DM

ReLiPh
Rehabilitation for Lower limb with Phantom pain

MASTER DISSERTATION

Carlos André Freitas Costa

MASTER IN INTERACTIVE MEDIA DESIGN

UNIVERSIDADE da MADEIRA

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ORIENTATION
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CO-ORIENTATION
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Resumo

O membro fantasma ou sensação fantasma, ao longo dos anos, têm se destacado por ser originada de diferentes causas. Pesquisas e estudos mostram que, após uma amputação, na maioria dos casos, experienciam a sensação de membro fantasma e em muitos desses casos dolorosos.

A presente tese baseia-se em uma pequena parte deste amplo tópico. Baseada na terapia de espelho usada na reabilitação e tratamento da dor fantasma. Ao longo do projeto, nós estudamos quais são os componentes mais relevantes para a reorganização/reestruturação, a fim de eliminar os sintomas negativos e futuros distúrbios/perturbações. Associada na relação do cérebro com o corpo, ou seja, as imagens formadas pelo cérebro em relação ao corpo físico desempenhando um papel crucial na relação do membro fantasma e da dor no membro fantasma, bem como no processo de cura e tratamento através de exercícios e no relacionamento da imagem que o cérebro tem do corpo físico.

Esta dissertação tem como objetivo na construção de uma nova abordagem tecnológica, baseando-se nos princípios e critérios utilizados na terapia de espelho. A metodologia assenta na criação de um ambiente de realidade virtual controlado por um dispositivo que captura a atividade muscular em tempo real. Implementado num jogo baseado em movimentos/exercícios simples e naturais, sem uso de força ou esforço.

Os elevados resultados verificados e testados, em indivíduos saudáveis e em um estudo de caso, na redução da dor fantasma, gerando um interesse e motivação, além de um melhor senso de presença e foco durante o seu uso. Concluindo, o projeto abre novas direções futuras de como novas abordagens tecnológicas podem ser usados nas pesquisas médicas na área do membro e na dor fantasma, em ambientes controlados e contextualizados. Melhorando a eficácia e eficiência, garantindo uma maior flexibilidade nos diferentes casos de amputação.

Palavras-chave: sensação fantasma, membro fantasma, dor fantasma, imagem, cérebro, realidade virtual, realidade aumentada, tratamento não medicinal, neuromatrix, sistema sensorial, reabilitação cognitivo-motora.

Abstract

The phantom limb or phantom sensation, over the years, has stood out being originated from different causes. Research and studies show that after an amputation, in most cases, they experience the sensation of a phantom limb and in many of those painful feelings.

This thesis is based on a small part of this wide topic. Based on the mirror therapy used in rehabilitation and treatment for phantom pain. Throughout the project, we study what are the most relevant components to reorganization/restructuring in order to eliminate negative symptoms and future disturbances. Moreover it is established in the relationship of the brain with the body, that the images formed by the brain in relation to the physical body play a crucial role in the relationship with the phantom limb and phantom limb pain, as well as in the process of healing and treatment throughout exercises and the relationship of the image that the brain has to the physical body.

This dissertation aims to build a new technological approach, based on the principles and criteria used in mirror therapy. The methodology is based on the creation of a virtual reality environment controlled by a device which captures the muscle activity in real time. Implemented in a game based on natural and simple effortless exercises without the use of strength.

The high results verified and tested, in healthy subjects and in a case study, to reduce phantom pain, generating an interest and motivation, as well as a better sense of presence and focus during its use. In conclusion, the project opens up new future directions of how new technological approaches can be used in medical research in the field of phantom limbs and in phantom pain, in a controlled and contextualized environments and/or movements. Improving effectiveness and efficiency ensuring greater flexibility in different cases of amputation.

Keywords: phantom sensation, phantom limb, phantom pain, image, brain, virtual reality, augmented reality, non-medical treatment, neuromatrix, somatosensorial system, cognitive-motor rehabilitation.

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List of Abbreviations (Acronyms)

AR - Augmented Reality

CNS - Central Nervous System

EDA - Electrodermal Activity

EMG - Electromyography

fMRI – functional Magnetic Resonance Imaging

GMI - Graded Motor Imagery

HMD – Head-mounted Display

IMUs - Inertial Measurement Units

MEG – Magnetoencephalography

MT - Mirror Therapy

M1 - Primary Motor Cortex

VR - Virtual Reality

PL - Phantom Limb

PLP - Phantom Limb Pain

RMS - Root Mean Square

S1 - Primary Somatosensory Cortex

TENS - Transcutaneous Electrical Nerve Stimulation

W.H.O - World Health Organization

Table of Contents

1. Introduction

The present thesis is divided into three main parts, starting with the contextualization of the topic and the reason behind the development. Following this, the primary purpose and goals of this dissertation are described. Finally, a brief description of the document structure follows.

1.1. Motivation

Phantom limb (PL) is a sensation felt by patients that have suffered from a deafferentation/amputation or when they are missing a limb. Research and statistics show that between sixty to eighty percent of cases that suffer from amputations can feel phantom limb sensations, in most cases, painful [1], [2].

These sensations are not restricted to the amputation of a limb but also other body parts, such as an eye or a simple tooth removal, turning, for example, tooth pain in a tooth phantom pain. This sensation that the body part is still there and alive, in some cases, can turn into a harrowing experience.

PL and phantom limb pain (PLP) are complex topics due to the areas it covers. This topic is composed of different subjects extending from the human brain to the physical body. Overall, all human beings and animals can suffer from it, which offers the opportunity to study the brain and its relationship with the respective bodies. That is, it can be useful to deconstruct and study some of our brain's functionalities, behavior, complexity, and the mechanisms behind the way we interact with our bodies.

Researchers have found different mechanisms and treatment approaches to healing the PL and PLP with different levels of success. These can be split into pharmacological, surgical, and adjuvant therapies, and are explained in detail more ahead [5], [6].

The thesis will rely on a significant adjuvant therapies mirror therapy, which compel our brain to reorganize our connections and restructure the somatosensory and motor systems. Likewise promoting the creation of new cortex/neural connections and/or reuses of the area of the deafferentation body part by the advent parts in the brain. Additionally, we are proposing a new real-time technological development using electromyography and virtual reality.

1.2. Objectives

The primary purposes of this thesis are 1) RQ1. Is it feasible to implement a gamified therapeutic approach for Phantom Limb Pain using VR and EMG?; 2) RQ2. Is the proposed system fulfilling its therapeutic goals in terms of Engagement, Usability and User Experience?, and finally 3) RQ3. Can the approach mitigate Phantom Limb Pain?

1.3. Document Structure

The research and development process are described in the seven chapters of this thesis with the following structure: Chapter I is the introduction where we give an overview of the document, the motivation, the contextualization behind it, the objectives and main goals as well as presenting the document structure. In chapter II, there is a compilation of literature review related to the thesis' focus. The state of the art presents and familiarizes the reader with the subject, showing other researchers' works, projects, and updates to the present year of this thesis. Also, it discusses some of the technological approaches of the user, their constraints, and their effectiveness. Chapter III talks about the methodologies and methods that we took on, the effort, and all development of the project itself. Also, it shows how the implementation and all choices regarding interaction and design. Chapter IV and Chapter V consists of the methodology description used for two studies with a healthy sample and a patient case study. We analyse and discuss the results throughout the use of system usability scale, intrinsic motivation inventory, presence, and pain/sensation questionnaires. Chapter VI relates to the conclusion based on the results of the chosen methodology which the discussed two studies and the final conclusions to the development of the project. Finally, Chapter VII talks about future work, providing some guidelines and future directions.

2. State of the art

This chapter represents the statement of the art and literature review for the main thesis topic. It gives the context and background about the research, case studies, and updates of the topic, introducing the reader to the matter.

To ensure that this literature is up to date, the search and inclusion of papers, scientific magazines, discussions, and books follow these inclusion criteria:

- All the search has been done following the keywords: phantom sensation, phantom limb, phantom pain, body representations, virtual reality, augmented reality, non-medical treatment and mechanisms, neuromatrix, somatosensorial system, cognitive-motor rehabilitation, mirror therapy, somatosensory disturbances, motor disturbances, effective therapies for PL and PLP;
- Articles should have a significant number of citations;
- Most of the search was made in Google Scholar and PubMed databases.

2.1. Phantom limb (PL)

In 1866, S. Weir Mitchell, an American neurologist, published an anonymous short story in the scientific journal Atlantic Monthly. The story tells us about a man who undergoes an arm amputation during the Civil War. Later, he awakes in a hospital, and also suffers deafferentation on both legs, making him start feeling the phantom limb sensation.

In truth, phantom limb phenomena are quite common, and they usually come with sharp pain on these invisible body parts. Even nowadays, the causes and the associated suffering are not well understood. Many researchers are trying to explain this sensation and researching treatments, leading them to discover new ways to resolve this sensation and intractable pain [1], [2].

This theme conveys and proposes questions on some contemporary areas of psychology and neuroscience. Phantom limbs are extraordinary for their reality, vivid sensations, and precise location [2].

Phantoms happen almost immediately after amputations of a limb, and studies show that between ninety to ninety-eight percent of cases experience this vivid sensation [1]. There are some hints that this experience is mostly felt after a traumatic incident or a pre-existing pain condition and after a surgical intervention of a non-painful body part. Also, phantoms are less seen in younger ages (childhood and earlier), not rejecting the hypothesis that a child who was born without a body part has not any less probability of suffering from PL [1]. Some studies say the reason behind this is that our mind has not had enough time to take full conscience of our body schema.

However, PL is more about the brain and its relationship with the body and the perception that our body has about itself. Multiple areas form our brain with different modalities and functionalities, this includes a variety of framed maps that are set by our DNA.

2.1.1. The brain and its relationships with the body - the theory behind the phantom limb sensation and phantom limb pain

Phantom limb sensation is a very complex subject in which two main areas are incorporated, being the mental and physical parts. In this section, we give the reader two main theories behind the mental state and its impact on the physical body.

Starting by the mental, our brain is divided into two sections, the left side of the brain is more related to the sensorial system and the right side to the motor system. They communicate between them, and it is how we receive information from the senses that our brain sends information of movement or perform a movement.

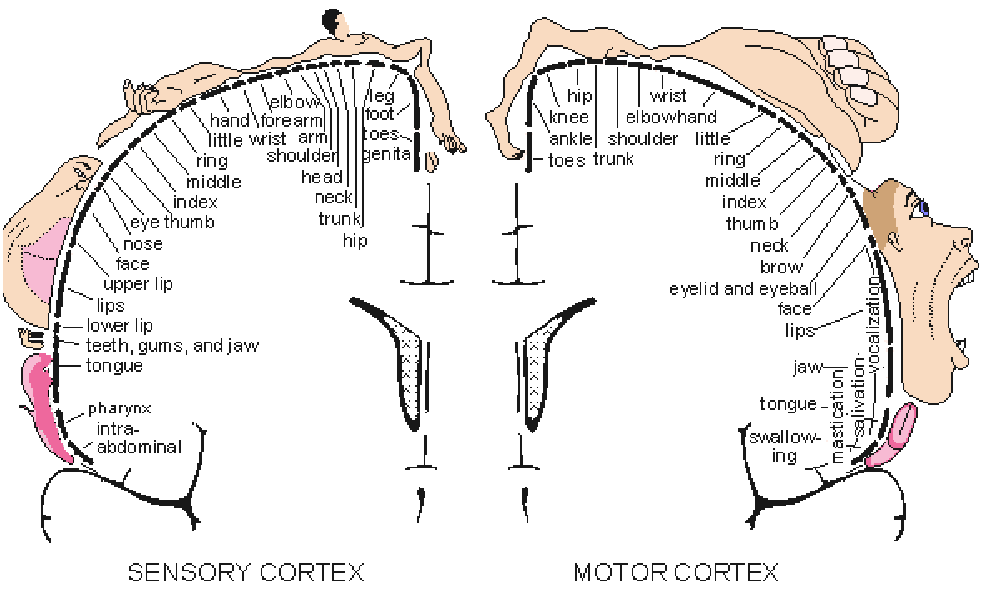


Figure 2-1 Representation of homunculus, brain areas, and responsible body parts [33]

In 1998, V. S. Ramachandran and William Hirstein et al. focus mainly on the sensorial system, which divides the brain into several smaller areas with the function of controlling and sensing for a corresponding part of the body, this function is called somatosensory system (Figure 2-1). What happens when an amputation is performed? Researchers developed a somatotopic map where we can check the areas and which body part is interconnected. After deafferentation, the brain assumes that an area does not exist because it is not performing its base functionality and behavior, so adjacent areas surrounding that section take it for themselves (Figure 2-2). One of the commonly cited cases is an experiment on a monkey in which the middle finger is amputated. Sometime after the area occupied by the finger, in the brain cortex, it was taken over by the adjacent fingers and the sensory inputs from the adjacent fingers. This function of the brain is called cortical reorganization [2].

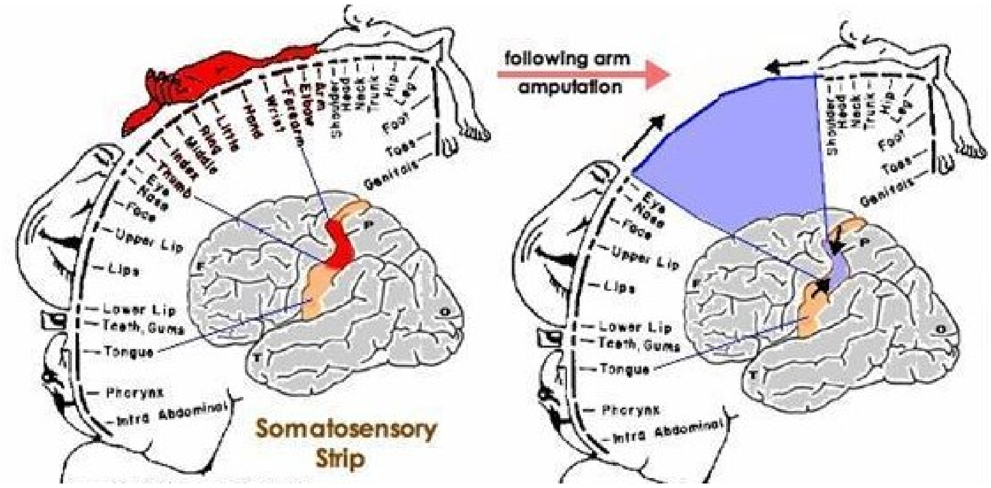


Figure 2-2 Representation *of the behavior of the human brain after amputation [34].*

On the other hand, a broader theory based on the neural mechanisms related to the experiences learned by the physical self and suggests a more traditional point-of-view, the body schema [3]. Between 1990 and 1992, Ronald Melzack et al. believe that PL also starts on the human brain but refutes the idea of the somatosensory cortex, saying that both phantom limb and phantom limb pain can return, proposing a new concept of the nervous system called neuromatrix. The neuromatrix is the inside brain to which every other billion impulse nerves arrive at throughout the proprioceptive and cutaneous systems, and from the visual and vestibular systems (Figure 2-3). These sensory inputs sculpt a network, composing a neuromatrix [2], [3], [5].

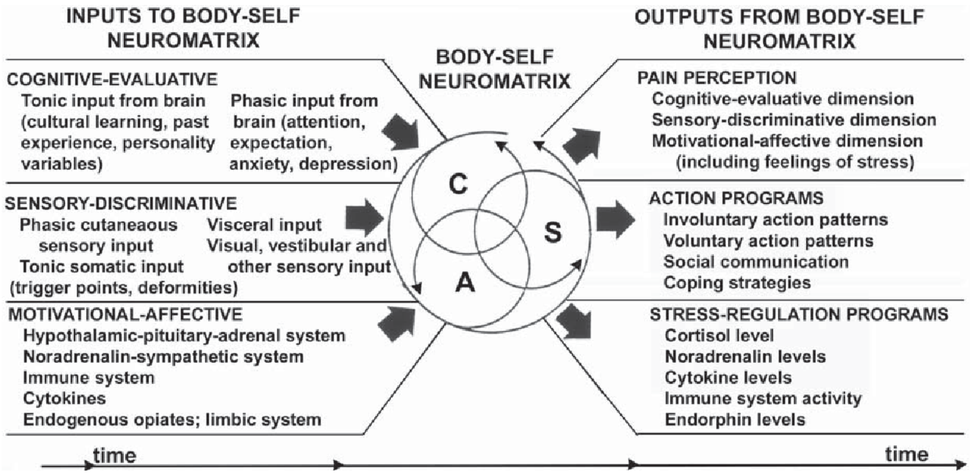


Figure 2-3 Neuromatrix inputs and outputs by Melzack et al. [2].

The sensory inputs have a characteristic pattern or neurosignature produced throughout the patterns of synaptic connections, which are initiated and changed by the experience in the entire neuromatrix. Some areas of the neuromatrix are related to the significant sensory events as an injury, for example, which impress deafferentation on a larger neurosignature [3].

These theories have not discarded all the effects that the patients suffer, and they try to find some justification and reason behind why it happens and how, contributing to solving patients' problems [2], [3], [5]. Overall, our brains have several mechanisms to reorganize themselves and different perceptions which cause the neural plasticity and the pain.

2.1.2. Central neural plasticity and pathology of pain

Phantom limbs have a complicated relationship between central neuroplasticity and pain pathology. The neuroplasticity is the ability of the brain to adapt and change at a cellular/neural level and it can involve a cortical remapping when in a large-scales. Moreover, brain areas can be change by the neuroplasticity and it is a cause of a pain pathology. The way to visualize these changes is through a somatotopic map that reveals the neuroplasticity changes in the representations/perceptions in the central nervous system from the spinal cord to the cerebral cortex [16]. The brain cells responsible for controlling that part of the body have their inputs changed, contrary to the output of these cells, which is still the same. These changes happen in the amputated part and the brain after an amputation due to the fact of having the existing neurons removed which respond to stimulation from the removed body part. The neural network, the neuromatrix, is built and modified by the sensory inputs while the output stays consistent in producing the representation of the deafferented body part [1], [2], [3], [5], [16].

These can explain the reason behind telescoping, the process that our brain does through when reorganizing/restructuring to match the brain-physical image with the physical body. Telescoping, a marked plasticity in the brain, changes the sensory areas but the core stays intact, which continues sending signals for perception and responding because the body is genetically designed for it [1], [2], [3], [5], [16].

Plasticity continues happening in our brains, it does not change its role or activity entirely within the brain structures [16]. The concept of neuroplasticity suggests that neural and synaptic functions are capable of being moulded or shaped, influencing perceptual experiences [16].

Furthermore, the brain has been accepted as an active system capable of filtering, selecting, and modulating inputs originating a gate control theory that emphasizes the central nervous system (CNS). The CNS highlights the pain as a process and an essential component for its mechanisms [16]. Pain functions/operates as a warning and a consequence, activated by pain receptors and fibres, sent to the pain center in the brain throughout the spinal channels responsible for the transmission of pain impulses, known as spinal pain pathways. Today, for instance, pain is seen to be a pathology since patients do present signs of organic disease or injury [16].

PLP is referred to and explained as a consequence of the pain felt before the amputation, also known as “pain memories” [1], [2], [3], [5], [16]. The two leading causes of PLP are inhibition of pain during the pre-amputation time, which continues being sent to the brain, from an old injury, centrally represented. The second is due to the continued visual perception of the lost limb, a mechanism responsible for confirming or denying the information, and the ways the perceptive sensorimotor mechanisms deal with the absence of visual and touch sensation [16].

Figure 2-4 Visual representation of the sensation felt in different body areas[1].

Findings suggest that this type of pain occurs more often in PL patients being a sign of central neuroplasticity and it is related to the cortical reorganization [16]. Central neural mechanisms, specifically those with changes at the brain level, have been most studied in the recent years. This due to the cortical reorganization explaining the reason for the neurons on the stump and surrounding areas. The stimulation in the neuroceptives, produces a sensation in the phantom limb (Figure 2-4) [6].

Overall, the neurons present in the somatosensory provoking CNS hyperactivity produce high firing rates, abnormal burst activity, and evokes the stimulation to body areas. Pieces of evidence have shown that pain could be dependent on CNS changes, which can provoke sensory disturbances caused by the excitability of CNS neurons involving pain transmitters [16].

The sensitization to the pain is increased by the spontaneous activity, the afferent inputs or reduced thresholds, and prolonged after discharges to repeated stimulation. These are localized in the spinal cord and other areas in the somatosensory pathways [16]. Understanding these concepts and the neuroplasticity bring therapeutic possibilities advances in pain relief for treatments [1], [2], [3], [5], [16].

2.1.3. Phantom limb pain (PLP)

The phantom limb pain is the most common sensation felt, occurring in more than seventy percent of the cases. Frequently, the pain sensation happens six months after the amputation, and it can persist twenty-five years after the deafferentation commonly described as burning and cramping sensations in the whole phantom body part [1], [2].

V. S. Ramachandran and William Hirstein et al. explain this pain as being triggered and occurring throughout emotional distress and/or a "pain memory" present in the spinal cord [1], [5]. On the other hand, Ronald Melzack et al. said that the pain can result as activation of the neuromatrix. The response is due to the absence of the limb, as the human brain tries to communicate with the missing part sending messages to the muscles as a way to promote movement. Ronald Melzack et al. concluded that all the pain and painful sensation starts in the human brain [2].

Deafferentation is part of these changing experiences where an anomaly is created in the system input, generating overactivity and lacking sensation activity. These changes were believed to occur when the organism developed for a limited time period, but PL and PLP proved a new perspective and a new point-of-view.

