	**Axis y**	**Axis z**
Following the path	**45.07±9.46**	57.77 ± 14.62	-
Picking bananas	155.65 ± 12.25	-	153.10 ± 12.82
Destroying stars	54.77 ± 10.28	54.19 ± 10.23	-

Table 5.5: Average of the number of peaks for healthy group

	SCI patients		
Game	**Axis x**	**Axis y**	**Axis z**
Following the path	**81.59±21.81**	80.82 ± 23.17	-
Picking bananas	165.71 ± 18.14	-	164.59 ± 16.52
Destroying stars	65.74 ± 26.89	70.19 ± 23.17	-

Table 5.6: Average of the number of peaks for SCI group

In Tables 5.5 and 5.6 are presented the average of the number of peak for each game and for each axes corresponding with the two groups, healthy subjects and SCI patients. After the execution of Mann-Whitney U test, the result highlight indicates a rejection of the null hypothesis at the 5% significance level.

The EMG information coming from the eight sensors of the bracelet is useful for monitoring the muscle contraction during the games performance. In a posterior analysis, these data can be utilized to check the changes in the patterns of motor activity during the rehabilitation process.

In Figure 5.7 the muscle contraction in the UL during a SCI patient performance of the three serious games can be appreciated. These data have been analyzed taking into account the range of values obtained from the Myo armband which are between -128 and 127. To represent the muscle contraction, the absolute value of the data collected from the sensor place in the muscle of interest have been calculated.

The muscle contraction is low, obtaining an average of 38.13 in Following the path game, 39.64 in Picking bananas games and finally 53.35 in Destroying stars. These averages values are far from the maximum value receive from the Myo armband. This effect occurs because the load of work is not intense. Therefore, the muscle activity that patients need to perform for overcome the force feedback is moderate. It can be appreciated that in the game where the force feedback applied is higher, which is the Destroying star game, the muscle contraction is also higher.

5.5 Questionnaire

After the performance of the therapy, SCI patients provided a feedback about their experience with the platform in the form of a questionnaire. This test is very useful for improving some features of the platform and having a personal opinion of the SCI patients about the robot aided virtual therapy. The questionnaire used a 7-point Likert scale (1: 'Disagree strongly', 7: 'Agree strongly', 4: 'Neither agree nor disagree'). The questions were extract from (Zariffa et al., 2012), due to the similarity of the study performed with robot aided and VR, but the questionnaire has been modified by adding some questions centered on the design of the platform.

Some highlight questions are the two that have obtained a result of unanimity with 7-point answers. This questions are "It was easy to understand how to use the games" and "The games are appropriate for someone with your level of lesion". The first question indicates that the instructions which appear in the games are clear and the games' goals are easy to understand. The second question shows that the game is appropriated for their level lesson because the force feedback implemented is not very strong, this allows them to perform the exercises in a safety environment.