Many of these phantom sensations are present in the first few days or weeks gradually fade from consciousness after an amputation. On the other hand, in some patients, this pain persists for years and decades. There are even some cases where patients can revive their phantom limb through intense concentration or just rubbing on the stump [1]. In many instances, a phantom limb commonly reported in amputations done in arms, legs, and internal organs. An important observation, in clinical implications, is the attention given to the body part during the pre-amputation time. This attention can contribute to a subsequent vividness of the PL, provided by "repressed memories" [2].

PLP can have several psychological factors attached that contribute to it, for example when a deafferentation occurs. Sometimes, peripheral changes promotes and/or evokes some manifestations, the most common are tickling, warmth, cold, and muscle cramp. Such mechanisms help us to gain understand the relationship between the pain, and how it is triggered, and their effects on the brain and its systems [6]. These peripheral changes have been significant to PL and PLP provided by an input from a residual limb [5]. This explores and understands the relationships in social, psychological, and behavioural factors on body process and quality of life [5].

When comparing studies, several constraints and factors were found. The majority prove that PLP is less in men than women and reduces overtime when compared to the upper limbs. The reasoning behind the upper limbs are more sensitive and feeling more intense, due to the fact of their usage and importance for our daily life. Besides, the World Health Organization (WHO) research and study show that neuronal plasticity is related to age, provoking distortion, sensation, and perception loss in later life stages [8].

As previously explained by Melzack, the spinal cord mechanisms rule some of these causes, and it involves several brain areas that are related to the neuromatrix [2], [3], [5]. A network in the human brain composed of neurons present in several brain areas from the somatosensory system, the brainstem, the thalamus, and the cortex. This neuromatrix ware determines when the human system was born and adapts according to living experiences.

2.1.4. Telescoping and sensations

An extraordinary fact about the PL is the vivid sensory information and the precise location in space that it occupies. This effect happens almost immediately after the deafferentation. In the beginning, the limb feels normal and vivid as if it was still there, with the same shape and size. At this state, the amputees can "use" the phantom to reach objects or "walk" with the phantom leg, acting as a normal limb or body part. Despite this, it can assume awkward positions sometimes, getting stuck in an unusual position, and it can move by itself. The patients report that these invisible limbs coordinate and move together with other parts, similarly when walking occurs [1], [2].

Overall, some factors can enhance and/or attenuate PL, generally enhanced by the sensation that appears before deafferentation. Phantom sensation mimics the feeling of the limb [1]. A pre-amputation history can arouse a more vivid representation that persists long after a traumatic loss. A pre-existing pain after a planned surgical amputation of a non-painful limb can also influence PLP. In 1872, Mitchell et al. explain that if the stump heals, the phantom quickly fades faster. However, when anaesthetics are applied to the stump, these can contribute to a more vivid sensation and sometimes resurrect the phantom sensation [2]. Melzack and Katz et al. in 1990, showed that more persistent pain in amputation cases compared to the painless ones can have a significant influence in the phantom pains and neutral phantom sensations [2]. The condition and stimulation of the stump can also influence the vividness and the duration of this phenomenon.

As time passes, the phantom begins to change in size and shape, starting "telescoping" as if the limb begins to be shorter until matches reality, going into the stump (Figure 2-5).

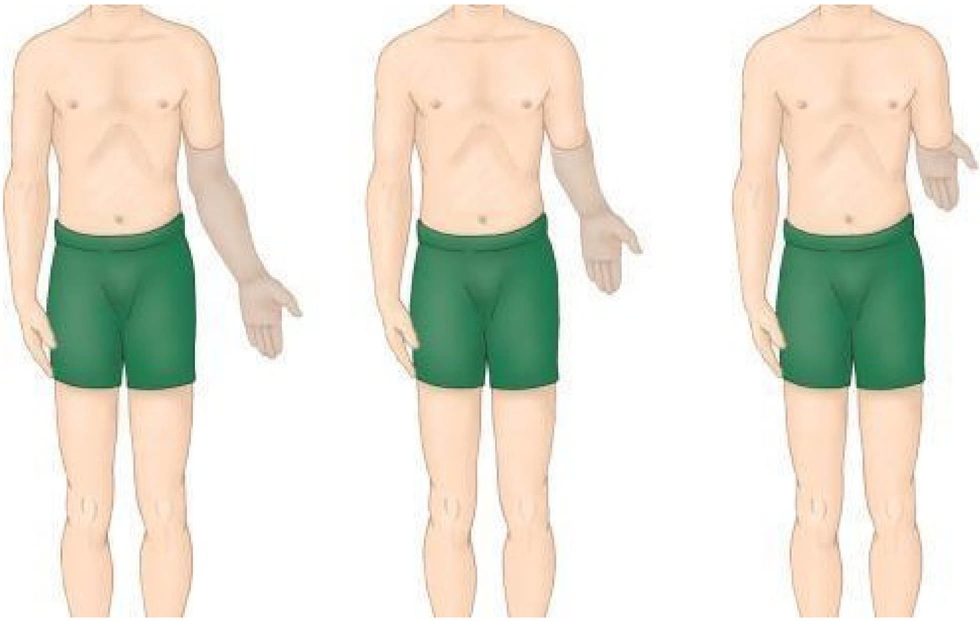


Figure 2-5 Visual representation of the telescoping effect [35].

The amputation, nerve destruction, and nerve damage do not have any influence on the occurrence of the phantom sensation [2]. Sometimes, the phantom limb can be in a specific position, in regular or angled states. In other cases, the limb passes through the body [2].

Another important fact is the "repressed memories," that consists of sensations, feelings, pain, movements, and memories before the amputation that re-emerge after the deafferentation. These sensations typically mimic feelings perceived before the deafferentation, which are a variety of feelings and sensations that have been described by amputees. They can be perceived as burning, cramping, warmth, cold, pressure, wet, and other types, as well as the PL assuming unnatural positions (Figure 2-6).

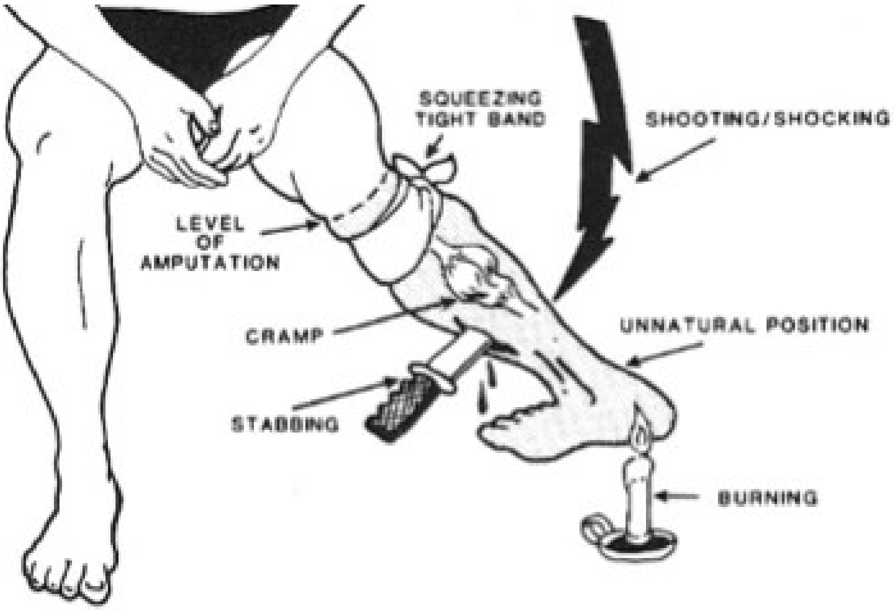


Figure 2-6 The most common sensations felt in the phantom limb [36].

The sensations are more vivid when the amputee wears a prosthesis, as the brain assumes that it is a healthy body part, which enhances and strengthens these experiences [3].

In 1992, Melzack et al. shows more recently that phantoms can be enhanced when wearing a prosthesis, the phantom adapting to the artificial limb as a hand fits a glove [2], influenced by the multiple perceptions and representations that our brain has and creates from our physical body [3].

2.1.5. The multiple representations of the human body

The multiple human body representations are essential for the PL and PLP topic, bringing answers and explaining the relationship between physical and mental perceptions, as many case studies and researchers have done.

In 2005, John Schwoebel and H. Branch Coslett et al. studied body representations evidence and what triggers them. They correlate these pieces of evidence with the three human representations described in the literature being the body schema, the body structural description, and the body image. Also, their relationship with the human brain because of their activation parts and the tasks to assess the social representations [4].

The body schema establishes the relationship between the motor and sensory systems throughout the inputs, such as proprioceptive, visual, and touch, provided by the positions of body parts, which interact with the motor system started by actions. Body schema is used by the human to adjust the posture and guide the movements in conjunction with the sensory system part responsible for commanding and performing proper body postures. This prevents errors or wrong body positions to be performed and generated. Additionally, it establishes a meaningful relationship between the performance of a task, the ability of space, and accurate temporal movements. The requirements for the activation of this body representation are the performance of a task in an imagined and real environment. When performing a movement our brain has a representation of the trajectory of the movement while performing the action at the same time, using the imaginary resources and the body itself [4].

The second representation, the body structure is derived from the sensory and motor inputs such as the body schema. It is primarily provided from visual inputs, meaning that components are more related to space, specifically from an isolated location of a body part, the touch location of input, and matching the body parts related to the target. This representation is related to the structural and spatial components of the body itself, the muscles and bones [4].

The third representation, the body image represents the semantic and lexical of the human body and body parts. The association of words and images, the body parts and objects, and the function/behaviors are related to the human body parts. Furthermore, the body image is assessed when a behavior is the rightful movement of that body part, as well as, when a cloth or an object are suggesting a certain function/behavior, for example, the jeans are worn when putting each leg on each correct side [4].

John Schwoebel and H. Branch Coslett et al. concluded that there is a dissociation among the body schema, the body structural description, and the body image. Following these suggestions, the human body relies on functional body representations. Also, it has noticed a distinct association amongst processes, the brain regions and the representations. The brain regions followed by the recognitions and the knowledge of the world and the representations are related to locations and performance of actions. The body schema is more related to actions. On the other hand, body structure and body image relate to the movements and the lexical-semantic knowledge to the human body [4].

2.2. The sensory and motor disturbances

Between 2017 and 2018, Clementine Brun et al. studied the sensory perceptions of healthy and abnormal chronic pain populations. The main objective is to study the disturbance between both motor and sensory, and if they suffer any influence by the pain or any increase in the presence of pain [21], [22].

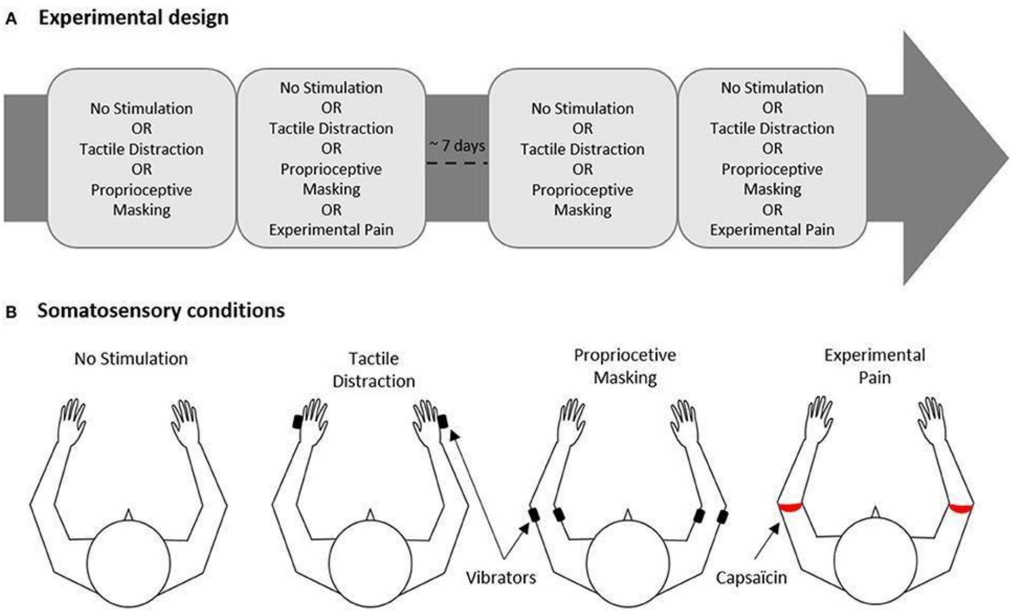


Figure 2-7 Experimental design and Somatosensory conditions by Clementine Brun [21], [22].

The experiment focused on the relationship among the somatosensory conditions. It was tested throughout the no stimulation, tactile distraction, proprioceptive masking and experimental pain, and the visual conditions (Figure 2-7). These visual conditions is set as congruent visual feedback (VF), no VF, flipped VF and mirror VF (Figure 2-8) [21], [22].

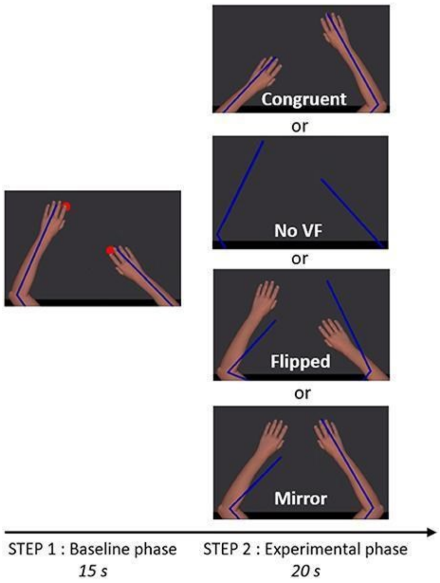


Figure 2-8 Visual feedback conditions by Clementine Brun [21], [22].

In the visual field, Clementine Brun et al. set several conditions as referred before in 2017. The congruent reproduces the movements as the patients perform them. The no VF does not provide visual feedback to the user, it shows a black screen. The flipped VF, as self-explanatory, flipped the arms, and the movements reflected. In the example, the right arm movements control the left virtual arm and vice-versa. On the mirror VF, both virtual arms reproduce the movements of a non-determinant arm (Figure 2-8) [21].

On the healthy subjects, they divided into two groups the passive and active feedback. In the passive patients are in a relaxed state and try not to follow or perform a movement. On the other hand, in the active condition, the patients must perform the movement that is requested. In conjunction, they have the congruent consist of visual feedback and movement matching each other. In the incongruent, the virtual feedback changes in the velocity, angle of the arm, and the amplitude of the movements [22].

The conclusion of the experiment is that touch feedback did not affect the sensory feedback, and it does not enhance the pain felt. The increased disturbance and pain did not depend on visual feedback, congruent, and incongruent. The experiments showed that conflicts induced in motor and sensory disturbances are not related to each other. These disturbances are minimal when the realism in shape, matching, and length are present. The absence of VF creates more significant disturbances than incongruent, mirrored, and flipped visual feedback conditions.

Finally, the acute pain does not interfere directly in the sensory disturbances, but in the way, these disturbances are perceived. However, they can impact the body representations. Overall, the experiments show that pain could not impact directly or have a relationship with the motor and sensory disturbances [21], [22].

In 2018, Clementine Brun et al. suggests that virtual environments can help suppress these disturbances, access the body perception, body representations, and sensorimotor integration, in the context of movements, and could support rehabilitation. It may help overcome the fear of movement, just scaling the visual feedback about the movement, reinforcing that pain in the sensory and motor disturbances are underpinned by two different processes [21], [22].

2.3. Therapies and approaches

In clinical characteristics, the PLP is commonly associated with damages on central, peripheral neurons and related to cortical reorganization. It is a part of the central sensory nervous system, in conjunction with sensory nerves and the pathways that change at the surface or inside the body. Usually, the pain felt is compared to the one felt before a limb amputation [5].

At the start, the phantom sensation was seen by some as a curiosity whereas others saw an important research topic [7], [8]. PLP was considered to be a psychiatric illness in which many mechanisms such as a peripheral, central neural, changes at brain level and psychogenetic approaches were involved [6].

2.3.1. Treatments and mechanisms

Many of the patients reported “suffering” from telescoping, which is commonly associated with PL and serves as proof that something is changing in the central nervous system. Evidence suggests that these three components are related to each other: the central nervous system, PLP, and telescoping.

Psychological factors still happen in all cases, but their importance and contribution were not as useful in relation to PLP as they were to PL. Many researchers and studies showed that most of the treatments are ineffective and have not taken into account mechanisms that produce pain [5], [6], [40]. Furthermore, these factors influence the development and the harshness of the pain [5].

Recently treatments have been developed from pharmacotherapy, surgical/invasive procedures, and adjuvant therapy helping to alleviate the pain and sensations (Figure 2-9) [5], [6].

Pharmacotherapy	Surgical/invasive procedures	Adjuvant therapy
Opioids	Stump revision	Transcutaneous nerve stimulation
Morphine	Nerve block	Mirror therapy
Tramadol	Neurectomy	Biofeedback
Tricyclic Antidepressants	Rhizotomy	Temperature biofeedback
Amitriptyline	Cordotomy	Electro myographic biofeedback
Nortriptyline	Lobectomy	Massage
Imipramine	Sympathectomy	Ultrasound
Desipramine	CNS stimulation	Physiotherapy
AntiConvulsants	Spinal cord stimulation	Sensory discrimination training
Carbamazepine	Deep brain/thalamus stimulation	Prosthesis training
Oxcarbazepine	Cortical stimulation	Cognitive behavioral pain management
Gabapentin		Electroconvulsive therapy
Pregabalin		
Sodium channel blockers		
Lidocaine		
Bupivacaine		
Mexiletine		
NMDA receptor antagonist		
Memantine		
Ketamine		

Figure 2-9 All the treatments and mechanism approaches[5], [6].

Recently, the adjuvant therapy showed to be effective in most cases for an extended period, which was considered to be implemented and studied being TENS, mirror therapy, and biofeedback [5], [6].

Treatments and mechanisms are still being studied based on pain, cortical reorganization, central neuroplasticity and body schema necessary for future developments, understandings and recommendations [6], [40]. In many of these results obtained through various approaches, such as pharmacological interventions and treatments, therapies showed better reduction and/or alleviation of PLP in patients but the mechanisms behind were yet to be fully understood [40].

2.3.2. The effectiveness of different techniques treating phantom limb - Comparing adjuvant therapies

As time goes by, the reports from PL and PLP have been studied and researched. In adjuvant therapies, treatments, and interventions such as mirror therapy, motor imagery, and/or virtual visual feedback provide benefits to these patients [7], [8]. The treatments quoted before helped patients to better manage their pain and sensations. In 2018, Herrador et al., three methods were described and explained, whereas we do a brief preview.

An example such as virtual visual feedback is a simple video of an intact limb that encourages the subject to synchronize the movements promoting the visualization and motor changes in the injury and also at the brain level [8].

Furthermore, in Ramachandran et al. experiments, synaesthesia in phantom limb induced with mirrors shows different reports by patients while developing and improving a technique which they called “Virtual Box” (Figure 2-10). Nowadays, it has improved to a therapy known as mirror therapy. It helps to break up the problem and gives answers to several factors, problems and sensations felt by patients with PL [1], [7].

On one hand, the authors present an adjuvant therapy where they describe their process and objectives of the mirror box. This therapy is used in more different types of phantom pain, as well as the sensation felt after deafferentation.

Mirror therapy (MT) is an attempt to answer several problems from brain studies, the sensation, motor abilities, inhibition, or block of movement and the influence of visual feedback using a simple cardboard box with a mirror in the middle. Here, patients place each arm at each side and this procedure allows them to see perpendicularly from a right arm side reflection (Figure 2-10) [7].

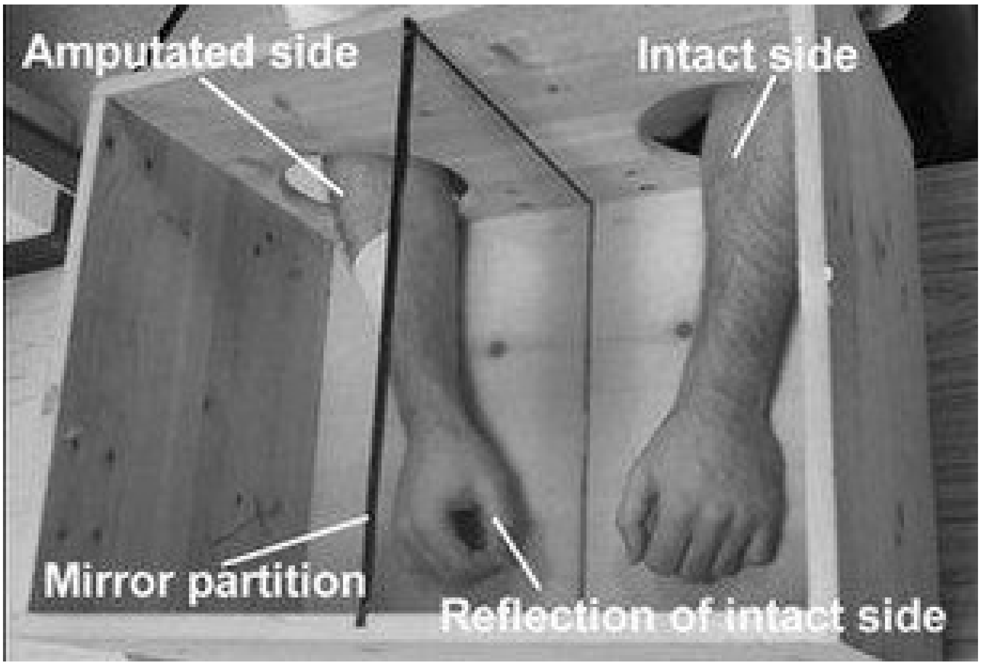


Figure 2-10 The virtual box used on Ramachandran et al. experiments [1], [7].