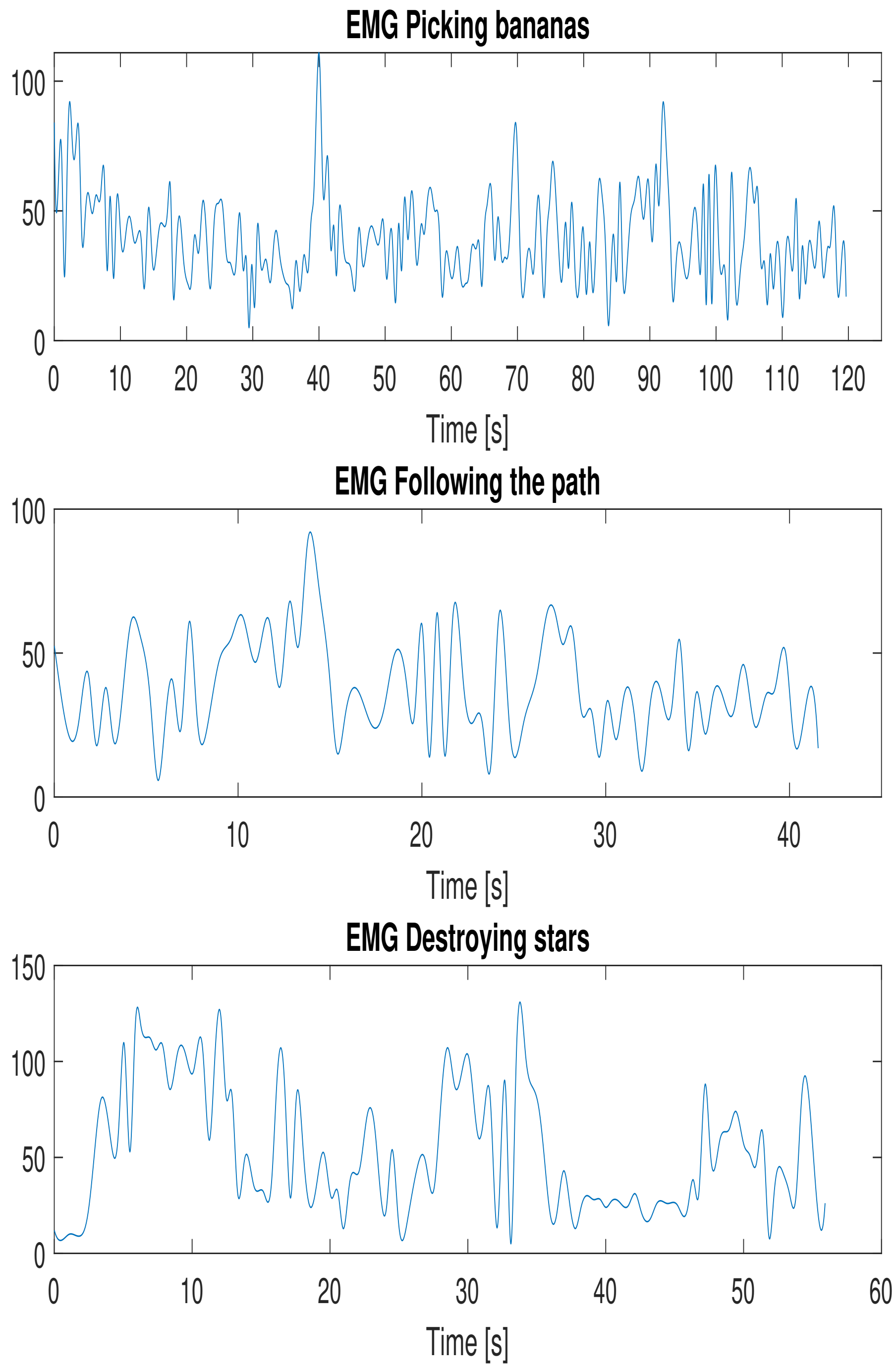


Figure 5.7: EMG signal recorded during SCI patient performance of the three serious games

Another question to underline is "The game helps you to recover the strength in the arm and dexterity of the movements" this question obtained a result of 6.5 ± 1. That means that patients consider that the game therapeutic objectives are fulfilled.

The questions and results of the questionnaire filled out by the patients are provided in Table 5.7.

Question	**Mean score ($\pm$ s.d.)**
Q1. The games were enjoyable to use.	6.50 ± 0.58
Q2. It was easy to understand how to use the games.	7.00 ± 0.00
Q3. The games increased your motivation to perform your exercises.	6.75 ± 0.5
Q4. You would be comfortable using the platform with only minimal supervision by a therapist.	6.50 ± 1.00
Q5. You felt that the training was as effective for rehabilitation as your usual rehabilitation sessions with a therapist.	6.50 ± 1.00
Q6. The platform was helpful for tracking the progress of your rehabilitation.	6.25 ± 0.96
Q7. The game helps you to recover the strength in the arm and dexterity of the movements	6.50 ± 1.00
Q8. You felt that the exercises implemented were more relevant to activities in your daily life than conventional rehabilitation.	4.25 ± 1.26
Q9. You would use the games in your free time if it was available to you.	6.75 ± 0.50
Q10. You preferred this training to conventional rehabilitation.	4.75 ± 2.06
Q11. The games are appropriate for someone with your level of lesion.	7.00 ± 0.00
Q12. The games are appropriate for someone with your type of injury (that is, ASIA A, B, C or D).	6.75 ± 0.50

Table 5.7: Patient questionnaire with mean score and standard deviation for each question

5.6 Conclusion

The results show that incorporating UL robotic training into the rehabilitation program of cervical SCI patients is feasible, and that the platform allowed to collect objective data for checking the SCI patients progress.

SCI patients found the serious games easy to use, helpful for tracking their progress and they reported high motivation to perform the exercises. Despite these benefits, patients did not express any preference for using the platform compared with conventional therapy.

The objective data obtained from the therapy allowed to perform a comparison between healthy and SCI participants. Although the result are not conclusive in all the games, it can be appreciated statistical difference in the game of Following the path. This comparison is made to know the motor performance of the two groups. Nevertheless, the small sample size prevents from drawing any definitive conclusions.

CHAPTER

6

CONCLUSIONS & FUTURE WORK

6.1 Conclusions

The use of new technologies in the rehabilitation field has been increased in the last years. These technologies present great advantages over traditional rehabilitation. Robot aided and VR rehabilitation provides higher motivational environment for the patient, facilitates the performance of the necessary movements repetitions for inducing the UL motor learning and increases the amount of therapy that patient received. However, these technologies are expensive, and a need for low-cost devices that can be afforded exists.

This work takes advantage of low-cost VR systems and robotic haptic devices to enhance involvement and engagement of patients, to provide a congruent multi-sensory afferent feedback during motor exercises, and to benefit from the flexibility of virtual scenarios for adapting the motor exercises to the needs of the patients.

This Thesis has reached the final goal of creating a low-cost rehabilitation platform. This platform enables the UL rehabilitation with haptic feedback and electromyography monitoring for SCI patients. Moreover, with this platform, SCI patients can increase the therapy time that spends in their rehabilitation process, which becomes more enjoyable. Patients are more involved in the therapy, in contrast with traditional methods that are boring and generate rejection of the therapy. As a result, this platform can be a perfect complement to the traditional rehabilitation methods.