In [7], some amputees were asked to put both arms and move their arms on both sides at the same time symmetrically. In theory, the phantom limb arm will remain unmovable, but, from the patient point-of-view, it creates the illusion that both are moving simultaneously. Also, the touch sensation was implemented. The paper concludes by showing enhanced reorganization/remapping in the brain is provided by MEG [7].

This therapy brings an understanding of several factors that PL and PLP could generate. One of the factors is "the learned paralysis", the tendency of the phantom and the position it occupies if a limb has paralyzed due to a peripheral nerve lesion, this is common to happen before an amputation [7]. Another factor consists of amputees that can generate voluntary movements with their phantom after a non-traumatic surgical intervention that fades over time [7]. The latter relies on painful and/or extremely painful symptoms where patients have difficulties in moving and the attempt to create movement increases significantly the pain felt by them [7].

The reflection promotes an illusion, with a concept similar to virtual visual feedback, but induces a vivid experience at muscle level, reducing the familiar sensation felt by the patients, promoting the control of movements on a paralyzed limb and in some cases induces the reduction of pain/sensation. There are some concerns about the therapy stating the unbalance between sensory and motor systems or the increased focus on a painful limb [8].

Another technique used is based on the complex cognitive, sensory, and perceptual processes. Motor imagery therapy uses the central nervous system, making use of the memory, to invoke a mental representation of a movement without moving physically; in these cases focusing the amputated limb [8].

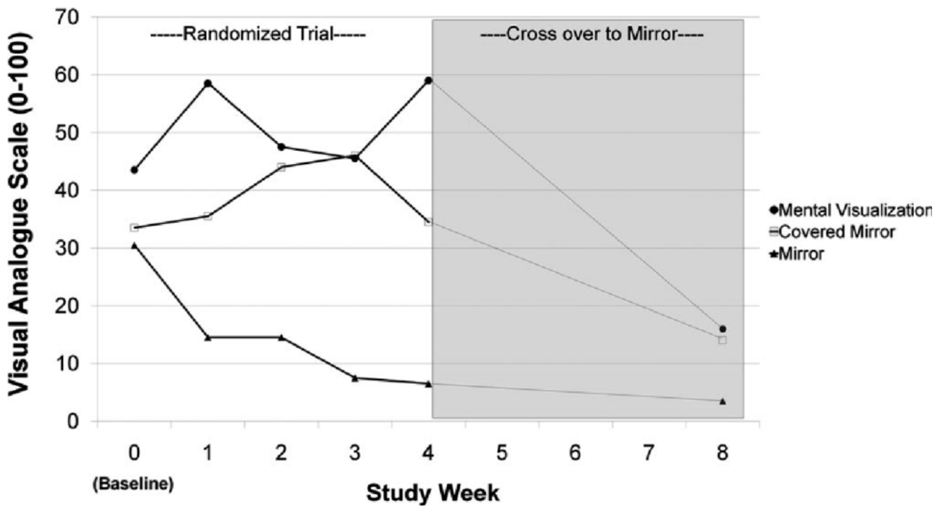


Figure 2-11 Experimental trial using mirror therapy [40].

Experiments were performed to verify the effectiveness of relieving PLP in unilateral lower limb amputees for four weeks. The results compare mental visualization and mirror therapy by verifying that MT has better results in reducing PLP over time (Figure 2-11) [40].

After all, an immersion into virtual reality (VR) therapies can provide a possible solution for the future. There are still some constraints in the therapies, on the lower limb level, especially in movements, when comparing daily life activities, where most of them are not symmetrical, with some exceptions such as walking or swimming. In [8], the paper analyses and studies the different points of these therapies, described previously, in a way to expose the strengths and weaknesses but also to focus on the benefits and constraints. Following this the mirror therapy is the one that best achieves this goal. The topic, in general and its importance, is related to promote a better life quality for the patients and to the entire humankind [8].

Overall, this research shows the use of mirror therapy, helping the pain reduction regardless the conditions, visual information for better feedback and the proceedings of movements, especially in patients with PLP and kinesiophobia, the ones that have the fear of movement. Motor imagery seems to be less motivating to patients and requires the use of higher cognitive resources. Mirror and mental visualization therapies are critical for visual feedback and PLP, but mirror therapy may help solve some incompatibilities with brain signal perception. Beyond MT and virtual they are more suitable for these patients [8], [40].

2.4. New technological approaches and its implications

PL and PLP have complex components [1], [2], [3], [5], [16] needing to be attentive to maximize the effectiveness and efficiency [10], [11], [12], [13], [17] as a way to develop a virtual reality adapted and based on the conventional mirror therapy [7], [8]. It is also vital to pay attention to the body representations [4], [21], [22]; the pain [3], [16] and the telescoping [2], [3] that promotes a more critical organization minimizing and relieving the pain in the process. These therapies may be useful in patients who suffer from PLP and those with phantom sensation, but their effectiveness and efficiency in virtual environments is still inconclusive. In future studies, these can decrease stress in clinical settings helping the phantom while performing treatments and depending on the quality of the illusion reducing the pain.

Nowadays, several technological improvements in the field could help to develop and improve these approaches as a way to promote the quality of life; improving the existing treatments [5], [6]; facilitating daily activities, helping patients to have control over these sensations/pain and in some specific cases promoting the usage of prosthesis [12]. Besides, these improvements contribute to a better understanding of the human brain, body representations, and cortex mechanisms, as well as being non-invasive, and not having any medical procedure to condition it. Since there is an area where muscles provide the most critical feedback, future approaches should consider capturing Electromyography (EMG) signals and combining with VR [9], [14], [15], [19].

2.4.1. New technological methods - the use of augmented reality and virtual reality

There is much evidences and studies that show several approaches and techniques [10], [11], [12], [13], [17]. Injuries on the primary somatosensory and motor cortical areas can be reduced through the stimulation, training, and workout sessions. These theories and studies were sensory discrimination, mental imagery, mirror therapy, and virtual reality that proposes to normalize the cortical representations of the body throughout corresponding visual predicted sensory feedback.

In 1999, Lotze et al., with the use of magnetic resonance imaging (fMRI), shows the myoelectric prosthesis on upper-limb amputee reducing the pain and promoting the cortical reorganization associated. The hemisphere achieves a maximum activation while and when performing a lip movement when a PLP was felt. The correlation made by the cortical organization influences and rules the pain and the prosthesis [12]. Overall, the muscular training and the visual feedback provided by the prosthesis have a beneficial effect on the reduction of pain over time and in cortical reorganization. On the other hand, the increase in pain decreases the motivation and the interest of making use of the prosthesis, this increased pain and has been seen by the patients resisting to the usage of prosthesis [12]. Similarly, Ülger et al. conducted a case study, following Lotze et al. experiment, noting that stimulation, muscle training using PL and visual feedback generate a beneficial effect on cortical reorganization and PLP. In 2009, Ülger et al. concluded that exercises, such as strengthening, stretching, dynamic, isometric exercises based on the level of amputation; making use of the phantom are practical, understandable and do not require medical equipment. In addition, Phantom exercises are safe and can be used to relieve PLP in both types of amputations, in the lower and upper limbs [41].

Similarly, the mirror box therapy is successful in reducing the pain for a group of patients, with several limitations as feedback in visualizing all illusion or just a part of it. The most limiting constraints are the control of this illusion, limited to movements and tasks that patients can be performed influencing the cortical reorganization. These limitations may be overcomed by the use of virtual reality, which consists of a computed image presented, likewise a limb in functionality and visual, enabling the control and the performance of several and/or series of movements with the virtual and real limb [10].

In 2018, Elisabetta Ambrose et al. show evidence of training with a low-cost bundle, an immersive virtual reality head-mounted display using IMUs to control and adjust. The IMUs technology are based on a gyroscope made for measuring the orientation and the angular velocity. This information is sent to the computer to move/control the avatar leg establishing a relationship between the real and virtual environments based on the coordinates and positioning. The main objective is finding evidence for real-time HMDs rendering of the intact and residual limb based on the theories, studies, and research previously done [10]. These studies demonstrated individuals in several training sessions having a reduction in pain felt by mimicking avatar movements. They also suggested haptic feedback and a realistic look of a limb which in the present study used a robotic avatar, thinking that enhance can be achieved by immersion provided to the player. These show a great potential to be implemented in treatments for PLP [10].

In 2016, Limakatso et al. described an intervention focusing the graded motor imagery (GMI) to treat the PLP. It mitigates the severity of PLP and uses strategies including laterality recognition, motor imagery and mirror visual feedback [11]. Laterality recognition, the ability to differentiate left from right correlates to the entire body schema and the planning of movements, which in amputees' perception is inaccurate and delayed, especially on those with PLP. These approaches are commonly known as implicit motor imagery by the fact that patients are unconscious of the processes of movements, mentally unconscious, matching the limb performance computed on the virtual environment. Another strategy follows the mirror therapy; instead of patients using their legs mirrored, a computer-generated limb presents and performs several movements while the patient imagines their leg moving at the same time. The main objective aims to promote cortical reorganization without pain feedback. Laterality recognition or motor imagery activates the premotor and supplementary areas [11]. In conjunction, visual mirror feedback changes the somatosensory and the motor cortices by providing visual inputs to execute the movements [11]. The implementation of these systems supporting and guiding non-invasive and cost-efficient treatments has been studied and suggested by many researchers [11].

Nowadays, several replications and adaptations inspired by the mirror box have been transposed to the virtual and augmented systems [17]. The majority of the deafferentation cases suffer from a "generic" pain, which is caused by the "deactivation" and disconnection in an area where the brain is responsible for the control, space, movement and sensations. This type of sensation and pain happens when a motor command is sent to the amputated body part. The body assumes an error due to proprioception and visual feedback [17]. The "deactivation" or disconnection can be suppressed by the use of the sense of agency and analgesic effect. The sense of agency comes from the sense of being active, intention and the initiation of the action. Also, the analgesic effect is present, meaning the distraction occurs when a person is immersive and concentrated [17].

In 2009, Cole et al. use a display and a motion capture device to study pain reduction, the sense of agency and the analgesic effects. For that, a virtual environment is displayed targeting two amputated body parts, the arm and leg. On the arm game, the user movements consist of grabbing, reaching and replacing an apple from and to a virtual table while using HMDs (Figure 2-12).

Figure 2-12 Upper limb game in Jonathan Cole et al. experiment [17].

The leg game involves playing a drum using normal and natural movements, such as rising, pedal, and pressing (Figure 2-13) [17].

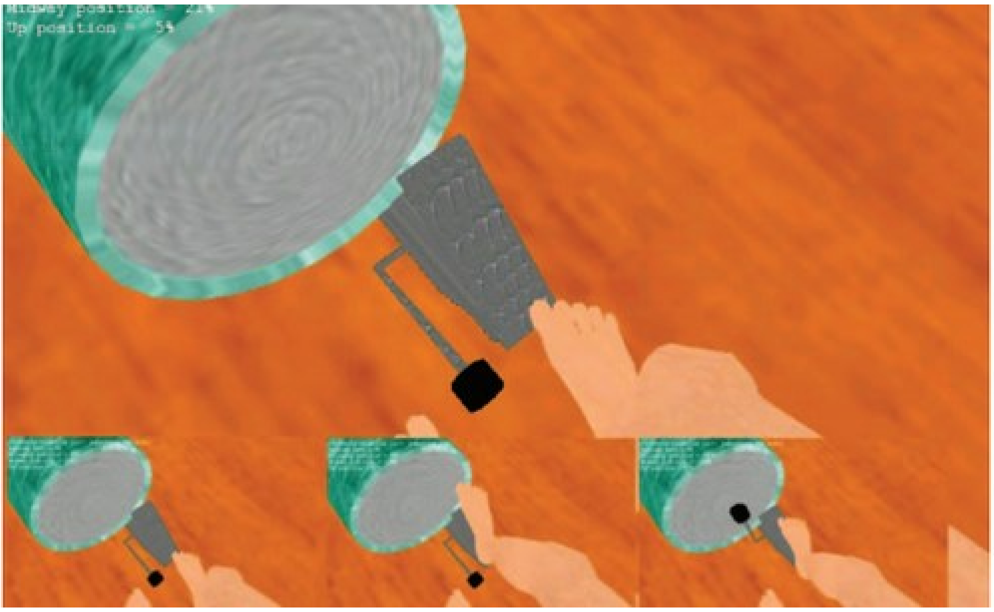


Figure 2-13 Lower limb game in the Jonathan Cole et al. experiment [17].

The sense of agency and the sensations do not happen when the immersion is weak, they happen when the motion is capturing the movements and making the avatar move. After several trials, a conclusion in the reduction of pain happened when the agency was re-established (Figure 2-14) [17].

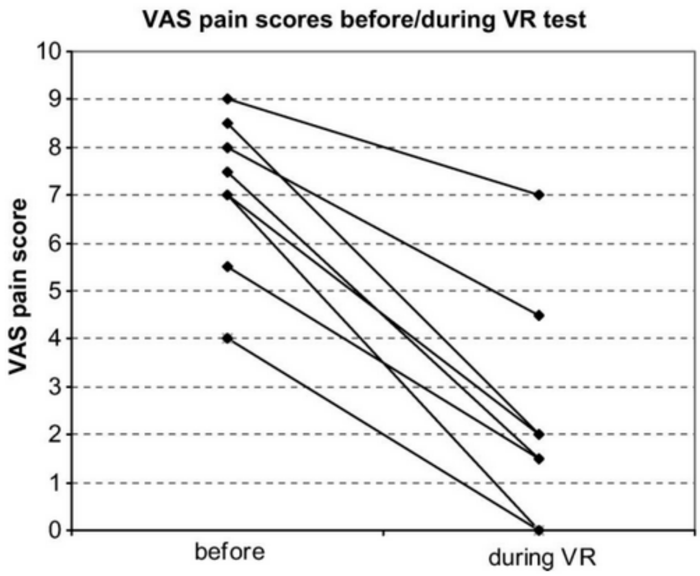


Figure 2-14 Graphical representations of VAS pain scores by Jonathan Cole et al. [17].

In summary, successful immersion factors are determined agency and analgesic effectiveness that could also be involved with motivation. Enhancing the sense of embodiment is possibly connected to the immersion created by the environment and the tasks proposed. When comparing projects and experiments with previous ones, they are similar in results. In mirror therapy, the movements are symmetrical, which is quite uncommon in daily activities and even more so in leg movements. Improved environment and tasks are more suitable to enhance the sense of immersion, promoting the agency and analgesic effects and improving the reduction of the pain [17], [42].

In common, in 2006, Desmond et al. developed an augmented mirror box using a graphical representation, a computer screen and a wireless data glove. The experiment focused upper limb amputations using reflected movements controlled by the data glove or may be remotely controlled by the computer. The authors found that incongruent movements that may induce phantom pain used in the standard mirror box. The augmented mirror box helps reduce the perception of discomfort and pain by suggesting different daily-like movements that could not be used in conventional mirror therapy, providing better visual feedback, awareness and controllability to patients [42], [43], [44].

Following Cole et al. and Desmond et al experiments, between 2007 and 2010, Murray et al. conducted a virtual reality experiment which makes use of a head-mounted display (HMD) instead of using a screen stated in the previous projects. The main goal is to build a virtual environment/scenario enhancing the feel of presence and embodiment. The scene helps the participants to establish a relationship with the computer-generated environment and promotes immersion. The project provides better coordination by incorporating the movements used in physical therapy and rehabilitation exercises, where it may not be implemented in the Cole et al. and Desmond et al. studies [42], [45].

Furthermore, in 2014, Ortiz-Catalan et al. performed a case study where they make use of augmented reality controlled by EMG pattern recognition. Patient was instructed to perform eight movements while being guided by a virtual limb. The movements were randomized and recorded [13]. After this, they performed sessions of approximately ten minutes each, using the movements of extension/reflexion and pronation/supination targeting the wrist and elbow, it uses game controllers where the wrists are used for turning left/right and the elbows controlling the speed of a car. The pain slightly decreases with the progression of the sessions [13].

In the daily life activities, patients reported some days of painful periods but since they started the sessions, these pain levels, were dramatically reduced, improving their performance. The sessions also contributed to control their PL and enable them to control the pain episodes. More specifically, the patient from the case study was able to stop or reduce these pain periods more effectively and pain during sleep time. Another observation made was related to the positioning of the PL, which initially was in a stressed and strong contracted position. After some sessions, the PL was in a relaxed position and in some cases, the pain felt was reduced mentioned by the patients [13]. The intervention has an association with mirror therapy due to the visual feedback and the correlation with the cortical reorganization [6], [12], which can prevent PLP, correct the haptic deafferentation and reduce the pain through brain plasticity. Feedback and motor execution were the base, as well as the patients' performance and intention to execute the motion itself [13].

Moreover, augmented reality approaches have been developed focusing the environments, the visual feedback and the reduction of PLP. The approaches have the same principles and criteria as the conventional mirror therapy. Overall, the main goal is to develop a system using the reality instead of transferring the participants to a pure virtual environment avoiding the lack of realism and enhancing the immersivity [46], [47], [48], [49], [51]. In 2014, Carrino et al. focused on developing a system with a low-cost equipment making use of Kinect, Vuzix Warp HMD and a NaturalPoint TrackIR. The experiment studies the limitation and constrains of the devices for home training. The system is limited for tracking the phantom and the devices were not suitable for this target audience. At the end, Carrino et al. could provide entertaining exercises and promoting an immersive environment compensation concerning some of the restrictions [46].

Similarly, in 2012, Pettifer et al. provide a virtual reality system. In the project, the equipment was identical to the Carrino et al. using the Kinect and the HMD. The project conveys the results observed in the virtual environments approaches - seen in Cole et al., Desmond et al. and Murray et al. experiments from 2006 to 2010. Pettifer uses a wireless communication device to guide the computer representation throughout an accelerometer and a gyroscope. The study has a significant impact in the realism and build up scene helping the immersion and the reduction of the pain. The experiment lacks of clinical studies showing the efficiency and effectiveness for the targeted audience [47].

Finally, in 2015, the ViLimbs and the Sano et al. aims to provide a multimodal and a multisensory stimulus for upper limb amputees. The studies convey all the equipment's reviewed in the previous approaches. The research approaches have similar impact in suppressing the need of a comfortable interaction with a wireless system desired in clinical areas [49], [51]. ViLimbs lacks clinical investigation for treating PLP [49]. On the other hand, Sano et al. had an average result for relieving the PLP, but it has a good stimulus in the brain areas showing the fMRI, optical topography and electroencephalograph [51].

In these VR and AR studies, patients prefer a more realistic limb over an imaginary creation as feedback. Overall, VR treatments boost and activate a sensory stimulation where neuromuscular rehabilitation is encouraged to help. On the contrary, the augmented reality games are more commonly designed to do a specific range of motions and exercises in a controlled environment. The study follows the natural and straightforward movements from the MT as a way to promote the neurological activity in the brain.

As described in these approaches, the visual feedback creates the illusion of the presence of a limb. Also, the intention and the working on the muscle levels can relieve the PLP. On the other hand, virtual reality interventions show a relief in the pain without working or focusing on the muscular level. Future studies should focus on developing systems to be used in clinics and at the patient's homes driven by computer games and using a low-cost VR equipment, such us Oculus Rift [50]. However, it is still needed further clinical investigation. To conclude, these systems brings several advantages. Portability, personalization and engagement benefits of digital games can increase the quality of patient's life, where other conventional treatments have proved to be unsuccessful [13].

2.5. Conclusions

In summary, the phantom limb sensation is a complex subject, which has an impact on our physical performance, our daily life and our daily activities. Cortical reorganization and the neuromatrix can have several influences, inputs, and outputs, depending on the body representations and the image that our brain has of itself in many forms, types, and shapes [2], [3], [5]. The body representations and the neural plasticity are the most critical functionalities to be taken into consideration, as well as the telescoping effect being a good sign that the reorganization and the "normalization" of the correspondence between the physical and the mental is doing well [1], [2], [3], [4], [5], [16].

Several therapies and treatments have been developed in a way of decreasing the pain felt while promoting the cortical reorganization, serving as an adjuvant approach to other clinical treatments. Besides, "virtual box" or the mirror therapy has been used whereas includes a visual feedback component facilitating the "activation" of the neural plasticity and the areas responsible for the amputated body part [5], [6], [7], [8]. Furthermore, new treatments and technological-based approaches were developed with the use of virtual reality and augmented reality, following the same principles and criteria of the "virtual box" [1], [7], [8]. However, more research is needed to understand the needs for the cortical reorganization to occur, its relation to the pain felt [40], the primary triggers, the different types of movements that are more suitable for the activation of the brain areas, the sense of embodiment, what can be enhanced the virtual reality to the real world and their disturbances [10], [11], [12], [13], [17], [21], [22], [41].