First of all, three serious games have been designed and implemented. For this, the video game tool Unity 3D has been used. The design and implementation of each of the serious games have required the definition of a unique interface and adequate physical models relating to haptic feedback. These three serious games have been implemented meeting the needed requirements for an adequate SCI rehabilitation.

This study has gone a step further and has made a proof of concept to check the usability of the platform with SCI patients. The interface and the model of interaction with the patient have been properly evaluated and tested. The haptic force feedback has been strictly regulated using real information from testing users to avoid causing harm to patients. In the proof of concept performed, all the SCI patients finished the experimental sessions in a successful way. According to this, it can be affirmed that the environment implemented and the haptic device end-effector designed were properly adapted to the SCI people capabilities.

The pilot test shows some differences between the smoothness of the trajectory made by healthy and SCI patients. However, the result obtained from the clinical validation are not conclusive due to the the small sample size. This does not allow to clearly distinguish between the results of the two groups.

The potential of the three serious games to obtain relevant information about patients has been considered. This information is important for different aspects, such as monitoring the patient's progress. For this reason, the design of a system of collection and presentation of objective data has been implemented.

Results obtained are encouraging. Some of the main benefits drawn from this Thesis are exposed as follows:

- All the devices utilizing in the platform are low-cost and easily adaptable for different people, with a short spend time preparation for the serious games performance.
- The configuration options used in this project allows to create different scenarios, in order to represent distinct training situations for patient personalized.
- The final design generates a good haptic response and reliable monitorization of the muscle contractions.

In summary, this Thesis presents an innovative rehabilitation platform, based on an impedance haptic behavior, for training the strength and fine movements with the UL. It is a customizable, low-cost, haptic and VR based platform that can increase the time spent in therapy sessions and can be used as a complement to the traditional rehabilitation, improving the motivation of the patients in their rehabilitation process.

6.2 Future work

The work presented in this Thesis opens several lines of future work to improve this rehabilitation platform:

- Designing a new grip for the Novint Falcon to obtain more DOF and ROM, increasing the usability of the platform.
- Focused on the serious games, the number of objectives in the exercises can be increased including an endlessness mode. In this way, the therapy can be more intense and motivating.
- Validating the data obtained from the Myo Armband comparing with other electromyographic equipment used for clinical purposes. To achieve a relationship between the values obtained and the voltage.
- Utilizing the data provide from the electromyography records for controlling the appearance of peripheral fatigue, since bibliography suggests that muscle fatigue produces the decrease of median frequency in EMG data. Its supervision is important to avoid damaging the patient's muscle with an overload of work.
- Improvement in the muscle contraction acquisition, by changing the Myo armband by surface electrodes that can enable more exhaustive placement in the muscle group.
- The proof of concept performed shows encouraging results and provides positive feedback with regards to the serious games. However, it will be necessary to increase the number of patients who participate in the study and the time spent in therapy.
- It is a priority the scientific dissemination of the new rehabilitation platform presented and the main results obtained in this research. Making these results available to the scientific community can mean the beginning of new lines of research.

BIBLIOGRAPHY

American Spinal Injury Association (2018). Asia impairment scale (ais) steps in classification.

Basteris, A., Nijenhuis, S. M., Stienen, A. H. A., Buurke, J. H., Prange, G. B., and Amirabdollahian, F. (2014). Training modalities in robot-mediated upper limb rehabilitation in stroke: a framework for classification based on a systematic review. *Journal of neuroengineering and rehabilitation*, 11:111.

Björkdahl, A., Broeren, J., Claesson, L., and Rydmark, M. (2008). Virtual rehabilitation after stroke. *Studies in health technology and informatics*, 136(9):77–82.

Bone&Spine (2018). Spinal cord injury levels | bone and spine. `http://www.boneandspine.com/spinal-cord-injury-levels`. [Online; accessed June 2018].

Broeren, J., Sunnerhagen, K. S., and Rydmark, M. (2009). Haptic virtual rehabilitation in stroke: transferring research into clinical practice. *Physical Therapy Reviews*, 14(5):322–335.

Carignan, C. R. and Cleary, K. R. (2000). Closed-loop force control for haptic simulation of virtual environments. *Haptics-e*, 1(2):1–13.

Carlsbad, F. (2017). A guide to the muscles of the arm. `http://blog.carlsbadbootcamps.com/guide-muscles-arm/`. [Online; accessed June 2018].

Castro Sierra, A. and Bravo Payno, P. (1993). *Paraplejia otra forma de vida.* Editorial Sandro, Madrid, Spain.

Chortis, A., Standen, P. J., and Walker, M. (2008). Virtual reality system for upper extremity rehabilitation of chronic stroke patients living in the community. *Division of Rehabilitation & Ageing, University of Nottingham*.

Colombo, R. and Sanguineti, V. (2001). *Rehabilitation robotics : technology and application*. Academic Press.

Connell, L., McMahon, N., Eng, J., and Watkins, C. (2014). Prescribing upper limb exercises after stroke: A survey of current uk therapy practice. *Journal of Rehabilitation Medicine*, 46(3):212–218.