Future systems and new approaches should be taken into consideration concerning these findings presented in this chapter. Most systems lack of realism regarding the virtual body to the physical body, systems not easily used by the professionals in the rehabilitation field, need for increased motivation and immersion enhancing the users experience and finally further investigation is needed concerning the disturbances and reduction of the pain felt [42], [43], [44], [45]. So, this project should start by developing a system that can connect the physical and virtual body accurately providing visual feedback adding different types of feedback, such as audio and haptic, to enhance realistic factors and promoting a better association with the PL. In the immersion and motivation level, the system should be gamified to promote the agency and analgesic effects to the user making it to be focused on the effortless tasks, combining the nature of the movements with some sports or daily activities, for instance like walking or cycling [46], [47], [48], [49], [50], [51]. Most of the approaches reviewed lack of trials done in clinics and medical fields verifying its efficiency and effectiveness with the target audience [50].

3. Methods and materials

This chapter describes the thought process on which this thesis is based, the main findings obtained through state of the art research, the construction, and the project development. Following the research topics referred to in chapter I, mirror therapy has great importance, and its adaptation to a more digital counterpart is required and desired by many researchers to improve the treatments, workout, and training sessions, as a highly efficient and practical approach. At this moment, there are two ways of transforming this: one linked to virtual environments transports patient to a purely digital environment with relationships and associations with space, time, and real actions, the virtual reality. Another one in which, augmented reality transports elements from the digital world to the physical reality where interaction is made through visualizations concerning space, time, and actions performed in the real world.

The state of the art research, chapter II, has shown that virtual reality is effective to enhance motivation, intervention, and activation of both motor and sensory systems, and the brain areas responsible for them. Therefore, a purely virtual environment similar to the physical world is needed for creating a more realistic experience. The higher the realism, fidelity of the movements, the environment and the interactions, the better the human brain can assume and understand that the avatar is part of its body and the surrounding environment is real. The same is also true and happens with the prostheses worn by many of these patients.

However, such technology requires a way of understanding the movements performed by the patient, acquiring the data information, and transmitting to the virtual environment to be executed with precision, naturalness, and in real-time. This system should be able to be adapted to each patient's situation and later to the exercises and treatments proposed by the therapists and the medical field.

In the end, the system should be designed and constructed for clinical intervention and rehabilitation. The entire system should be low-cost, easy to assemble, and to handle. To minimize possible errors and problems, it requires a controlled environment without distractions to improve both the patient's focus/attention on gameplay, reducing the external interference with the system, and providing better immersion [37].

3.1. System Requirements

For this thesis the system should be coherent with the following requirements:

- The system should be non-invasive;
- The system should be simple to use and easy to set up;
- The system must be precise in targeting the muscle groups desired by the therapist or the medical doctor;
- The virtual reality display should maintain a minimum of thirty to sixty frames rates, to be realistic and give a sense of naturalness;
- All the calculations, signal acquisitions, transformations, and storage should be processed in the background, parallel and simultaneous with the VR display. Not influencing the VR display frame rates;
- The signal rate should be between 300 to 500 hertz for EMG signals based on the electrodes;
- The system should promote natural, non-symmetrical, slow movements exercises without the use of strength, effort, and adaptive behavior;
- The system should induce the agency effect, analgesic effect and be motivating and immersive;
- The system will not provide any sound or haptic feedback to minimize the sensory disturbances;
- The system should not cause pain, discomfort, change temperature, nausea, dizziness and the impression of missing limb;
- For avoiding disturbances and maintain the realism, the shape, the matching position, length, and the movements itself should be realistic and natural to the user.

3.2. The system base and the choice of tools

In this part, we will describe the design process. Also, we present the choices of the selected tools to implement the needs of the project, following the project goal and to be in accordance with the system requirements.

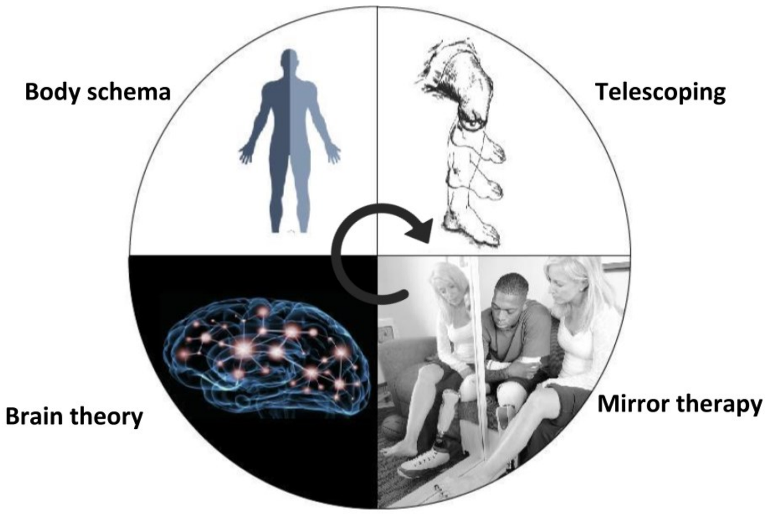


Figure 3-1 The splitting parts of the project focus and their association with the literature.

The project's goal is to develop an approach that can support and treat the PL and PLP. It should exploit the mechanisms for promoting the cortical reorganization to activate the amputated part of the body as well as activating the neurosignatures responsible for the same body part and decreasing the pain felt in the rehabilitation process. Figure 3-2 illustrates the approach and the most relevant parts of the project.

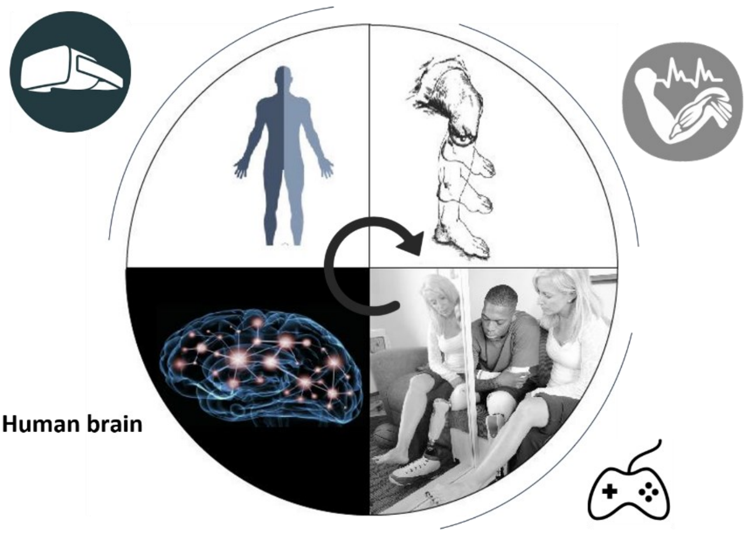


Figure 3-2 The association of the literature and the tools selection.

The first quadrant, in the bottom left, the human brain sets what should happen in the brain, recommendations, and constraints that will be needed to have special attention. The first consideration is about the central neural plasticity, described in chapter II, to understand the brain changes when deafferentation occurs independently of their cause. When the stimulation of the amputated area is stimulated, there is a natural mechanism for the reorganization of the brain and is triggered based on the sensory and motor stimulus.

In the second quadrant focused in the body schema, a facility of the brain to perceive its own body. This faculty is responsible for establishing the relation between the motor and sensory proprioceptive inputs to adjust posture and guiding the movements. This works, in conjunction with the sensorimotor system part responsible to command and perform accurate body positions mediating among the performance of a task, the ability of space and the performing temporal accurate movements. In the state of the art, the body schema have a direct relationship with the visual feedback and the performance of an action. With that in mind, a adequate to support the role of the body schema is a head-mounted display (HMD), which is responsible for the visualization of the virtual environment, transporting the patient to a world where it is seen in the first person. A system such as the oculus rift allows for appropriate visual feedback and establishes the correlation bounding the corresponding area that is occupied by the person in the real world, with an avatar, in the virtual world — allowing us to relate the patient's space and the occupied area with the avatar’s space.

In the third quadrant, telescoping effect is related to the physical, the vivid sensory, and the precise location in the size, shape, and space occupied by the phantom limb. A technological approach for relating the physical with digital in this case is through muscle activity since the phantom cannot be racked through sensors. Hence, our system should be targeting a specific body part and a specific muscle. In our case we will target the leg, which is composed of several primary and smaller muscles, the muscle group, and they are responsible for its extension and contraction of the leg. A biosignal device should be able to target a specific muscle EMG, the muscle where the majority of the strength is made for the desired movement. This needs to be a portable and wireless system so as not to affect the performance of the tasks. For this reason, the device chosen was the biosignal deice shown to meet the requirements described before.

In the final quadrant, mirror therapy is used on the visual feedback and the performance of an action, as it is well known to be a useful trigger for the brain act between sensory and motor senses. To correlate the two parts, the body schema with the telescoping, the system should have a connection between the two devices, and they should communicate with each other. With this purpose, the Unity 3D software was used and allowed us to create a gamified-based task. The program has a variety of features to create an immersive and motivational rehabilitation approach for patients. These bring challenges to the system for the type of movements, the immersion, the agency effect, the analgesic effect, and the disturbances that they can cause. The gameplay should use the same type of movements targeting both legs, and with movements based on natural daily activities. As a first approach, a simple football game was made with simple interactions and simple movements, focusing on the effects and trying to minimize the disturbances that may occur.

To conclude, our proposal is a system with these features built in, and easy to use by technical staff and professionals in the medical field.

3.3. System Architecture

The system architecture of this project is split into major and minor parts representing their functionality, behavior, and communications within the system, as well as the equipment used, the specifications, the software processing, and the visual feedback provided. Figure 3-3 shows the hardware, all the devices to be used, and the software in Unity, and their respective functionalities.

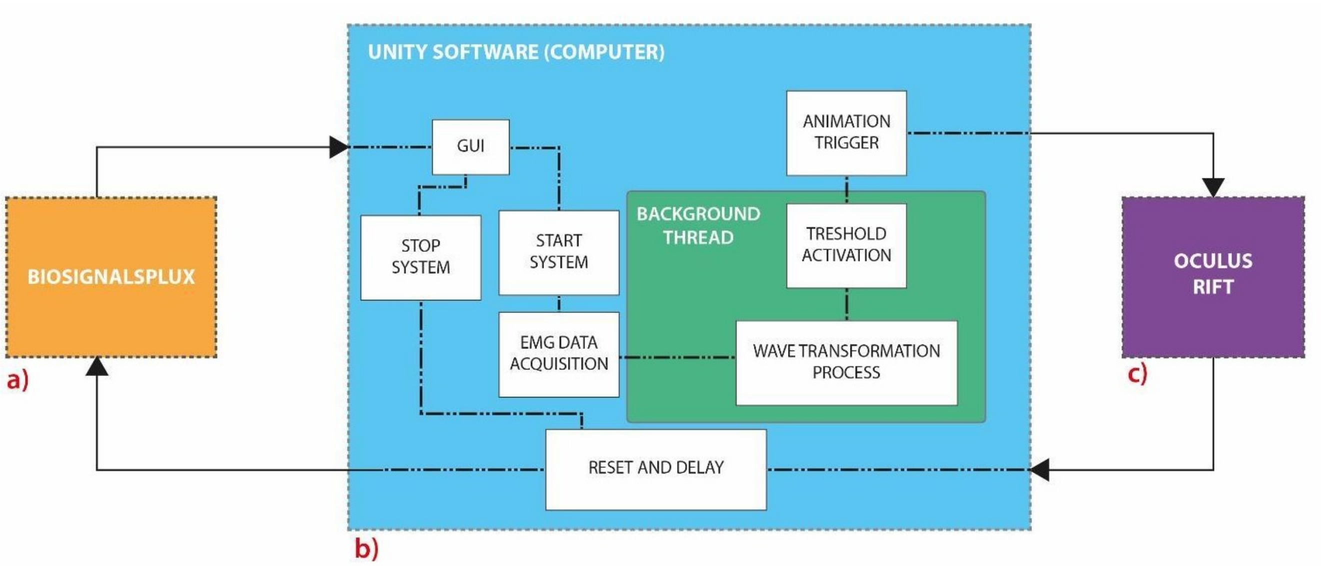


Figure 3-3 The project system architecture.

The biosignalsplux (Figure 3-3.a) has the primary function to acquire the data from the muscles and send it to the Unity software to reconstruct and transform the signal. The transformation is essential for reducing the noise and minimizing the errors acquired. Furthermore, the signal will be used for the animation and gameplay processes explained further ahead.

The Unity software (Figure 3-3.b) is used to connect and disconnect the biosignalsplux device as well as the Oculus, establishing the connection between the two devices. This software is responsible for the communication between devices, the wave transformation, and the gameplay itself.

The Oculus (Figure 3-3.c) receives the information provided by the software and it is where the visualization is presented to the user, based on the relationship between the physical and the virtual world. The sequences of animation and the scores are also presented to the user as visual feedback. The Oculus has the main functionality to provide visual feedback creating a bond between the player and the character.

3.4. The hardware

In this section, the hardware illustrates the physical components of the system and the hardware architecture, enhancing their communication and interrelationships. The hardware helps in the software development providing to the construction of the project all the details needed for the development and the integration for every component of the system.

The hardware scheme has three major parts of the biosignalsplux device, the computer machine, and the oculus rift. The device allows us to be verified and relate all the external system components, the biosignalsplux, and the oculus, within the system and between them. The communication is always through the primary system machine, the computer, to maintain accurate and precise to provide/receive from/to each device their data information.

3.4.1. The biosignalsplux

The use of this technology has many applications, especially in fields where the motion and locomotions must be measured on biometrics and biomedicine, as well as in clinical, medical research areas, rehabilitation, sports science, training, and human interactions. It is also used in the kinesiological fields where movement analysis and other types is related to actions [9], [14], [15]. It allows measurements of the muscle activity, before and after surgery, in treatments, training regimes, and for analysing and studying EMG data.

The biosignalsplux device is a commercial version device that is commonly used to capture and send the data information provided by the muscles (Figure 3-4). This device can capture several biosignals. It just needs to change the electrodes and the sampling rate, depending on the signal. It is composed of two main inputs, one for analogue signals and others for digital signals.

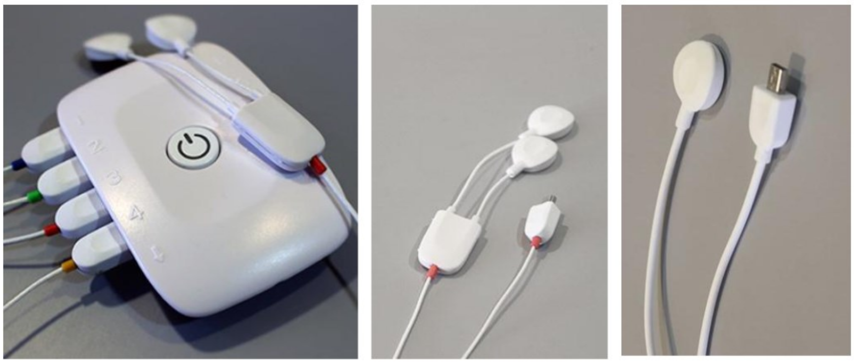


Figure 3-4 The biosignalsplux device, the electrodes, and the ground electrode [14].

Surface electrodes can be split into two types, the actives and the passives. Surface type brings advantages in comparison to needle electrodes. They are easy to use, painless, more reproducible, and perfect for movement application. The passive electrodes are most commonly used to measure and record small muscle areas and those areas of more difficult access [14].

The active electrodes comprise amplifiers, which in turn amplify the captured signal, and usually, they come in pairs. These types of electrodes generally require a "ground reference" for improving and maximizing the quality of the signal [14].

Electrodes have several specific positions to be placed. Usually, they are placed by measuring the length of the muscle tissues and placing in the mid-way, where the strength and the contractions of the muscle are stronger and hence a higher myoelectric signal, the EMG signal (Figure 3-5) [9].

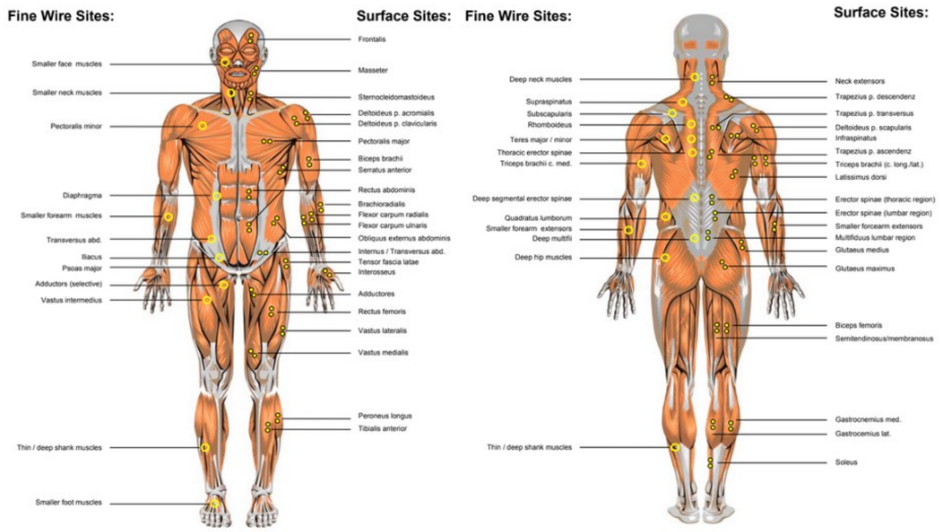


Figure 3-5 Position of the surface electrodes, The ABC of EMG by Konrad [9].

Ground is used in bone areas where there is no presence of muscle activity (Figure 3-6) [9].

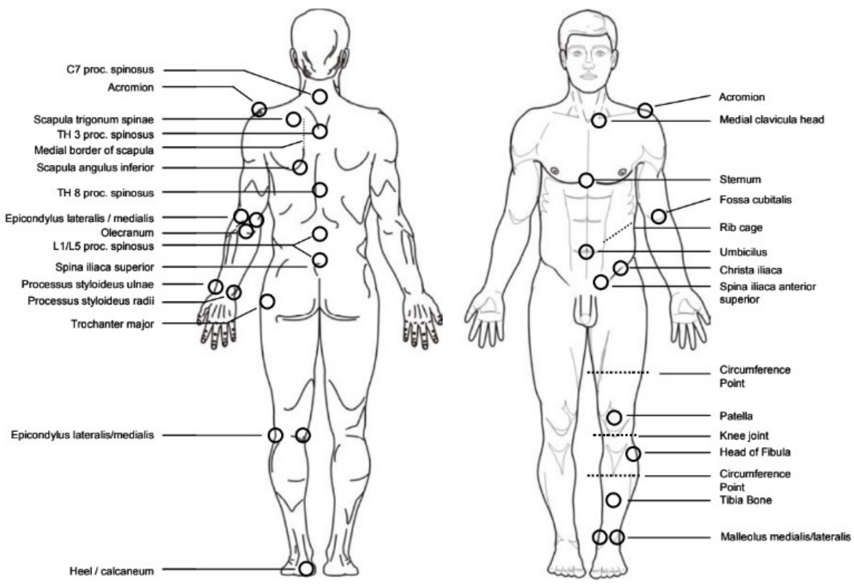


Figure 3-6 Position of the ground electrodes, The ABC of EMG by Konrad [9].

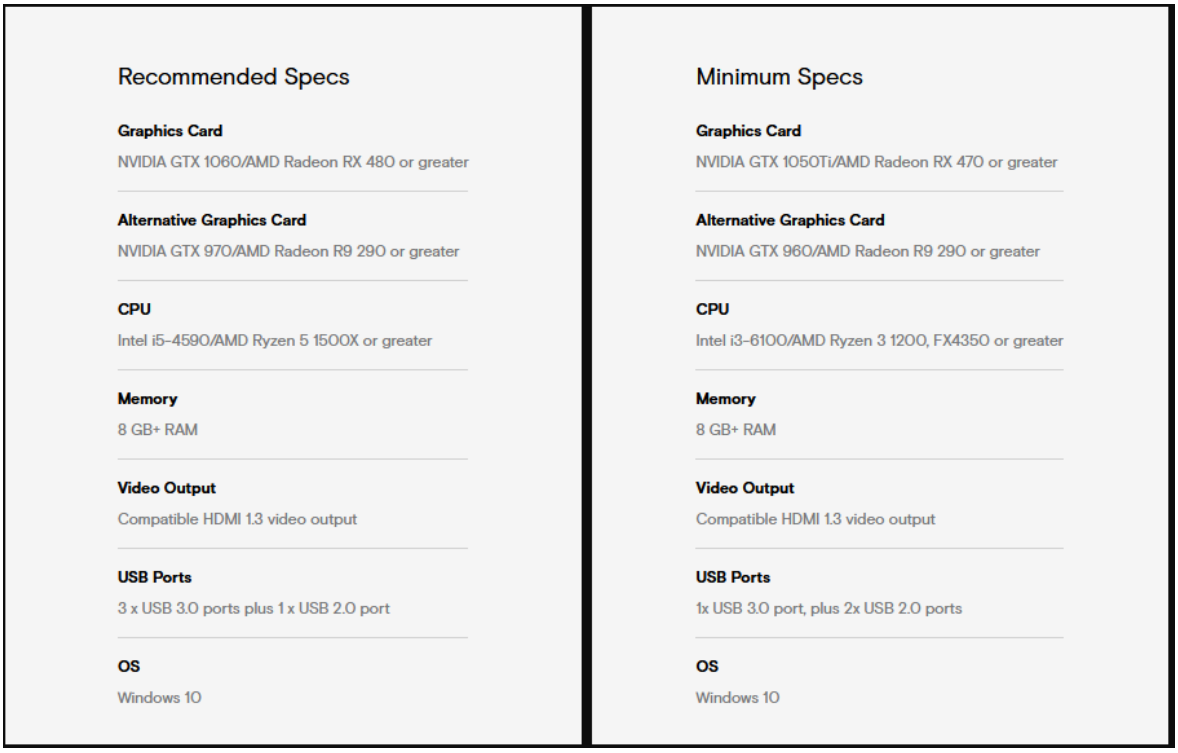
A possible problem when measuring EMG is crosstalk, it consists of basically capturing the electromagnetic signal from the adjuvant/adjacent areas that are being targeted or desired to be measured. The crosstalk can also happen in the recording, processing, and collecting phases [14]. For this reason, the setups always use ground electrode to reduce the noise captured. At the end, the collected data from the muscles is captured and sent through the biosignalsplux device, via Bluetooth, to the Unity software.

3.4.2. The Oculus rift

The oculus rift technology [24] was selected for its functionalities and flexibility of use to different environments (Figure 3-7). The virtual headset allows the user to experience in first-person view perspective, which is the virtual reality perspective recommended and suggested from the literature review. This allows more immersion and an integrated experience to promote and trigger the reorganization in the brain, allowing those connections responsible for the corresponding body part to be activated and reducing the reorganization pain.

Figure 3-7 Oculus Rift [24].

A set of infrared sensors are used to establish the relation between real coordinates and those of the virtual reality environment. The oculus software [29] can verify that all the systems are connected correctly. The patient sitting in a chair in the real world are henced mirrored in the virtual world by an avatar and in a wheelchair.



Recommended Specs

Graphics Card
NVIDIA GTX 1060/AMD Radeon RX 480 or greater

Alternative Graphics Card
NVIDIA GTX 970/AMD Radeon R9 290 or greater

CPU
Intel i5-4590/AMD Ryzen 5 1500X or greater

Memory
8 GB+ RAM

Video Output
Compatible HDMI 1.3 video output

USB Ports
3 x USB 3.0 ports plus 1 x USB 2.0 port

OS
Windows 10

Minimum Specs

Graphics Card
NVIDIA GTX 1050Ti/AMD Radeon RX 470 or greater

Alternative Graphics Card
NVIDIA GTX 960/AMD Radeon R9 290 or greater

CPU
Intel i3-6100/AMD Ryzen 3 1200, FX4350 or greater

Memory
8 GB+ RAM

Video Output
Compatible HDMI 1.3 video output

USB Ports
1x USB 3.0 port, plus 2x USB 2.0 ports

OS
Windows 10

Figure 3-8 Specifications for the use of Oculus Rift by Oculus company [24].

The oculus has specifications that need to be followed to achieve high performance and fulfil the system requirements. The oculus rift company provides a list of specifications to its users to be followed, enhancing the experience and immersion (Figure 3-8).

3.4.3. The computer

Computer Specs					
OS	***CPU***	***Memory***	***Graphics Card***	***USB Ports***	***Video Output***
Windows 10	AMD Ryzen 5 1400	8 GB RAM	AMD RX 580	Minimum of 3x USB 3.0	Minimum of 2x HDMI

Table 3-1 Computer specification used on the project.

The minimum specifications of the system are defined in (Table 3-1). The system should have enough memory for processing the data, a minimum of three USB 3.0 ports and an HDMI port for the oculus rift, and a Bluetooth dongle to connect the biosignalsplux to the system. The machine also needs to support Unity 3D software where all the code will be stored, processed, and accessed by the system in real-time while all the processes will be continually happening and accessed.

3.5. The software

The software makes use of the Unity 3D software [25], described further ahead, a library provided by biosignalsplux [23], a plugin collection by Steam VR [28], and a digital media collection such as game objects, animations, score, colliders, signal transformation, and the threshold explained later on this section.

The system starts acquiring the data from the muscles with the biosignalsplux device and sending it to the Unity software [25] via Bluetooth. In the Unity software, the EMG data suffers some transformations, reducing the noise and computing muscle activity. After all the signal transformations and the noise reduction, a threshold is used as an animation trigger. Once the animation trigger is active, a visual representation of the leg movement is produced in Unity and displayed using Oculus as feedback for the user interaction.

All these steps will be detailed ahead in the document, explaining the procedures, the code involved, and the resulting data.

3.5.1. The EMG - the electromyogram data process

An electromyogram, or EMG, is a voluntary or involuntary muscle contraction manifested by an electrical impulse, formed by a corporal variation in the muscle tissue. The EMG signal is composed of several anatomical and physiological manifestations of a muscle area, the peripheral nervous system, and the device itself [9], [14]. The first and primary source of the signal are the motor units activated when performing an action or a movement (Figure 3-9). The measurement is made by putting the electrodes on a body part, allowing measurement of the muscle contractions [9].

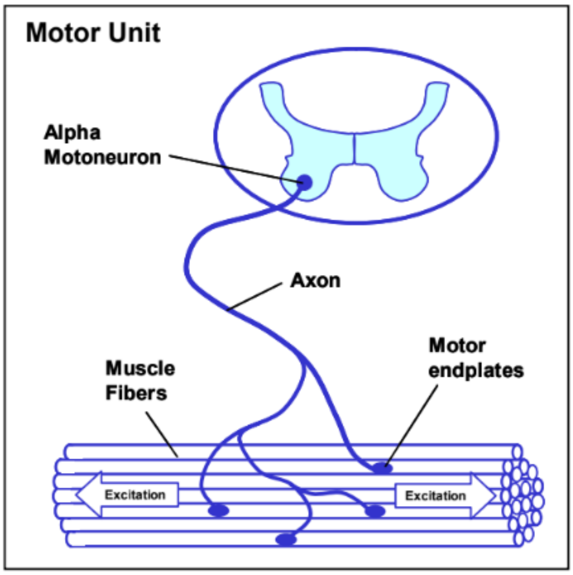


Figure 3-9 Motor unit from The ABC of EMG by Peter Konrad [9].

The motor neurons signal propagates until the part of the body in which the intention is presented, activating the muscle fibers, contracting, or extending a particular muscle area — resulting in multiple signals captured at the same time, different in amplitudes and duration. The EMG signal is a superposition of several signals captured being a bipolar signal, meaning that the signal has positive and negative amplitudes [14].

As an isometric signal, the EMG has a direct relationship with many variables. These are directly associated and related to the joint motions, the force, the velocity and the muscle fatigue [14].

Overall, the "raw" signal, without any filters, captured by the electrodes is composed of two different baselines (Figure 3-10). A relaxed muscle is perceived as a small signal, and a less noise-free signal when performing a contraction throughout an action/movement [9].

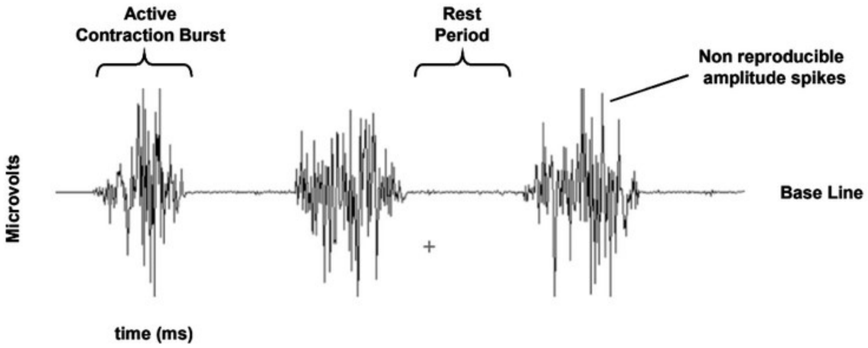


Figure 3-10 Raw signal, contractions, and states from The ABC of EMG by Peter Konrad [9].

Besides, the measurement of the signal has a relationship with the type of electrodes to be used. Surface electrodes are considered to use a range between 10 hertz to 500 hertz, while needle electrodes are recommended to use from 2 hertz to 1000 hertz [14]. EMG shows the most frequency power between the 20 hertz to a 150 hertz, being influenced by the tissue characteristics, external noises, and the types of electrodes [9]. Due to the existence of different types of skins, the thickness, physiological changes, temperature changes and the types of electrodes influencing the signal. The recording happens at multiple channels and at high speed. The waves are usually five times higher than the baseline (Voltz) [14].

Also, the external noises provided by the environment, the device in use, the devices surrounding, and the noise produced can influence the signal captured. In these cases it is recommended to use a room/laboratory to minimize and control the conditions and constraints [9], [14].

There are still other constraints when working with the signal, such as the Nyquist theorem, or commonly known as the sampling theorem. The theorem is the sampling conditions to be made for reconstructing the EMG signal. The recommendations are to use double the value of the frequency related to the one captured. If the frequency of 250 hertz is recorded, the sample should be double, meaning the sample should be 500 hertz [14]. If that is not performed, there can be problems replicating the signal, called aliasing problems. It can occur in lower and higher frequency levels when the signal is not filtered. A solution for removing this is doing lower-pass and high-pass filters. The pass filters remove any unexpected vibration and help to remove the aliasing error [14].

The quality of the data acquisition and the measurement are related to the skin preparation, the position of the electrodes, which stables the electrodes and reduces the amount of skin between the electrodes and the muscle tissue [9].

In order to obtain a clear signal, there are several steps, and some transformations the raw signal should pass through: the lower-pass and high-pass filters, a half-wave rectification, a linear envelope, and a root mean square [14].

The high-pass removes the noises in the lower frequencies, while the low-pass filter removes the unwanted high-frequency noises [14].

The half-rectification transforms all the negative points to positive. The linear envelop gathers and passes a low filter in the rectified wave [14].

The root mean square, square the signal in a specific window within a determined time window, then take the square root [14].

Other considerations are the type of movement or exercise to be performed. During static performance and slow-motion movements, the amplitudes do not suffer lowering the chances of errors [9].

In 2015, Ho-sun Shin et al. developed a project built from a system based on electromyography, a gyroscope, and an accelerometer to understand some gestures and measure the forearm muscle activity — using this technology as an element to capture, record and evaluate the activity in the muscle to connect it with the biomechanics of the human movements. The user performs simple movements to control a virtual robotic arm; the movements are the wave, spread the fingers, rise, grab, release, and double-tap all controlled through the EMG sensor [18]. This experiment concluded that the use of the technology is in demand for rehabilitation and medical fields [18].

3.5.2. Unity software

The Unity 3D software [25] is an essential tool for the project, not only establishing the relations and communication within the devices allowing the development of games and new tools. API to interface the biosignalsplux device is provided by the biosignalsplux team.

The API [23] consists of a collection of code, creating a connection, and receiving the data information from the biosignalsplux device, the EMG data explained before. A GUI [23] is used to control, connect or disconnect, and change the sample rate representing the amount of data that will be received, transformed, storage and calculated in the processing state.

The perception of reality, based on the senses, is made through a virtual stimulation of the sensory and motor senses. Games are a way to trigger these senses. The user has their attention on the gameplay while maintaining immersion through an extreme focus. The agency and analgesic effects, described in the literature, will be the significant components in maintaining the user's concentration and focus while feeling the intention and movements, visualized and initiated by the player [17].

Furthermore, a game targeting limb movement developed and inspired by the natural movements and actions performed in our daily activities or the ones used in sports. The game tried to maintain the naturalness, the simplicity of movements, and takes into consideration the intention to act, the analgesic, and agency effects [17].

In order to enhance and give focus to the sensory senses, an avatar was created to help the motor coordination, the sense of movement, and provide visual feedback to the player. For that, a ball and a score panel were also made to control the movement actions and calculate the number of movements. The frequency of a low ball is also calculated. This results in prevention of faster movements to be performed and provides a relaxation time between movements.

The oculus rift provides the visual feedback, and to achieve the purpose of this thesis, a first-person view was built simulating a natural and sight view of a healthy body. For this, the Steam VR plugins were installed and setup for connecting the HMD with the system [28].

3.5.3. Graphical user interface

The graphical user interface establishes the connection between the biosignalsplux device and the system software, and it was made and developed by the biosignalsplux. The "PLUX Unity API" was used as a base for accelerating the process, and the package comes with the code for connectivity and acceptance of multiple channels connections [23].

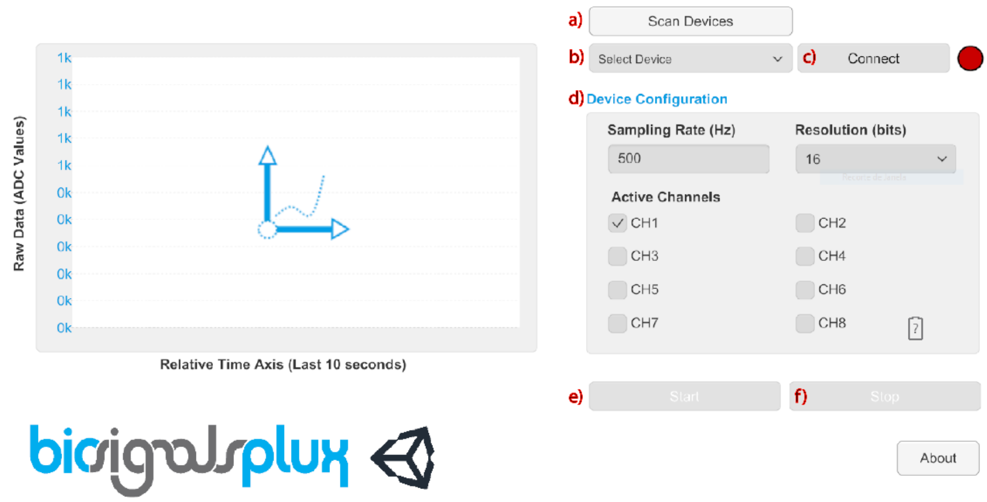


Figure 3-11 The graphical user interface by the Biosignalsplux API [23].

The interface has several buttons, and it comes with a graphical visualization of the raw signal captured by the device. The GUI facilitates the programming processes and the integration of the device and the unity program. The interface did not suffer any changes since all the components were used in the experience, with the exception of the transformation of the signal received, the storage of it, and the trigger of the animation. The buttons are intuitive and straightforward to use in Unity 3D [25]. It provides a real-time acquisition and graphical visualization. For enhancing the performance, we deactivate the graphical visualization, but it can be switched in the code.

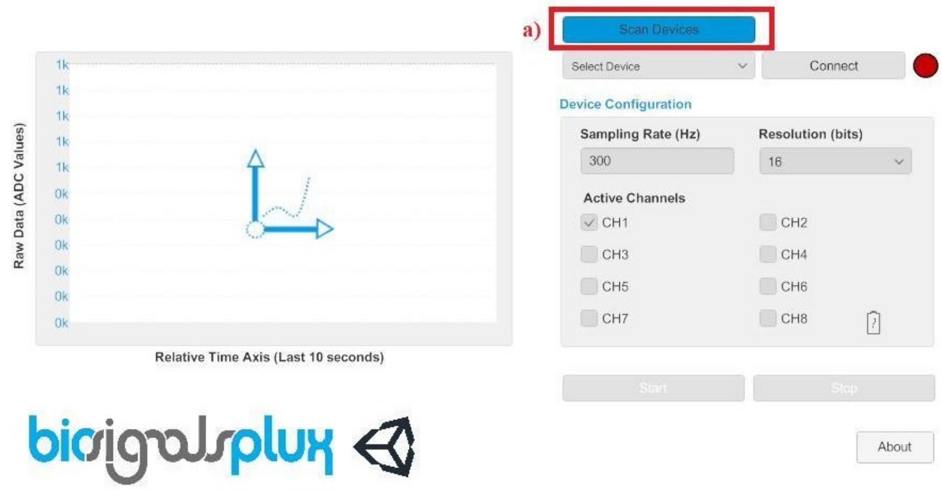


Figure 3-12 Scan button [23].

After the device is turned on, there is a "Scan Devices" button (Figure 3-12) with the function of searching the biosignalsplux device throughout a Bluetooth connection. This button establishes the connection and finds the device showing the mac-address on the blanc field above the button, the "Select Device" field (Figure 3-11.b). As visual feedback for finding and pairing the device, the GUI automatically selects the mac-address or the unique device identifier.

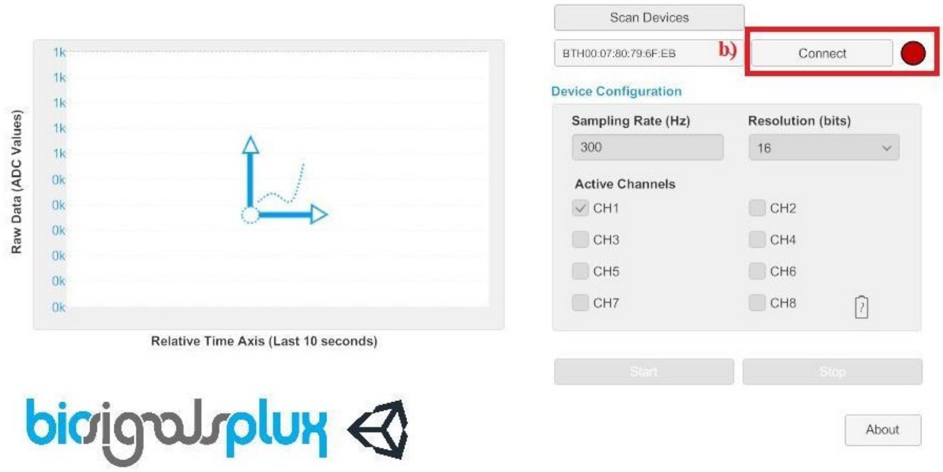


Figure 3-13 Connect button [23].

The "Connection" button (Figure 3-13) establishes the connection of the device with the Unity software. It creates a link where the signal captured is sent to the unity software.

On the "Device Configuration" (Figure 3-11.d), there is a sampling rate allowing it to be changed. For this project, the sampling rate range is between 300 and 500 hertz, maintaining an amount of data accurate and coherent with all the processes and procedures to be made by the system.

```
// Function invoked during the onClick event of "StartButton".
public void StartButtonFunction()
{
    // Specification of the callback function (defined on this/the user Unity script) which will receive the acquired data
    // samples as inputs.
    PluxDevManager.SetCallbackHandler(CallbackHandler);

    // Get Device Configuration input values.
    SamplingRate = Int32.Parse(SamplingRateInput.text);
    int resolution = Int32.Parse(ResolutionDropDownOptions[ResolutionDropdown.value]);

    // Update graphical window size variable (the plotting zone should contain 10 seconds of data).
    GraphWindSize = SamplingRate * 10;

    // Number of Active Channels.
    int nbrChannels = 0;
    Toggle[] toggleArray = new Toggle[] { CH1Toggle, CH2Toggle, CH3Toggle, CH4Toggle, CH5Toggle, CH6Toggle, CH7Toggle, CH8Toggle };
    MultiThreadList.Add(new List<int>(Enumerable.Repeat(0, GraphWindSize).ToList()));
    for (int i = 0; i < toggleArray.Length; i++)...

    // Check if at least one channel is active.
    if (ActiveChannels.Count != 0)...
    else...

    tread = true;

    th.Start();
}
```

Figure 3-14 Start button code for starting acquisition and the background thread.

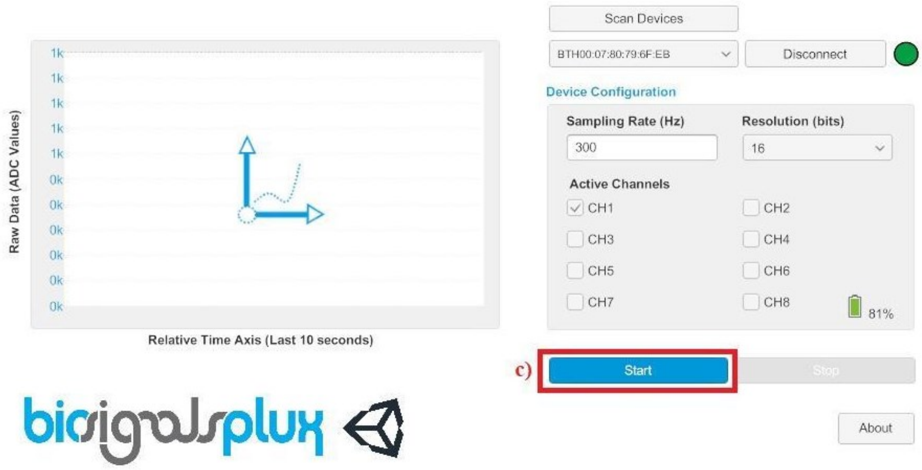


Figure 3-15 Start button to begin acquisition [23].

To begin the acquisition, the "Start" button (Figure 3-15) starts gathering the signal information with the paired device, and with some modification made in the code, it also starts a background thread (Figure 3-14). This thread consists of reconstructing the wave received, calculating, transforming, and storing it.

```
// Function invoked during the onClick event of "StopButton".
public void StopButtonFunction()
{
    // Invoke stop function from PluxDeviceManager.
    PluxDevManager.StopAcquisitionUnity();

    // Disable StopButton.
    StopButton.interactable = false;

    // Enable About Button.
    AboutButton.interactable = true;

    // Enable ConnectButton.
    ConnectButton.interactable = true;

    // Stop Message.
    Debug.Log("Acquisition was Stopped!");
    outStream1.Close();
    outStream2.Close();

    tread = false;
}
```

Figure 3-16 Stop button code for stopping acquisition and the background thread.

Firstly swap the cameras by pressing the alpha 1 to the GUI and click on the stop button (Figure 3-11.f).