Connolly, S. J., McIntyre, A., Mehta, S., Foulon, B. L., and Teasell, R. W. (2013). Upper limb rehabilitation following spinal cord injury. *SCIRE Spinal Cord Injury Rehabilitation Evidence*, pages 149–61.

Curtin, M. (1999). An analysis of tetraplegic hand grips. *British Journal of Occupational Therapy*, 62(10):444–450.

de los Reyes-Guzmán, A. (2015). *Defnición e implementación de métricas objetivas para la evaluación funcional del miembro superior: aplicación a población con lesién medular cervical*. PhD thesis, Escuela Técnica Superior de Ingenieros de Telecomunicación, Universidad Politéctnica de Madrid.

D'Elia, B., Bernabucci, I., Bibbo, D., Conforto, S., D'Alessio, T., Sciuto, A., Scorza, A., and Schmid, M. (2016). Measuring regularity of fine upper limb movements with a haptic platform for motor learning and rehabilitation. *Lekar a Technika*, 46(1):5–12.

der Meijden, O. A. J. and Schijven, M. P. (2009). The value of haptic feedback in conventional and robot-assisted minimal invasive surgery and virtual reality training: a current review. *Surgical Endoscopy*, 23(6):1180–1190.

Dietz, V. (2012). Neuronal plasticity after a human spinal cord injury: Positive and negative effects. *Experimental Neurology*, 235(1):110–115.

Dimbwadyo-Terrer, I., Gil-Agudo, A., Segura-Fragoso, A., de los Reyes-Guzmán, A., Trincado-Alonso, F., Piazza, S., and Polonio-López, B. (2016a). Effectiveness of the virtual reality system toyra on upper limb function in people with tetraplegia: A pilot randomized clinical trial. *BioMed Research International*, 2016:1–12.

Dimbwadyo-Terrer, I., Trincado-Alonso, F., de los Reyes-Guzmán, A., A. Aznar, M., Alcubilla, C., Pérez-Nombela, S., del Ama-Espinosa, A., Polonio-López, B., and Gil-Agudo, A. (2016b). Upper limb rehabilitation after spinal cord injury: a treatment based on a data glove and an immersive virtual reality environment. *Disability and Rehabilitation: Assistive Technology*, 11(6):462–467.

Dimbwadyo-Terrer, I., Trincado-Alonso, F., De los Reyes-Guzmán, A., López-Monteagudo, P., Polonio-López, B., and Gil-Agudo, A. (2016c). Activities of daily living assessment in spinal cord injury using the virtual reality system toyra®: functional and kinematic correlations. *Virtual Reality*, 20(1):17–26.

Dimension, F. (2018). delta.3 - force dimension. `http://www.forcedimension.com/products/delta-3/overview`. [Online; accessed June 2018].

Ding, Y., Kastin, A. J., and Pan, W. (2005). Neural plasticity after spinal cord injury. *Current pharmaceutical design*, 11(11):41–50.

García-Altés, A., Pérez, K., Novoa, A., Suelves, J. M., Bernabeu, M., Vidal, J., Arrufat, V., Santamariña-Rubio, E., Ferrando, J., Cogollos, M., Cantera, C. M., and Luque, J. C. (2012). Spinal cord injury and traumatic brain injury: A cost-of-illness study. *Neuroepidemiology*, 39(2):103–108.

Gibbons, J. D. and Chakraborti, S. (2011). *Nonparametric Statistical Inference*. Springer Berlin Heidelberg, Berlin, Heidelberg.

Goel, S., Modi, H., Dave, B., and Patel, P. (2016). Socio-economic impact of cervical spinal cord injury operated in patients with lower income group. *Global Spine Journal*, 6(1):264.

González-Viejo, M. Á. (2014). Adaptación del paciente con lmat. la perspectiva del paciente y los profesionales. In *Congreso Paraplejia*, pages 12–16, Oviedo, Spain.

Guttmann, L. (1981). *Lesiones medulares. Tratamiento global e investigación.* Editorial Jims, Barcelona, Spain.

Guzmán, J. (2016). Upper limb rehabilitation with virtual environments: a review. *Revista Mexicana de Ingeniería Biomédica*, 37(3):271–285.

Hanson, R. W. and Franklin, M. R. (1976). Sexual loss in relation to other functional losses for spinal cord injured males. *Archives of physical medicine and rehabilitation*, 57(6):291–3.

Haption (2018). Virtuose™ 6d - haption sa. `http://www.haption.com/en/products-en/virtuose-6d-en.html`. [Online; accessed June 2018].

Hocoma (2018). Armeospring - hocoma. http://www.hocoma.com/solutions/armeo-spring/. [Online; accessed June 2018].

Hoffman, H. G., Patterson, D. R., and Carrougher, G. (2000). Use of virtual reality for adjunctive treatment of adult burn pain during physical therapy: A controlled study. *The Clinical Journal of Pain*, 16(3):244–250.

Hospital Medical School University of London, S. G. (2017). Upper Limb Treatment Schedule Booklet: to accompany the Upper Limb Treatment Recording Form.

Hospital Nacional de Parapléjicos (2018). Lesión medular espinal | hospital nacional de parapléjicos. http://hnparaplejicos.sescam.castillalamancha.es/es/pacientes/lesion-medular. [Online; accessed June 2018].

Huete-García, A andDíaz-Velázquez, E. (2012). Analisis sobre lesion medular en españa. *Federación Nacional Aspaym*, pages 1–20.

INDRA (2018). Toyra – sistema de rehabilitación. http://www.toyra.org/. [Online; accessed June 2018].

Institut-Guttmann (2018). Spinal cord injury | institut guttmann. http://www.guttmann.com/en/treatment/spinal-cord-injury. [Online; accessed June 2018].

Johns Hopkins Applied Physics Laboratory (2018). Revolutionizing prosthetics. http://www.jhuapl.edu/prosthetics/scientists/mpl.asp{#}. [Online; accessed June 2018].

Kaas, J. H. (2001). *International Encyclopedia of the Social & Behavioral Sciences*. Elsevier.

Kalsi-Ryan, S., Curt, A., Verrier, M. C., and Fehlings, M. G. (2012). Development of the graded redefined assessment of strength, sensibility and prehension (grassp): reviewing measurement specific to the upper limb in tetraplegia. *Journal of Neurosurgery: Spine*, 17:65–76.

Laver, K. E., Lange, B., George, S., Deutsch, J. E., Saposnik, G., and Crotty, M. (2017). Virtual reality for stroke rehabilitation. *Cochrane Database of Systematic Reviews*.

LiveScience (2018). Stroke therapy gets boost from virtual reality. http://www.livescience.com/35599-virtual-reality-games-stroke-recovery-rehabilitation-.html. [Online; accessed June 2018].

Lo, H. and Xie, S. (2012). Exoskeleton robots for upper-limb rehabilitation: State of the art and future prospects. *Medical Engineering & Physics*, 34(3):261–268.

Lu, X., M Zoghi, C. R., and Galea, M. P. (2015). Effects of training on upper limb function after cervical spinal cord injury: a systematic review. *Clinical Rehabilitation*, 29:3–13.

Ma, M., Jain, L. C., and Anderson, P. D. o. D. D. S. (2014). *Virtual, augmented reality and serious games for healthcare 1*. Springer Berlin Heidelberg.

Maciejasz, P., Eschweiler, J., Gerlach-Hahn, K., Jansen-Troy, A., and Leonhardt, S. (2014). A survey on robotic devices for upper limb rehabilitation. *Journal of NeuroEngineering and Rehabilitation*, 11(1):1–29.

Masiero, S., Celia, A., Rosati, G., and Armani, M. (2007). Robotic-assisted rehabilitation of the upper limb after acute stroke. *Archives of Physical Medicine and Rehabilitation*, 88(2):142–149.

Mazaira, J., Labanda, F., Romero, J., Garcia, M. E., Gambarruta, C., Sanchez, A., Alcaraz, M. A., Arroyo, O., Esclarin, A., Arzoz, T., Artime, C., and Labarta, C. (1998). Epidemiology and other aspects of spinal cord injuries. *Rehabilitació*, 32(6):365–372.

McCombe Waller, S. and Whitall, J. (2004). Fine motor control in adults with and without chronic hemiparesis: baseline comparison to nondisabled adults and effects of bilateral arm training. *Archives of Physical Medicine and Rehabilitation*, 85(7):1076–1083.

Merians, A. S., Poizner, H., Boian, R., Burdea, G., and Adamovich, S. (2006). Sensorimotor training in a virtual reality environment. *Neurorehabilitation and Neural Repair*, 20(2):252–267.

Microsoft (2018). Kinect for xbox one | xbox. `http://www.xbox.com/en-GB/xbox-one/accessories/kinect`. [Online; accessed June 2018].

MIT (2018). Mit-manus robot aids physical therapy of stroke victims. `http://news.mit.edu/2000/manus-0607`. [Online; accessed June 2018].

Monasterio-Huelin, F. and Gutiérrez, A. (2017). Introduction to Haptic Systems.

Murphy, M. A., Sunnerhagen, K. S., Johnels, B., and Willen, C. (2006). Three-dimensional kinematic motion analysis of a daily activity drinking from a glass: a pilot study. *Journal of NeuroEngineering and Rehabilitation*, 3.

Muscle Physiology (2006). Muscle physiology - types of contractions. `http://muscle.ucsd.edu/musintro/contractions.shtml`. [Online; accessed June 2018].

Nagaraj, S. B. and Constantinescu, D. (2009). Effect of haptic force feedback on upper limb. In *Second International Conference on Emerging Trends in Engineering & Technology*, pages 55–58, Nagpur, India. IEEE.

Nas, K., Yazmalar, L., Sah, V., Aydın, A., and Öneş, K. (2015). Rehabilitation of spinal cord injuries. *World journal of orthopedics*, 6(1):8–16.

National Spinal Cord Injury Statistical Center (2016). Spinal cord injury (sci) facts and figures.

Novint Falcon (2016). Novint falcon. `http://www.novint.com/index.php/products/novintfalcon`. [Online; accessed June 2018].

Novint Falcon (2018). Wide variety of games. `http://www.robotshop.com/media/files/PDF/datasheet-nf1-s01.pdf`. [Online; accessed June 2018].