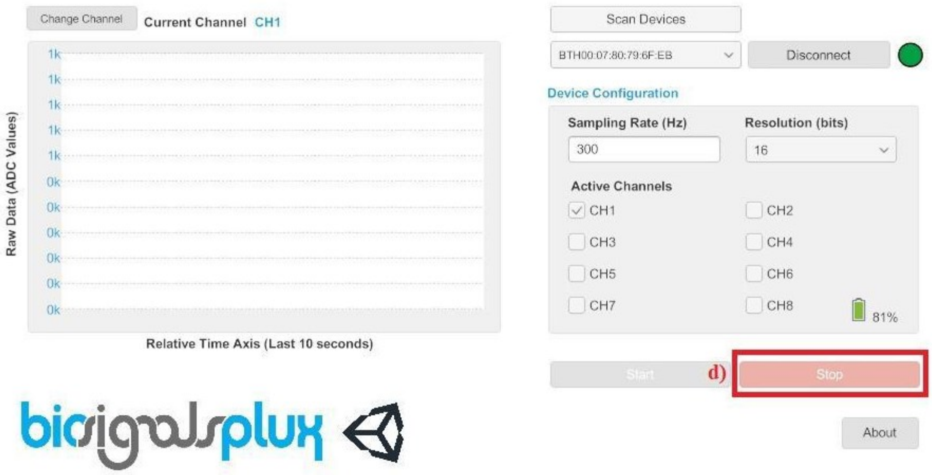


Figure 3-17 Stop button [23].

It needs to click on stop (Figure 3-17), disconnect (Figure 3-18) and to turn off the play mode to prevent malfunction in the system and reset the connection between the biosignalsplux and the Unity software.

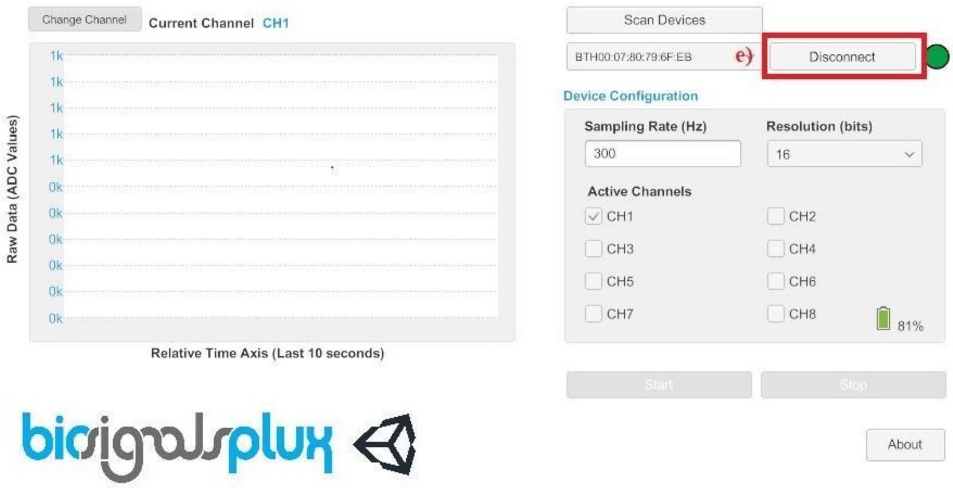


Figure 3-18 Disconnect button [23].

Finally, the software can turn off. It disables the option to gather the information, as well as stopping the background thread (Figure 3-16).

3.5.4. EMG Wave transformation

The EMG wave transformation happens in the background thread while using the acquisition and the device. Initially, it was performed with the application refresh rate, but due to optimization, to enhance the performance and to reduce the time to process it, it was configured to run in the background parallel to the Unity rendering processes.

```
void calculateMV( IntPtr data, int dataLength)
{

    lock (MultiThreadString_Milli_Volts) {

        MultiThreadString_Milli_Volts += "#"; //
        int[] dataArray = new int[dataLength];


        Marshal.Copy(data, dataArray, 0, dataLength);

        float [] mv_samples= new float[dataLength]; // milli volt sample array
        for (int i = 0; i < dataArray.Length; i++) {

            float emg_in_volt = (float)dataArray [i] / 65536;

            emg_in_volt = (emg_in_volt  - 0.5f) * 3; /// 500; // 2^16 = 65536
            mv_samples [i] = emg_in_volt;
            //emg_in_volt = emg_in_volt * 500; // converting volts into mv
            //Debug.Log("emg in volt ******"+emg_in_volt+" data in array"+ dataArray[i]);
            //MultiThreadString_Milli_Volts += emg_in_volt.ToString () + "&";

            //MultiThreadString_Milli_Volts += dataArray[i].ToString() + "&";
        }
```

Figure 3-19 Calculate code transforming and acquiring the data information provided by the biosignalsplux device [23].

The code starts with the acquisition of the data from the biosignals devices and stores them in an array (Figure 3-19).

After that, a new data array composed by the transformed raw data is created. The wave transformation is crucial for using this signal in the Unity base modules (Figure 3-19).

```
// *************************** wave rectification ******************************

//float [] dataa = { -0.0501708984375f, -0.0578155517578125f, -0.0487060546875f

//******* Backup of waves transformation *******

Signal target = Signal.FromArray(mv_samples, sampleRate: 1000);

WaveRectifier wr = new WaveRectifier(false);
Signal rectified_signal = wr.Apply(target);
double[] rectified_dataArray = new double[dataLength];
rectified_signal.CopyTo(rectified_dataArray);//rectified_signal.ToDouble ();

for (int i = 0; i < rectified_dataArray.Length; i++)
{
    //Debug.Log("rectified****" + rectified_dataArray[i]);
    outStream1.WriteLine(timeCounter + " " + dataArray[i]);
    outStream2.WriteLine(timeCounter + " " + rectified_dataArray[i]);

    if (rectified_dataArray[i] >= threshold_value) // threshhold values { 0.00
    {
        isContract = true;
    }
}
```

Figure 3-20 Rectification and flipping code for the points acquired in the previous array and triggering animations.

The data array suffers a rectification, flipping all the negative points from the signal into positive. This makes signal stable avoiding the lower noises and focusing on the more stable higher amplitudes (Figure 3-20).

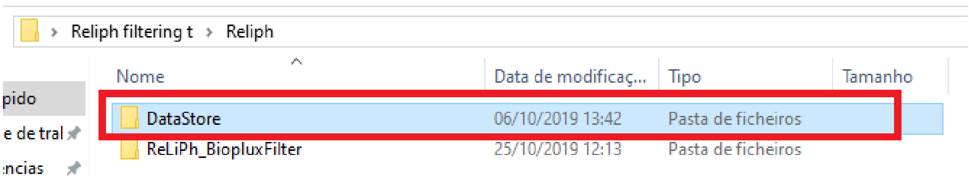


Figure 3-21 Location of the DataStore folder.

All the EMG data information will be stored outside the main Unity project folder to be visible for easy access with the name of "DataStore" (Figure 3-21). Data acquired is stored in a text file format to be analysed in the future and verify if all the process is accurate, checking all stages if the desired functionally and behavior occurs.

The signal is stored in raw format and after the wave rectification. We can use these waves for metrics and verifying, in a non-real-time process, the most accurate threshold value for each patient. The waves are stored with the name

"Raw_Year_Month_Day_Hour_Minutes_Seconds", providing an accurate session date in the day.

The wave starts in a raw type (Figure 3-22), in millivolts, and then it is rectified (Figure 3-23) to reduce the noises, reviewed in the EMG section.

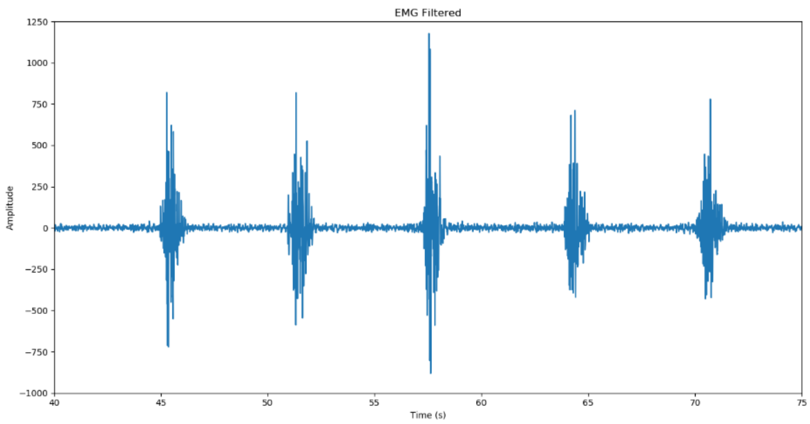


Figure 3-22 Graphical visualization of the raw signal in the offline process using python.

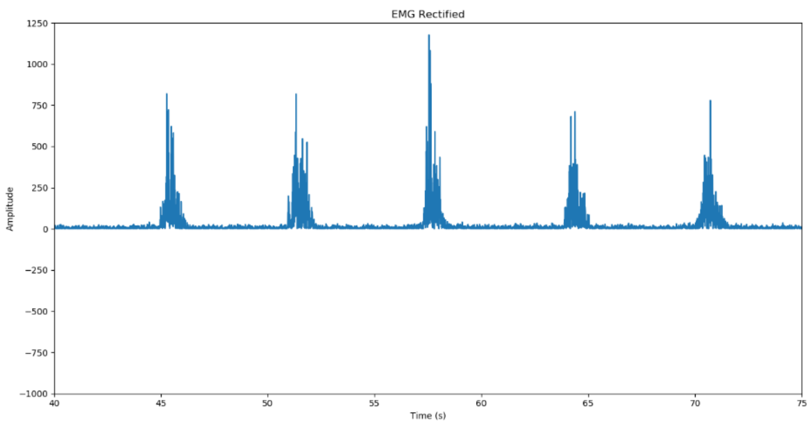


Figure 3-23 Graphical visualization of the rectified signal in the offline process using python.

3.5.5. The threshold

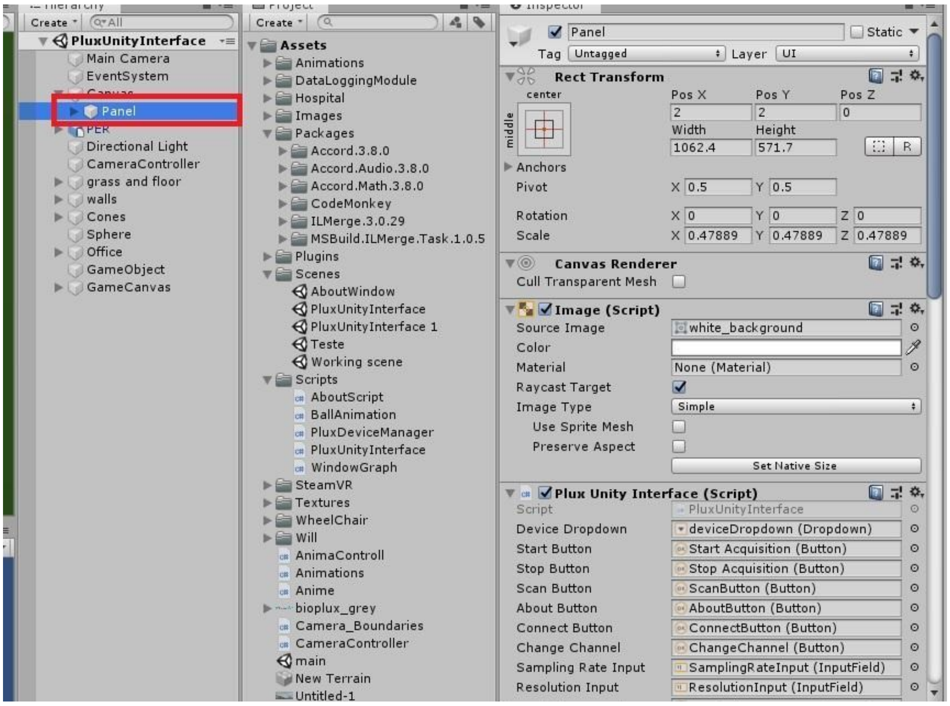


Figure 3-24 Threshold value can change in the script inside the panel.

The threshold is a reference settled manually based on the mean value of the data acquired (Figure 3-24). The threshold is used to trigger the animation making it coherent and accurate with the movement performed by the player, as well as to match the real movements with those performed by the avatar.

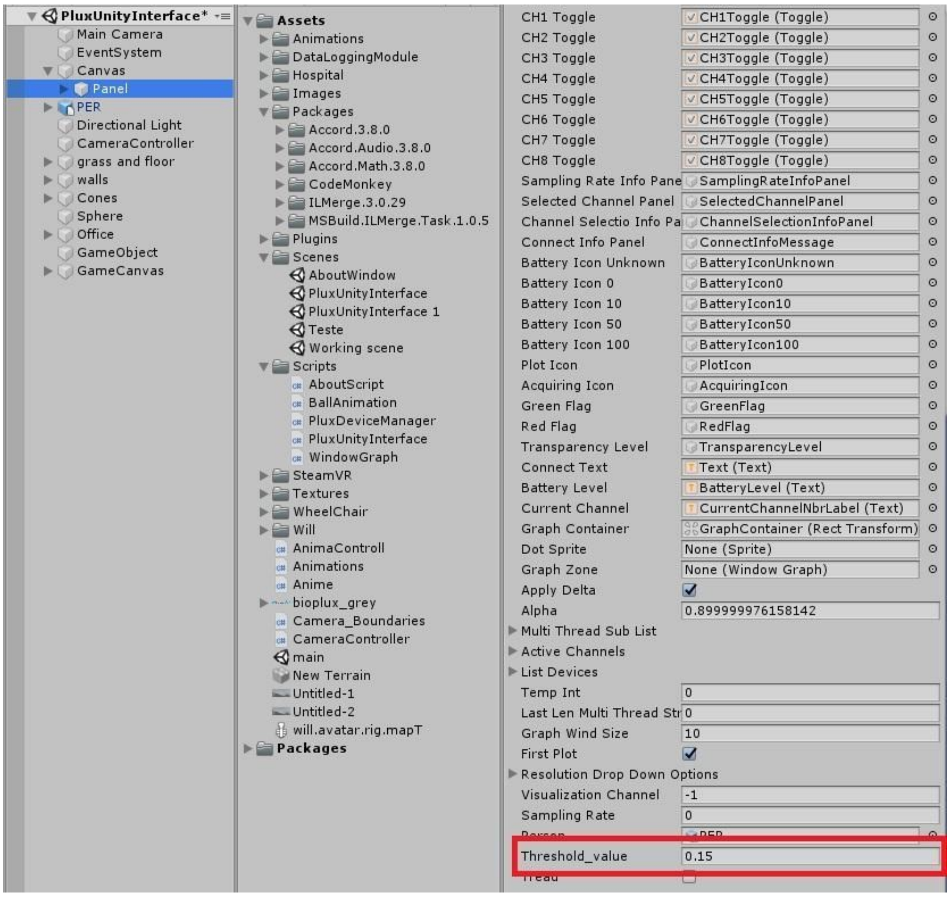


Figure 3-25 Threshold value change area.

The threshold values should be adjusted to the person before the session, on the panel at "Threshold_value" (Figure 3-25). Testing this value is recommended before the training or workout sessions with the purpose of having more accurate and natural movements in the session. These values could influence the motivation and the immersion of the users. After some experimentation, the conclusion was that the range of threshold value was between a minimum of 0.1 to a maximum of 0.2. During the tests, the most common values had a minimum of 0.13 and for stronger people, a value of 0.18.

3.5.6. Game objects and animations

This part shows the game objects used and developed for the environment and all the animation concerns. The aim was to develop a more natural environment for the users based on the type of gameplay from the phantom patient's perspective. All the objects, materials, and animations modelled in Maya were transferred to Unity 3D later.

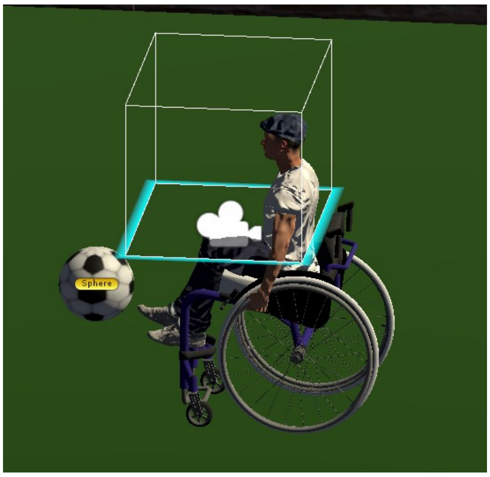


Figure 3-26 The most crucial game objects to the interactivity and immersion [26], [27].

We used a wheelchair and avatar from an available resource from the internet to accelerate the project process, testing, and verifying the accuracy of these game objects. The virtual avatar came with some issues in the skeleton and the skin weights, which were corrected in Maya before doing the animation (Figure 3-26).

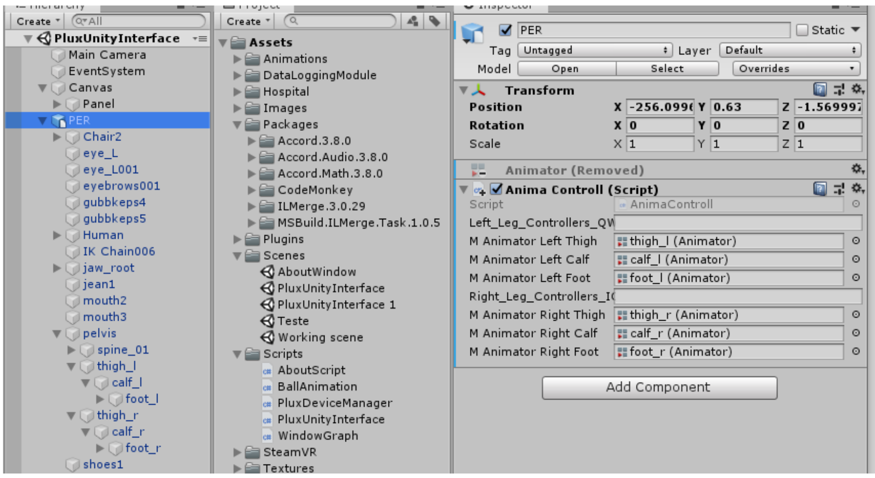


Figure 3-27 Avatars panel and animations associated with the lower leg parts, respectively.

The rest of the environment, including the game objects, were built in the Unity 3D software as well as the animation of the leg parts (Figure 3-27), and the ball animation. Before developing all the movement animations, we studied natural and realistic movements which were developed by observing the human body, the kick movements, and ball movements in sports. The search for the animation movements was also based on the exercises practiced in the treatments for PLP. Although, the naturalness of the movements was also based on sports and daily life activities like running, cycling, football and walking.

After all, the chosen animation for the leg included rising, shooting, and pedal movements. For this thesis, the selected movement to be tested is the shooting ball animation (Figure 3-27).

3.5.7. Oculus rift software and the visual feedback

Finally, the oculus needs a collection of plugins to connect with the Unity software and allow their configuration in the development phase [24], [28], [29].

For that, the Steam VR [28] - installation in the unity project helps us to associate the virtual world with the physical one. The two environments rely on their functionality, behavior, association, and configuration through on the Steam VR plugins [28].

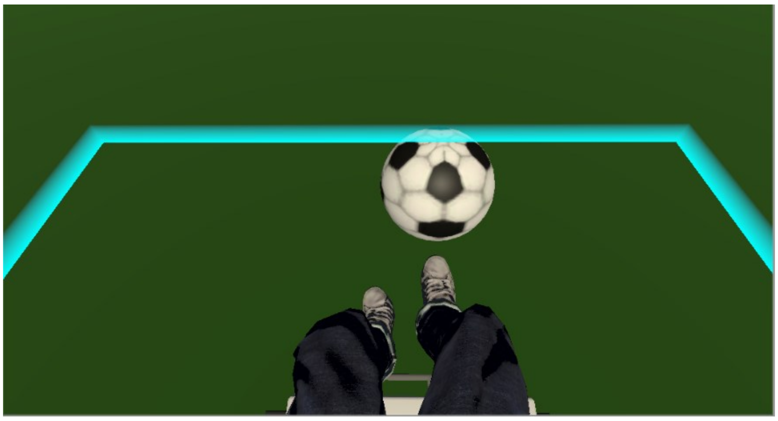


Figure 3-28 The guardian area and the first-person camera point of view.

Firstly, the physical and virtual area is associated and connected. This area will be called the "guardian area" in the oculus program (Figure 3-28).

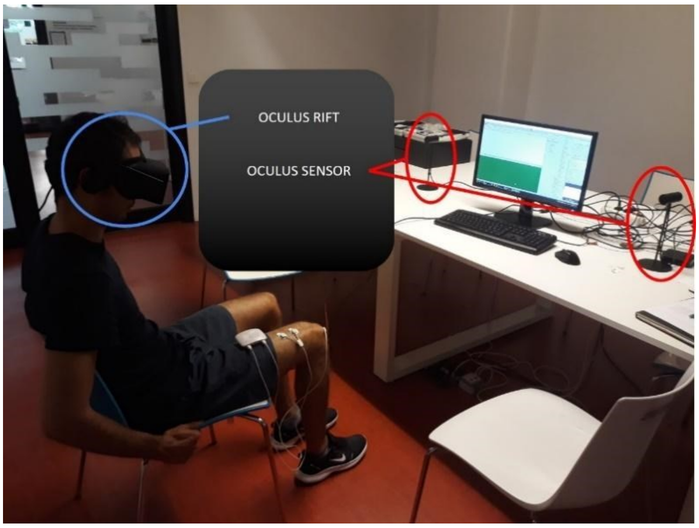


Figure 3-29 Set up of the oculus rift device in the real world [24].