Omelina, L., Jansen, B., Bonnechère, B., Van Sint Jan, S., and Cornelis, J. (2012). Serious games for physical rehabilitation: designing highly configurable and adaptable games. *Virtual Reality & Associated Technologies Laval 2012 ICDVRAT*, pages 10–12.

Oujamaa, L., Relave, I., Froger, J., Mottet, D., and Pelissier, J. Y. (2009). Rehabilitation of arm function after stroke. literature review. *Annals of Physical and Rehabilitation Medicine*, 52(3):269–293.

Palsbo, S. E., Marr, D., Streng, T., Bay, B. K., and Walter Norblad, A. (2011). Towards a modified consumer haptic device for robotic-assisted fine-motor repetitive motion training. *Disability and Rehabilitation: Assistive Technology*, 6(6):546–551.

Peñasco-Martín, B., De Los Reyes-Guzmán, A., Gil-Agudo, A., Bernal-Sahún, A., Pérez-Aguilar, B., and De La Peña-González, A. I. (2010). Application of virtual reality in the motor aspects of neurorehabilitation. *Revista de Neurologia*, 51(8):481–488.

Poli, P., Morone, G., Rosati, G., and Masiero, S. (2013). Robotic technologies and rehabilitation: new tools for stroke patients' therapy. *BioMed research international*, 2013:153872.

Rohrer, B., Fasoli, S., Krebs, H. I., Hughes, R., Volpe, B., Frontera, W. R., Stein, J., and Hogan, N. (2002). Movement smoothness changes during stroke recovery. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 22(18):8297–8304.

Schouten, B., Fedtke, S., Schijven, M., Vosmeer, M., and Gekker, A. (2014). *Games for Health 2014 : proceedings of the 4th conference on gaming and playful interaction in healthcare*. Springer Berlin Heidelberg.

Sensable (2016). Phantom. `http://www.dentsable.com/haptic-phantom-omni.htm`. [Online; accessed June 2018].

Sveistrup, H. (2004). Motor rehabilitation using virtual reality. *Journal of NeuroEngineering and Rehabilitation*, 1(1):10.

Taylor-Schroeder, S., LaBarbera, J., McDowell, S., Zanca, J. M., Natale, A., Mumma, S., Gassaway, J., and Backus, D. (2011). The scirehab project: treatment time spent in sci rehabilitation. physical therapy treatment time during inpatient spinal cord injury rehabilitation. *The journal of spinal cord medicine*, 34(2):149–61.

ThalmicLabs (2018a). Myo armband product specs – welcome to myo support. `http://support.getmyo.com/hc/en-us/articles/202648103-Myo-armband-product-specs`. [Online; accessed June 2018].

ThalmicLabs (2018b). Myo gesture control armband | wearable technology by thalmic labs. `http://www.myo.com/`. [Online; accessed June 2018].

Tiest, W. M. and Kappers, A. M. L. (2009). Tactile perception of thermal diffusivity. *Attention, perception & psychophysics*, 71(3):481–489.

Tropea, P., Cesqui, B., Monaco, V., Aliboni, S., Posteraro, F., and Micera, S. (2013). Effects of the alternate combination of error-enhancing and active assistive robot-mediated treatments on stroke patients. *IEEE Journal of Translational Engineering in Health and Medicine*, 1.

Unity3D (2018). Unity - manual: Creating gameplay. `http://docs.unity3d.com/Manual/CreatingGameplay.html`. [Online; accessed June 2018].

Virtual Reality Society, V. (2018). The novint falcon haptic system - virtual reality society. `http://www.vrs.org.uk/virtual-reality-gear/haptic/novint-falcon.html`. [Online; accessed June 2018].

VirtualRehab (2018s). Virtualrehab - Virtual physical rehabilitation system CE marked. `http://www.virtualrehab.info/`. [Online; accessed June 2018].

Westergaard, H. M. (1952). *Theory of Elasticity and Plasticity*. Harvard University Press, Cambridge, MA and London, England.

World Health Organization (2017). Rehabilitation 2030: A call for action. In *Rehabilitation*, pages 3–22, Geneva, Switzerland. WHO.

World Health Organization (2018). Spinal cord injury. `http://www.who.int/news-room/fact-sheets/detail/spinal-cord-injury`. [Online; accessed June 2018].

Wyndaele, M. and Wyndaele, J. J. (2006). Incidence, prevalence and epidemiology of spinal cord injury: what learns a worldwide literature survey? *Spinal Cord*, 44:523–529.

Yates, M., Kelemen, A., and Sik Lanyi, C. (2016). Virtual reality gaming in the rehabilitation of the upper extremities post-stroke. *Brain Injury*, 30(7):855–863.

Zariffa, J., Kapadia, N., Kramer, J. L. K., Taylor, P., Alizadeh-Meghrazi, M., Zivanovic, V., Willms, R., Townson, A., Curt, A., Popovic, M. R., and Steeves, J. D. (2012). Feasibility and efficacy of upper limb robotic rehabilitation in a subacute cervical spinal cord injury population. *Spinal Cord*, 50(3):220–226.

Appendices

APPENDIX

A

TECHNICAL MANUAL

This manual has been develop for the technicians of the Hospital Nacional de Paráplejicos of Toledo (Spain), therefore, its content is in Spanish to facilitate its reading.

Requisitos del sistema

Sistema operativo: Ubuntu 16.04 LTS o superior de 64 bits.

Permisos de usuario: plugdev, dialout

Librerías de Ubuntu: cmake, gcc, libusb-1.0

Gráfica: Open GL 3.0

Instalación

Para el uso de la plataforma ArmRehab es necesario instalar previamente las librerías de los instrumentos de rehabilitación (Novint Falcon) y monitorización (Myo Armband).

Librería Novint Falcon

Para permitir el control de la plataforma mediante el Novint Falcon, se han de actualizar algunas algunas reglas e instalar la librería.

1. Descargar el archivo 11-forcedimension.rules y copiarlo en la ruta "/etc/udev/rules.d".

2. Recargar las reglas:

   sudo udevadm control –reload-rules

3. Descargar $libnifalcon - 1.0.1.tar.gz$. Descomprimir el fichero .tar.gz. Abrir la terminar y seguir los siguientes pasos.

   - cd $libnifalcon - 1.0.1$
   - mkdir build
   - cd build
   - cmake -G "Unix Makefiles" ..
   - make
   - make install

Librería Myo Armband

Para permitir el control de la plataforma mediante el Myo Armband, se ha de instalar la librería.

1. Descargar el archivo $myolinux\_1.1.0\_x86\_64.tar.gz$. Descomprimir el fichero .tar.gz. Abrir la terminar y seguir los siguientes pasos.

   - cd $myolinux\_1.1.0\_x86\_64$
   - mkdir build
   - cd build
   - make ..
   - make
   - make install

Manual de extracción de datos

La plataforma contiene tres carpetas, una donde se almacenan los datos procedentes de Myo armband (Myo), otra con los datos almacenados de la posición procedentes de Novint Falcon (Pos) y una carpeta con los datos necesarios para la ejecución de la plataforma en Unity 3D (ArmRehabData). Finalmente aparece el ejecutable ($ArmRehab.x86\_64$) para el sistema operativo de 64 bits.

Los datos almacenados procedentes de Myo Armband Se encuentran almacenados en la carpeta Myo, aquí encontrará dos tipos de archivos los que almacenan los datos de electromiografía cuyo nombre comienza por el prefijo EMG y aquellos relacionados con la información de la unidad de medición inercial, que comienza con el prefijo IMU. Ambos datos se almacenan con el día y la hora pertenecientes al inicio de la terapia.

Los datos de posición extraídos del dispositivo Novint Falcon se almacenan en la carpeta Pos. Aquí encontrará archivos cuyo nombre comienza por el título de cada uno de los juegos, también con el día y la hora en la que se han ejecutado cada uno de ellos.

Finalmente, en la carpeta ArmRehabData, dentro de StreamingAssets, encontrará la carpeta de Perfiles donde están almacenados los datos de cada uno de los paciente en un fichero con el nombre proporcionado al realizar el registro.

APPENDIX

B

USER MANUAL

This manual has been develop for the clinicians of the Hospital Nacional de Paráplejicos of Toledo (Spain), therefore, its content is in Spanish to facilitate its reading.

Preparación del dispositivo de electromiografía

Para comenzar con la terapia, coloque el dispositivo Myo Armband en el grupo muscular de interés. Posicionando el electrodo que contiene el icono de Myo Armband en la zona muscular que desee visualizar durante la terapia. Asegúrese de que la línea que aparece en la parte inferior de ese mismo electrodo queda posicionada en la parte más cercana a la muñeca del paciente.

Manual para el uso de la plataforma

Para inicializar la plataforma se debe seleccionar el ejecutable $ArmRehab.x86\_64$. En ese momento se abrirá la pantalla de bienvenida.

1. **Entrar en la plataforma.** Para acceder a la plataforma, hacer click sobre el botón de Entrar, entonces se pasará a la pantalla de Pacientes.

2. **Selección de Registro o Nuevo ingreso.**

   (a) **Nuevo ingreso.**

      i. Si deseamos introducir un nuevo paciente al registro, seleccionar la opción de Nuevo ingreso.
      ii. En ese momento aparecerá una nueva pantalla con los datos solicitados para generar un nuevo perfil.
      iii. Una vez rellenados los campos solicitados, pasar a seleccionar el botón de Guardar. En ese momento el nuevo perfil del paciente se habrá generado. **NOTA:** El único campo obligatorio, al que se le deben proporcionar datos es el de Nombre del paciente.

   (b) **Registro.** Si se desea realizar la terapia con un paciente que ya tiene un perfil almacenado se pasará a seleccionar el botón de Registro.

3. **Selección del perfil del paciente.**

   (a) En este momento, aparece una pantalla con un desplegable, donde se debe seleccionar el nombre del paciente con el que se va a realizar la terapia.
   (b) Después de esta acción pulsar el botón Terapia.

4. **Selección del serious game.**

   (a) En este punto, aparece una pantalla con una imagen de cada serious game junto con el título de cada uno, así mismo encontrará el registro del EMG en la zona inferior de su pantalla.
   (b) Para comenzar la terapia simplemente haga click sobre la imagen del serious game que desee utilizar.