The device is settled with the two infrared sensors in front of the user to set the boundaries for the guardian and activating the head-mounted display when it is within this area (Figure 3-29).

The Oculus software [29] allows configuration of the height of the camera relating to the player's height. Also, it allows us to set the guardian according to the physical area and the program creates a corresponding scale to each other.

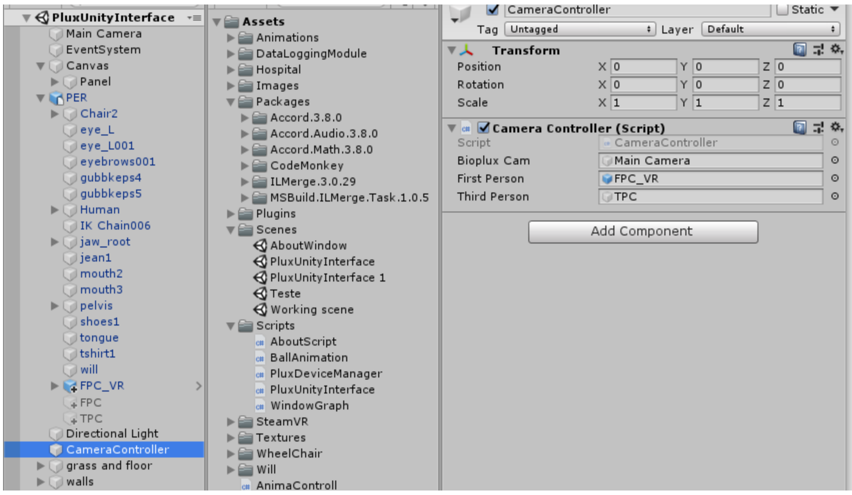


Figure 3-30 The camera controllers at the unity interface.

```
public class CameraController : MonoBehaviour {

    public GameObject BiopluxCam;
    public GameObject FirstPerson;
    public GameObject ThirdPerson;

    // Use this for initialization
    void Start () {
        BiopluxCam.SetActive(true);
        FirstPerson.SetActive(false);
        ThirdPerson.SetActive(false);
    }

    // Update is called once per frame
    void Update() {
        if (Input.GetKeyDown(KeyCode.Alpha1))
        {
            BiopluxCam.SetActive(true);
            FirstPerson.SetActive(false);
            ThirdPerson.SetActive(false);
        }
        if (Input.GetKeyDown(KeyCode.Alpha2))
        {
            BiopluxCam.SetActive(false);
            FirstPerson.SetActive(true);
            ThirdPerson.SetActive(false);
        }
        if (Input.GetKeyDown(KeyCode.Alpha3))
        {
            BiopluxCam.SetActive(false);
            FirstPerson.SetActive(false);
            ThirdPerson.SetActive(true);
        }
    }

}
```

Figure 3-31 The camera controllers code.

The oculus program comes with a feature of showing the guardian space while not in the area or when the virtual environment is not allowed in order to prevent motion sickness and dizziness to the players. Two cameras are used, one for the GUI interface and another for the first-person view (Figure 3-30), on Reliph software. The "Main Camera" shows the graphical user interface, and the "FPC_VR" is the first-person camera presenting the first-person view simulating a standard person view with the avatars sight (Figure 3-31).

3.6. Conclusion

In summary, in this section, we present a simple system to use and configure, allowing the technical and medical fields to be used in therapy, training and training sessions. The system requirements were made to make it a better approach serving the basic needs of the topic under study. Following this, the system requirements and the choices behind the design were consistent brain features and behavior. These natural mechanisms are taken into consideration when selecting hardware and software tools. The system still needs some manual adjustments to the threshold values or adjusting the oculus setting to avoid malfunctions, software errors and disturbances. Configurations designed to improve human-computer interaction provide better motivation, immersion and a sense of naturalness. With this in mind, the tasks implemented in the project are to promote these actions/movements, as a form of exercise, without the use of force, effort and adaptive behavior.

Finally, system validity and reliability need to be measured, ensuring that all system parameters and procedures are used in the field. With this in mind, some questionnaires will help measure usability, motivation, immersion, focus, presence, disturbance, and pain tracking during the field study phase to be explored in the next chapter.

4. Technical validation study

In this chapter, we detail a technical validation study with twelve healthy students and employees from University of Madeira (UMa) and Madeira Interactive Technologies Institute (M-ITI). The study describes the process for the validity and reliability of this project thesis based on the previous chapters II and III. We used some questionnaires allowing us not only to study the validity and reliability, but the agency, analgesic effects and disturbances described and measured in the literature.

The agency effect relates to the sense of action and movement, establishing a relationship with the motivation behind these actions. The questionnaire used to measure motivation is the "Intrinsic Motivation Inventory" (IMI) [30], [Appendix D]. Moreover, the purpose of measuring the extreme level of focus and presence state of a person when immersed and concentrated was assessed using the "Presence Questionnaire" related to the analgesic effect [31], [Appendix C]. In order to measure usability of the system, the System Usability Scale (SUS) was used [32], [Appendix B]. Therefore, we performed a technical and usability study with a healthy sample to confirm that the system performs as expected.

4.1. The chosen questionnaires

In this section, all the questionnaires and the choice of the questions will be explained, giving the details and establishing the relations between the system and the reasoning behind them. These will assist us in reducing disturbances, verifying the relationship between the virtual body and the physical body and promoting a better user experience.

4.1.1. The intrinsic motivation inventory

The intrinsic motivation inventory (IMI) is a measurement tool used to quantify, qualify and assess the user's intrinsic motivation and self-regulation related to the tasks, actions and set of activities verifying the motivation behind these tasks [30]. The IMI have a sample of questions that can be chosen according to the project needs and the ones that are relevant to the issues to be explored [30]. The chosen subscales have been discussed and reviewed with the medical field, therapists and according to the literature reviewed.

Intrinsic motivation inventory
1. I thought this activity was quite enjoyable.
2. I felt really distant to this person.
3. I believe doing this activity could be beneficial to someone.
4. I was very relaxed doing this.
5. This activity did not hold my attention at all.
6. After working at this activity for a while, I felt pretty competent.
7. It was important to me to do well at this task
8. I believe I had some choice while doing this activity.
9. I was anxious while working on this task.
10. I did not really have control about doing this task.
11. Comment section.

Table 4-1 A group of a selection of questions from the IMI [30].

The IMI questionnaire (Table 4-1) and its components provide a way to measure the agency effect, which correlates or can provoke some disturbances, described in chapter II.

IMI by section
Interest / Enjoyment
1. I thought this activity was quite enjoyable.
2. This activity did not hold my attention at all. *(R)**
Perceived Competence
1. After working at this activity for a while, I felt pretty competent.
Effort / Importance
1. It was important for me to do well at this task.
Pressure / Tension
1. I was very relaxed doing this. *(R)**
2. I was anxious while working on this task.
Perceived Choice/Control
1. I believe I had some choice while doing this activity.
2. I did not really have control while doing this task.
Value / Usefulness
1. I believe doing this activity could be beneficial to someone.
Relatedness
1. I felt really distant to this person. *(R)**
****(R) – reverse questions means they are subtracted.***

Table 4-2 IMI questions divided by category [30].

Overall, the questions cover the interest/enjoyment, perceived competence, effort/importance, pressure/tension, perceived choice/control, value/usefulness, and relatedness. The displayed questions were to provide a logical sequence of the events (Table 4-2) [Appendix D].

4.1.2. The presence questionnaire

The presence questionnaire, developed by Witmer and Singer, is used to measure the level of presence in the virtual environments. That is, the correlation between the person and the virtual environments, the virtual environment, the sensor placement and surroundings and the interaction with the virtual reality. It takes into account the components that influence the presence in the virtual environments. The presence can be divided and measured throughout factors from control, sensory, distractions, and realism [31].

The presence questionnaire (both groups)
1. How much were you able to control events? *
2. How responsive was the environment to the action that you initiated (or performed)? *
3. How natural did your interaction with the environment seem? *
4. How much did the visual aspects of the environment involve you? *
5. How natural was the mechanism with controlled movements through the environment? *
6. How compelling was your sense of the objects moving through space?
7. How much did your experiences in the virtual environment seem consistent with your real world experience? *
8. How involved were you in the virtual environment experience? *
9. How much delay did you experience between your actions and expected outcomes?
10. How quickly did you adjust to the virtual environment?

11. How much the control devices interfered with the performance of assigned tasks or activities? *
12. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks? *
Selected questions used in both studies.

Table 4-3 Questionnaire used in both groups [31].

The question selection targets the persons' immersion and interactivity (Table 4-3) [Appendix C].

4.1.3. The system usability scale

The usability scale (original)
1. I think I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think I would need the support of a technical person to be able to use this system.
5. I found the various functions in the system were well integrated.
6. I thought there was too much inconsistency in the system.
7. I would imagine that most people would learn to use the system very quickly.

8.	I found the system very cumbersome to use.
9.	I felt very confident using the system.
10.	I need to learn a lot of things before I could get going with this system.

Table 4-4 The questionnaire by John Brook, 1986 [32].

The system usability scale is a widely used questionnaire tool used to measure and classify the usability of systems, websites, applications or environments tested (Table 4-4) [32]. The subcomponents of SUS are the efficiency, ease of use, ease of learning and satisfaction factors (Table 4-4) [Appendix B].

4.2. The protocol for the healthy sample

The experiments were implemented in a closed environment to minimize the noise and interferences. The computer machine, the Biosignalsplux and the Oculus rift were the essential devices for the experience. In the technical validation study with the healthy group, the participants performed one session for at least fifteen to twenty minutes. The training time had a duration of three minutes followed by three minutes of resting. The questionnaires were completed at the end of the session.

Furthermore, all participants were over eighteen years old. The participants could quit at any time or pause if they desired. This could prevent any collateral effects due to the intense focus and long periods using the head-mounted display. The participants allowed recording their muscle activity information. Before each session, the threshold values were adjusted manually according to each person, based on their life activities and hobbies. The EMG data information was used to confirm the threshold values and to calculate the meaningful values. For example, if a person practices sports, the threshold will be higher than a sedentary person due to their muscle development and muscle strength.

4.3. Results

In this section, we present the results and analysis of the data collected in the conducted study [Appendix G]. Furthermore, we describe the comments and suggestions received during the intervention to understand the participant's perspective.

The healthy group had 12 participants (8 males, 4 females, 27.2±3.8 years old). The participants were invited to answer the system usability scale, presence and intrinsic motivation inventory questionnaires. None of the participants were familiar with the entire technologies used in the project. They reported using technologies mainly at work and leisure.

4.3.1. The intrinsic motivation

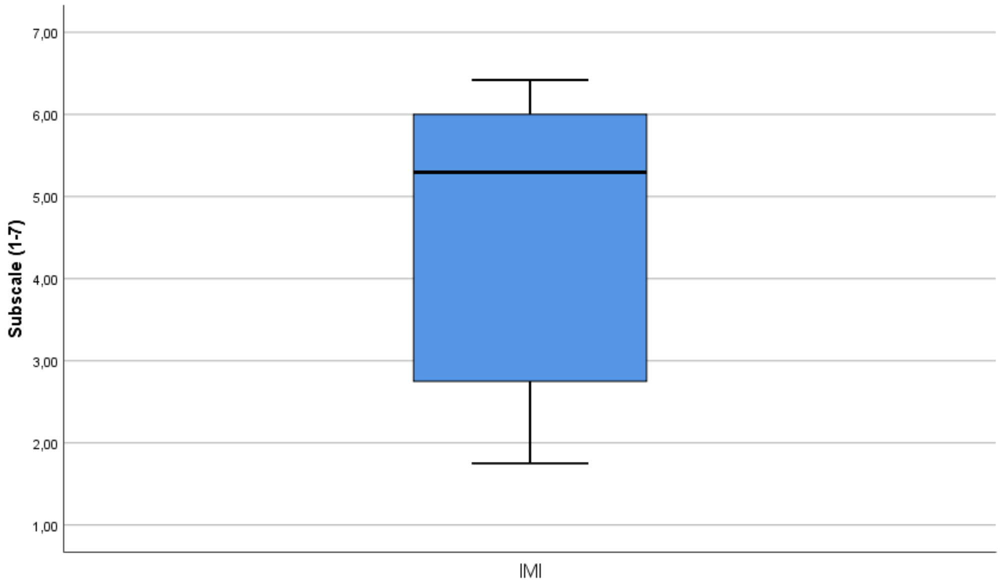


Figure 4-1 IMI results of the technical validation study.

The intrinsic motivation has its subdomains of interest, perceived competence, effort, tension, perceived choice, value and relatedness. The healthy group results from the IMI questionnaire were high and generally the participants reported that they had a high control of the virtual leg and the action of kicking the ball (Figure 4-1). Furthermore, the system gave a sense of free-choice behavior while maintaining interest/enjoyment.

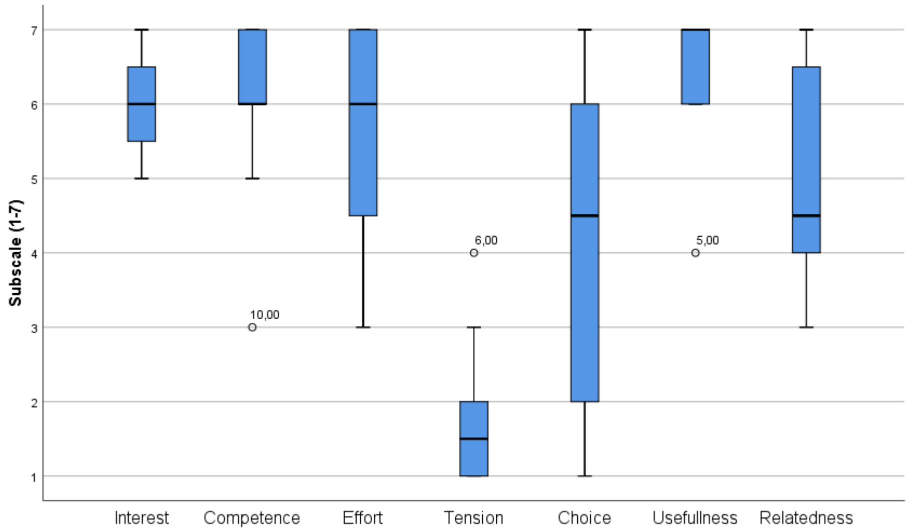


Figure 4-2 Domains of IMI results for the healthy sample.

The domains' (Figure 4-2) results show that the perceived competence (mean 6.0±1.13) and the usefulness (mean 6.42±0.90) had a high score, indicating that the participant felt more competent and valuable/useful, as well as the sense of perceived choice (mean 3.42 ±2.30).

Participants were well associated with the avatar measured by the relatedness (mean 4.92±1.51). Furthermore, the effort (mean 5.67±1.37) was high, understanding that the participant had the intention to perform well at the proposed task. The interest (mean 6.04±1.16) scores were higher and the tension lower (mean 1.83±1.13) indicating that the participants felt a sense of interest and enjoyment while the movements/action made were natural, straightforward and effortless.

4.3.2. The sense of presence

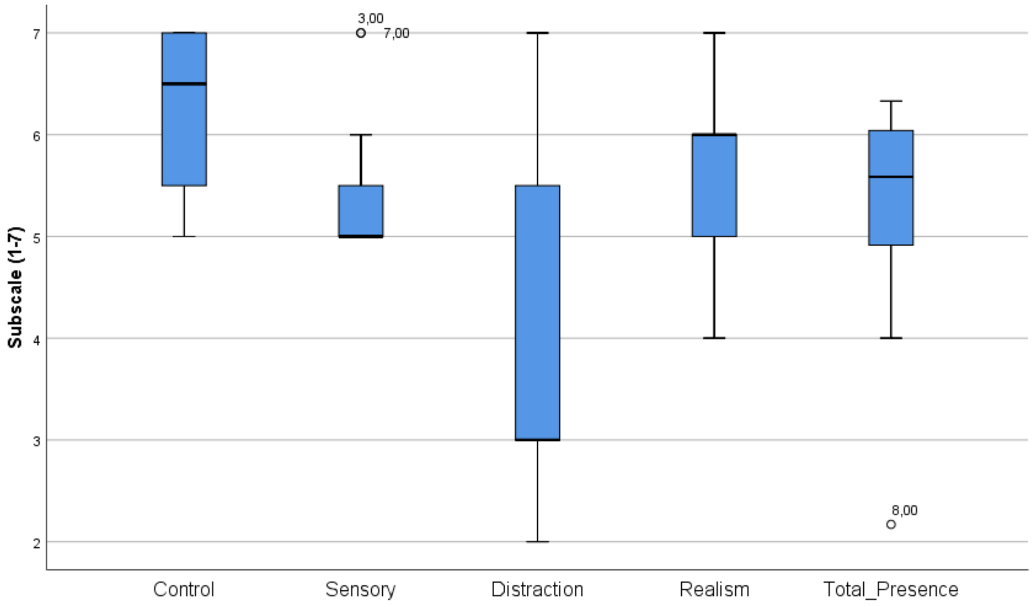


Figure 4-3 Obtained results for the Presence questionnaire of the healthy group.

The results for the sense of presence were high. The graphic shows all the domains for measuring the presence control, sensory, distraction, realism and at the end of the graph the results of the sense of presence (Figure 4-3).

In general, the sense of control (mean 5.64±1.29) indicates that participants had control of the actions happening in the virtual environment. The sensory aspects (mean 5.61±1.05) are lower, meaning that the sense of movement perception, the environmental richness and the sensory modality had a small influence in the senses. Besides, the distractions (mean 4.06±2.15) were minimal, and realism (mean 5.69±1.19) was consistent and enhancing the sense of realism.

4.3.3. The usability

The usability results, from the system usability scale (SUS), in the healthy were higher, meaning that the system fulfils the requirements of usability.

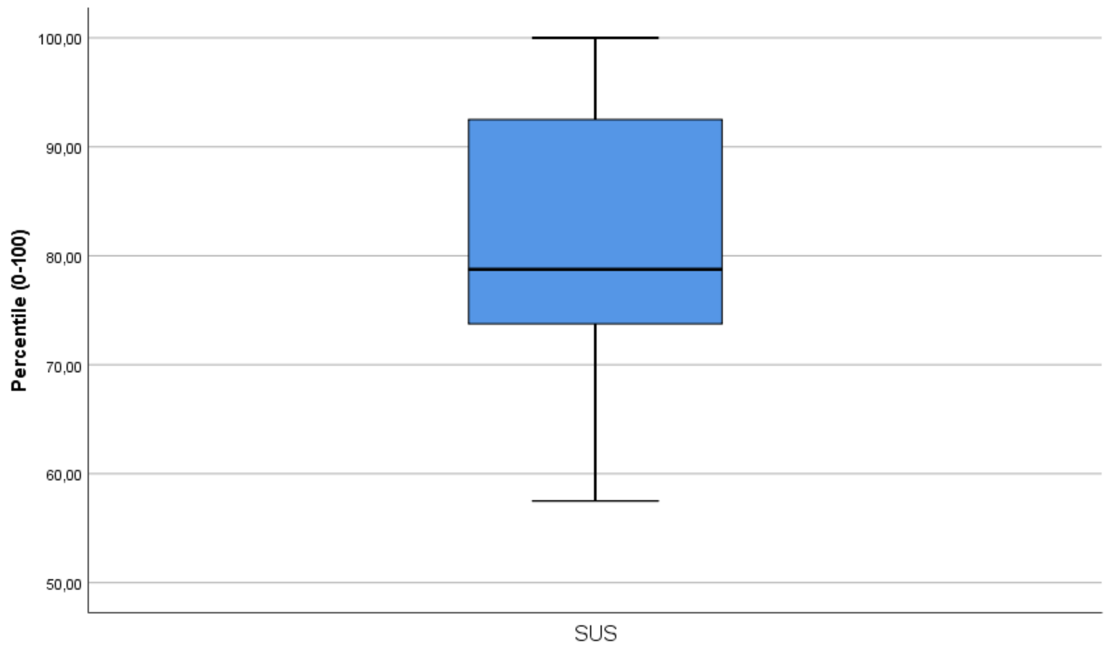


Figure 4-4 System usability scale results for the healthy group.

On the healthy group (Figure 4-4), the system usability score were analysed based on Brooke et al. [32] and Bangor et al. [38]. According to both references, our SUS score is higher (mean 81.25±11.99) corresponding to excellent usability meaning that the system is above average [39]. Hence, a higher score is related to the reliability of the system, indicating that all the system components were well integrated and their relationship is stable working together with a system. A high SUS scores supports the validity of the system meaning that the system has a solid base for being used in the field.

4.4. Conclusion

This intervention served as the basis for understanding and verifying all components reviewed in the literature and during the implementation and construction of this new approach. Based on this, the results obtained from the questionnaires show that this application has a strong component in visual feedback by developing a better way of promoting therapy and removing obvious physical difficulties in modern days. The questionnaires check in detail the relevant components and subcomponents for the development and technological implementation of PLP treatment. In addition, they promote a better experience to the user and familiarizing with the new technologies.