5. **Inicio del serious game.**

   (a) **Test**

      i. Si es la primera vez que el paciente se enfrenta a esta terapia o si desea realizar una prueba del serious game, seleccione el botón de Test.
      ii. Después del tiempo prefijado el test finalizará y se volverá a la pantalla de inicio del juego.

   (b) **Comenzar**. Si se desea comenzar la terapia pulse Terapia.

6. **Selección de los parámetros del juego.**

   (a) En esta fase, aparecerán tres barras de desplazamiento, encima de cada una de ellas aparece el parámetro a seleccionar y su rango de valores.
   (b) Sitúese encima de cada una de ellas y desplácese a derecha o izquierda, hasta que haya alcanzado el valor deseado.
   (c) A la derecha de cada una de las barras de desplazamiento aparece el valor que ha sido seleccionado.
   (d) Una vez ajustados todos los parámetro presionar el botón de Aceptar.

7. **Ajuste de la posición inicial.**
   (a) Se deberá solicitar al paciente que posicione la mano sujetando la empuñadura del dispositivo Novint Falcon.
   (b) Cuando el paciente se encuentre con la empuñadura pegada al icono del Novint Falcon, se procederá a pulsar el botón de Empezar.

8. **Juego en ejecución.**
   (a) Durante está fase se deberá asegurar de que el paciente no realiza movimientos compensatorios con el tronco.
   (b) Una vez que el juego ha comenzado, esperar a que el tiempo finalice o a que el paciente haya conseguido todos los objetivos.

9. **Juego finalizado.**
   (a) Una vez finalizado el ejercicio aparecerá una pantalla con el número de objetivos alcanzados por el paciente.
   (b) Pulsar botón Guardar para continuar.
   (c) Si se desea ejercitar al paciente con el mismo serious game prosiga con los pasos descritos en el punto 5. Si por el contrario se desea cambiar de serious game seleccione el botón Salir y vuelva al punto 4.

10. **Salir de la plataforma.** Si se ha terminado con la terapia pulse el botón Salir, si por el contrario desea realizar una sesión con otro paciente, seleccione el botón Volver y prosiga con el punto 3.

APPENDIX

C

IMPACT

There is an impact of 30 cases of spinal cord injury per million of inhabitants and there are approximately 1.000 new cases every year in Spain. A big problem derived from this injury is the lost of upper limb fine control. Therefore, this project pretends to set an objective and effective manner to accomplish a robot aided virtual reality platform for the rehabilitation of the upper limb, trying to recover the strength and complete control of the upper limb of spinal cord injury people.

- **Social impact:** this project will have a direct impact on people with spinal cord injury and therefore to an important group of the population. They could benefit from a rehabilitation platform that can improve their upper limb skills in a motivational environment.

- **Economical impact:** this project will have an impact in the economic field reducing the cost of the rehabilitation platform due to low-cost of the platform. Moreover, this project can impact in the therapist hours spend in the treatment because the process is almost automatic. This way the therapist can attend more people at once time.

- **Ethical impact:** this impact is controlled as the experiments performed at the Hospital Nacional de Parapléjicos have been approved by the Ethics Review Board in the context of physiotherapy rehabilitation fro upper limb. This project falls within this framework not causing any further ethical impact. Moreover, all experimental procedures performed in which human participants are involved were in accordance with the ethical standards of the 1964 Helsinki Declaration and its later amendments. Each participant in the test has been informed properly of all the procedures in which he or she was involved.

- **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.

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

APPENDIX

D

BUDGET

This project has been developed during four months in the Universidad Politécnica of Madrid using some of its resources. An approximate budget is estimated taking into account human resources, software, technical equipment and some laboratory material used during the project.

- **Costs derived from human resources**

  This item should consider the salary of all the people involved in the project: project manager (engineer), associated engineer, medical doctor, occupational therapist and the engineering student, author of this Master Thesis as shown in Table D.1.

- **Costs derived from sofware and technical equipment**

  For this Thesis, the software and technical equipment listed on Table D.2 has been used. The total costs are computed by the product of the depreciation cost per month and the time of use.

Table D.1: Costs derived from human resources

	Cost per hour (€)	Working hours	Total costs (€)
Project manager	22 €	200	4,400 €
Associated engineer	15 €	100	1,500 €
Medical doctor	25 €	30	750 €
Occupational therapist	15 €	100	1,500 €
Engineering student	10 €	900	9,000 €
TOTAL			**17,150€**

Table D.2: Costs derived from software and technical equipment

	Lifetime (years)	Units	Cost (€)	Depreciation (€/month)	Time used (month)	Total cost (€)
Myo Armband	2	1	200	3.33	5	41.66
Novint Falcon	2	1	200	3.33	5	42.66
3D printer	2	1	300	12.50	1	12.50
Unity 3D	1	1	300	25.00	5	125.00
MATLAB software	1	1	2,000	166.67	2	333.33
Office license	2	1	139	5.8	5	29.00
Personal Computer	5	1	800	13.33	5	66.67
TOTAL						**650.82**