5. Clinical case study

This chapter describes a clinical case study with a PLP patient to assess the feasibility of the approach. Moreover, the patient must answer the previous questionnaires performed with the healthy sample but adapted to make it simple and intuitive for the participant. Finally, the pain/sensation questionnaire is simple and relies on the frequency of the symptoms, the sensations felt and the intensity of pain [Appendix E]. With the consent of SESARAM [Appendix A.6] and the system tested in healthy people, we performed the clinical case study to confirm the system potential and effectiveness in this target audience. At the end, we conducted a semi-structured interview to find out patient opinion about the project [Appendix F].

5.1. Experimental Protocol

The experiments were conducted in a closed environment to minimize the noise and interferences similar to the technical validation protocol. Only the essential devices were allowed to be in the experience. The closed environment allows and enhances the patient's focus and immersion during the training time.

In the clinical validation study, the patient had to have a diagnostic with PLP. He/she should be more than eighteen years old, he/she needed to be in the rehabilitation program in Madeira regional health service (SESARAM), he/she should have a minimum of cognitive and motor capabilities and he/she should be part of pharmaceutical treatment for the phantom pain [Appendix A].

In this intervention, the patient is assigned to eight sessions with the duration of twenty minutes each. The patient has nine minutes of training and the same amount of resting time, meaning he/she will have three minutes of training and three minutes of break, respectively, happening three times per session. After the experience, the patient will answer the four questionnaires of SUS, Presence questionnaire, IMI, and the pain, respectively [Appendix B], [Appendix C], [Appendix D], [Appendix E]. The Presence questionnaire suffered some adaptations involving reducing and removing technical questions and some not applicable from the patient's point of view. The SUS, Presence, and IMI questionnaires were presented at the beginning, middle and at the end of the intervention, meaning that the patient answered these questionnaires at the first session, the fourth session, and finally, on the last one. The pain questionnaire was compartmentalized to be answered at the beginning and end of each session.

5.2. The pain/sensation questionnaire

The phantom pain/sensation questionnaire was based on several pain questionnaires identified in the literature. An adaptation to a simple questionnaire focusing on the pain level, the frequency of the pain, the duration, a subjective evaluation of the pain and description of the pain/sensation was done.

Pain questionnaire (patient)
1. In the previous week, how much pain did you feel?
2. At this moment, how intense is the pain felt?
3. How often does pain or phantom sensation happen?
4. How long does the pain or sensation last or could it last?
5. How do you describe the pain/sensation felt?
6. How do you rate pain/sensation, after the intervention?

Table 5-1 Pain questionnaire for the clinical case study.

These types of questions allow assessing the level of pain and its evolution, while the intervention with the system occurs for the patient who suffers from PL sensation (Table 5-1) [Appendix E].

5.3. The results

In this section, we present the results and analysis of the data collected in the conducted study [Appendix H]. Furthermore, we describe the comments and suggestions received during the intervention to understand the participant's perspective.

The case study was of one patient (male, 59 years old) who was invited to answer the system usability scale, presence, intrinsic motivation inventory questionnaires and pain questionnaire. The patient had been feeling the phantom sensation over two years (started at 7th of August 2017) and he had that feeling pain during this period of time. The patient reported taking pain killers and other types of medications. He also had periodic medical appointments for physiotherapy and the phantom pain/sensation [Appendix A].

5.3.1. The intrinsic motivation

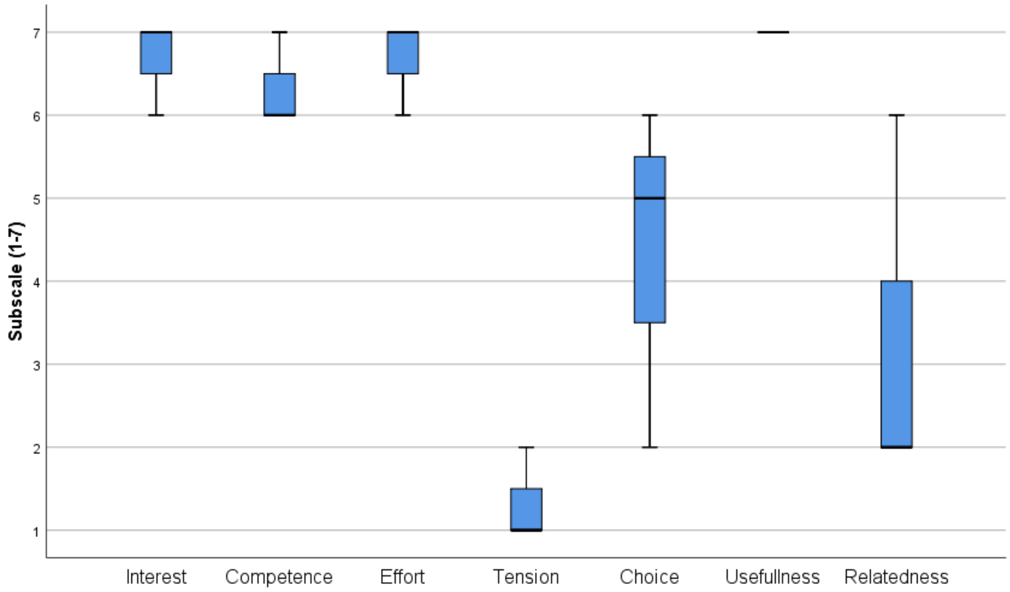


Figure 5-1 IMI results from the clinical case study.

In the IMI results, the patient reported a relatedness with the virtual avatar above average (mean 3.33±2.31) relating them in gender, shape and size. The effort (mean 6.67±0.58), the interest (mean 6.83±0.41), the competence (mean 6.33±0.58) and the usefulness (mean 7.00±0.00) were also high indicating that the patient had interest and competence without high effort. In addition, when performing the tasks or activities, there were beneficial effects while the sense of tension (mean 1.33±0.52) was also low while performing the tasks (Figure 5-1).

5.3.2. The sense of presence

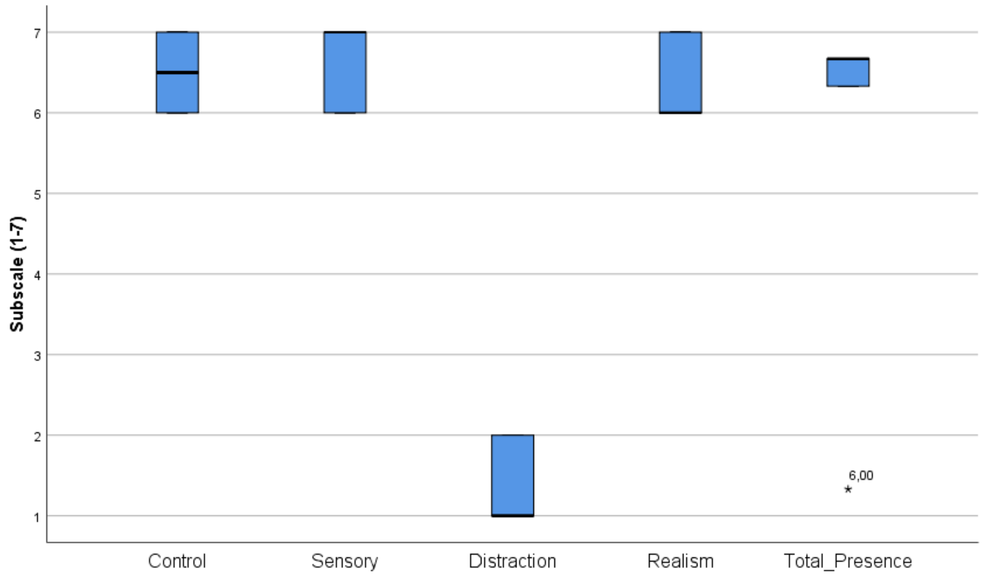


Figure 5-2 Presence questionnaire results from the clinical case study.

For the sense of presence (Figure 5-2), the patient had control of the actions happening in the virtual environment indicated by the sense of control (mean 6.56±0.53). The sensory aspects (mean 6.67±0.52) are higher, meaning that the sense of movement perception, the environmental richness, and the sensory modality enhanced perception. Besides, the distractions (mean 1.33±0.52) were small, and the realism (mean 6.33±0.52) above average. At the end, the sense of presence (mean 5.22±0.01) was above average, indicating focus and immersion in the task.

5.3.3. The usability

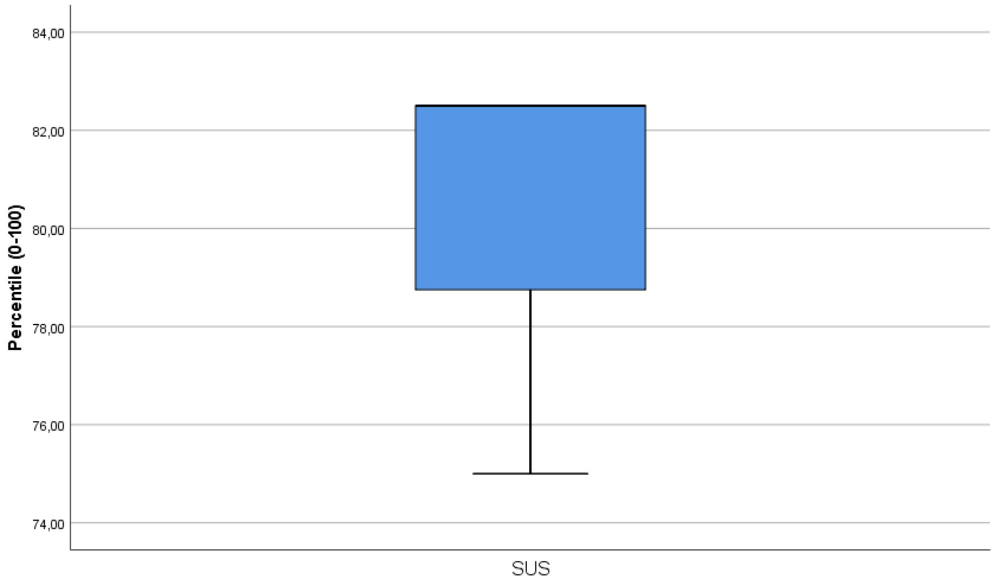


Figure 5-3 System usability scale results from the clinical case study.

In general, the case study has scored similarly to the healthy group results (Figure 4-4), (Figure 5-3). These results show that the validity and the reliability of the system is maintained during a clinical intervention process. The SUS (mean 80.00±4.33) has significant importance at this moment, showing that all the components and subcomponents of the system were well-designed and integrated. The devices and the system are well-integrated with each other, providing a positive experience.

5.3.4. The pain and sensation

The pain/sensation questionnaire was only assessed in the clinical case study, following the protocol described earlier in the present chapter. The tracking of the sensation and pain helps to understand the pain levels and the sensation that the patient felt during the intervention time.

		Session Number (scale 1-7)							
		1	2	3	4	5	6	7	8
Questions	Pain before	*4*	*1*	*1*	*1*	*1*	*1*	*1*	*1*
	Pain after	*1*	*3*	*1*	*1*	*1*	*1*	*1*	*1*
	Level of sensation	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*
	Frequency of pain	*2*	*1*	*1*	*1*	*1*	*1*	*1*	*1*

Table 5-2 Results for pain, sensation and frequency levels for the case study.

The intervention was made after the training sessions in physiotherapy, meaning that the pain level could increase due to the extreme focus and workout in physiotherapy. Before the intervention, the patient reported some pain in the PL (Table 5-2). The pain levels before treatment with our system (mean 1.38±1.06) decreased after the first session. There was a peak of pain level after the second session (mean 1.33±0.82).

The PL sensation (mean 1.0±0.0) also happened during this time, matching with what was reported in the literature: the burning, cramps and some sensitivity in the amputated part. The frequency (mean 1.13±0.35) of these pain levels was measured (referred to the previous week) at the beginning of the session and at the end of each session. It quantifies the frequency that these sensations and pain happened during the week before the intervention. We asked how much time usually these pain events took place and to describe the sensation and/or pain felt during this time (Table 5-3). The frequency of the sensation/pain decreased over the sessions and after the first two sessions, the sensation was substantially reduced.

Pain/sensation		
Session number	Duration (minute)	Description (comment)
1	< 1	Crampy, Burning, and Stabbing
2	< 1	Normal, slight sensitivity*
3	None	No pain or sensation felt
4	None	No pain or sensation felt
5	1 to 2	Normal, slight sensitivity and slight pain*
6	None	No pain or sensation felt
7	< 1	Crampy
8	None	No pain or sensation felt
Slight – it can occur three times per day and have a time break of two/three days without pain/sensations.		

Table 5-3 Duration and sensation of the phantom in times of pain felt at the intervention.

5.4. Conclusion

The chapter presented the methodology applied to the evaluation of this thesis project. The sessions were planned, controlling the intensity of training, the setup and usage of the different system elements. The threshold values were measured and fully compromised. This being that they are capable of fitting different types of users, types of amputations and different capability levels.

The high results on the SUS, Presence Questionnaire and Intrinsic Motivation Inventory show that this system is designed and conforms according to the goals of the project and that it can be for this targeted audience. Furthermore, our clinical case study showed consistent results with the healthy subjects concerning the usability, presence, motivation and a reduction of reported pain. Hence, showing that this approach is not only feasible but also has high therapeutic potential. However, some improvements should be considered to minimize the disturbances, enhancing the sense of embodiment, the focus and the immersion, motivating and keeping the interest in performing the required tasks. These improvements are based on gender, leg size, leg length and the person's height.

6. Discussion and conclusions

The present system was developed taking into consideration the possible constraints that a phantom limb pain provides to the daily life and daily activities of patients, with the goal of enhancing and improving the patients' lives and minimizing the pain/sensation feeling. Therefore, in periods of pain and sensibility in the leg, the system developed intent to help the patient to control their painful periods and reduce their duration.

In order to make the project feasible and accepted by the clinicians, we start by gathering information about the essential components for a real-time approach using virtual reality and electromyography. The project aimed to improve and enhance the mirror therapy used nowadays in the field. Serving as adjuvant therapy to promote the reduction of the pain levels and helping to reduce the pharmaceutical procedures to this target audience. The system was envisioned to serve as an adjuvant therapy to the mirror therapy, improving it with a technological approach consistent with the current times. Hence, reducing the lack of interest and the fear of patients, helping and preparing them for further medical recommendations, for example, the use of a prosthesis. Following the principles and the criteria by mirror therapy, the system does not mirror the limb, and it is suitable for patients with amputations in both legs. In this way, the system can adapt to different amputations without changing its principles. In the end, the surrounding environment can be adapted or changed according to the idealized context.

Following the first research question, our process started with performing a literature review and identifying case studies as well as searching for recommendations, constrains, different VR approaches and the reduction of disturbances. Allowing to verify the significant components for the development of the project planning a more suitable approach where the brain mechanism could be evoked and enhanced during the intervention time. The different studies on the brain mechanisms of pain and recovery helped in choosing the proper tools to achieve the needs of the patients. These systems used to promote these mechanisms have a positive influence on the topic but lacking in a real-time approach and without the aid of muscle activity. With this in mind, the development of a real-time interaction treatment has been aimed in order to reduce the pain, promoting the sense of agency and analgesic effect.

In this way, the use of a virtual world controlled by a biofeedback device for real-time feedback was a valuable contribution to this system. However, we need to do additional research for the project fulfil its therapeutic goals in terms of engagement, usability and user experience. Then, the gamification of the system came to help to capture the player's interest, to motivate, and enhance the focus on the movements and tasks required by the therapy. The target audience will be in an environment of extreme focus having reasoning and motivation behind the proposed tasks in a real-time interactable virtual environment assisted by the oculus and the biosignals technologies. In order to reinforce the intractability, natural and straightforward movements were used to maintain the coherence and adaptability to the environment, enhancing the realism required to show that the system is prepared to be used and serving its purpose.

Finally, the results of the healthy participants and the case study with a patient confirmed the usability, the sense of presence and motivation of using this system, as well as its feasibility as a tool to reduce pain in PLP patients. We start by verifying the sense of agency to measure the motivation where both groups have shown high scores in their domains. The healthy and case study showed interest in completing the proposed task without losing the sense of choice and competence. The movements and exercises were performed effortless and showing to be valuable/useful respecting the criteria and principles of mirror therapy. The tension scores may influence the pain feelings and the mitigation of pain, which it should be reduced depending on the target surrounding and self-regulation related to the motivation levels. The relatedness gives us the idea that the participants establish a related sense to the avatar in terms of interpersonal relationships, interactions and friendship formation. Moreover, the analgesic effect was measured through the sense of presence related to the concentration, focus and immersion, throughout the use of the presence questionnaire. The results show that the controlled environment and the participant established a positive relationship that enhances the sensory modalities connected to the real and virtual worlds. Additionally, the subcomponents of the presence allow us to verify and detect errors in the visual feedback, the performance of the actions and the immersion. The domains that revealed the sense of control and realism were positive and it relates to the sensory aspects while minimizing the distractions and possible disturbances enhancing and/or affecting the sense of presence. Later on, the system was measured, proving to be above average following the SUS, where we verified that the system was easy to learn and easy to use, as well as its efficiency and satisfaction.

Furthermore, we need to know if the project is feasible for the targeting audience and if it helps mitigating the phantom limb pain. In the case study, we conducted a questionnaire aiming to investigate the feasibility of the system reducing the pain and the sensation, before and after the intervention. We checked their duration and intensity during the days before each session. The results have shown lower or minimum scores in the sensation/pain levels, likewise in their intensity level and its duration. To double-check, we questioned about the type of feeling in order to authenticate and relate the pain/sensation felt in the previous days, this way we could correlate those described by the patients with the ones reviewed on the literature. Finally, the results obtained during the interventions differ from the literature and the other technological approaches. The system shows to be more efficient in reducing the pain, promoting the brain mechanisms related to the target body part, using natural and effortless movements when compared with others of similar nature. Thus, the present system proves to be a more effective approach where it can be improved and optimized to facilitate its use by assisting in the treatment of PLP.

The developments in the project try to provide an answer to the research questions, in Chapter I. The creation of a new approach for improving the mirror therapy using VR and EMG is motivated by the needs of these patients and the fact that they have a small set of options in technologies to enhance and help them during their training and workout sessions. Therefore, our thesis shows that the system is valid and reliable for use in the field as a new improved technological approach. With that in mind, the present thesis capitalizes on aspects of the use of mirror therapy to be exploited with the new technological method created. The ultimate goal of the system is to help trigger neuroplasticity in the brain creating and generating new neural connections or reusing the existing connections, thus updating the image that our minds have of the body throughout the body schema and body structural. Furthermore, the telescoping effect will happen as a normal reaction to the rightful activation of these parameters showing the system effectiveness helping the reduction of the pain feeling.

Some issues can occur when figuring and planning an approach such as this. To prevent and minimise these disturbances the method created was based on natural and realistic movements performed by human beings. These movements can be seen while performing daily activities during daily lives, following the literature in Chapter II. The sports have an active component by using our natural and simple movements, gamifying them interactively and socially. Implementing a gamified approach based on these types of movements was important to generate interest, immersion and motivation. The project uses similar lower limbs movements used in physical therapy and rehabilitation exercises, the movements used while doing the mirror therapy, just as those used in sports. After finding the right training movements, a contextualized virtual environment was created to mimic the games played nowadays promoting the analgesic and agency effects described in the literature. Enhancing the reorganization, restructuring of the brain, promoting the brain activity and updating/informing the human brain about the new body image maintaining the patients engaged, focused and giving a reason behind these movements.

Concluding, the system has been tested in healthy participants and with the targeting audience verifying the difference of the motivation of the movements, the presence in the virtual world, tracking the pain/sensation and the viability of the system. Therefore, this thesis achieved its goals and has developed a system with high therapeutic potential to use in future treatments.

7. Future considerations and recommendations

Finally, there are some considerations when doing a project with patients, especially those with some motor and sensory limitations. It is recommended to maintain a constant awareness of new publications and recommendations. The literature helps to track new developments, considerations and constraints. This project provides new approaches and contributes to the PL and PLP community, helping and proposing new avenues for promoting PLP treatments. The proposed project can have an enhanced impact when compared to the realism and simplicity of the movement in the game, which is upgradable and further developments can still take place. It is recommended that future works should pay attention to the realism of the game, based on natural and simple movements, enhancing the experience throughout the agency and analgesic effects and always tracking the possible disturbances and pain feeling if working with the same target audience. It can motivate to conduct more research and user testing with the targeting audience. Nevertheless, the system could be improved and enhanced eventually providing a better experience:

- To enhance the relationship between the avatar and the patients, different types of characters need to be selected before each session;
- The IMI results shows that the tension could be reduced during the training, eventually helping in the reduction of the sensation/pain;
- The sensory sense can be improved by having different types of animations for the legs and the ball movements, which could be triggered according to the data captured by the electrodes;
- The perceived competence could be enhanced by adding sound effects similar to reality, providing useful feedback to the interactions;
- Enhancement of the sense of control and realism by adding more channels to capture EMG signals allowing the player more complex movements, such as a variety of combos. This way enhances the sense of presence, the interactivity and allows the usage in patients with amputations on both legs;
- Different equipment and placements for the electrodes could be used for improving the performance of the system;
- The software could be further developed to make it possible for different game approaches, and to improve the system performance and the training time;

- The graphical user interface needs some adjustments to be more intuitive and tested for the therapeutic field.

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Appendix

7.1. Appendix A SESARAM Protocol

Appendix A.1 SESARAM protocol – Main goals and Methodology (Portuguese)

OBJECTIVOS

1. Compreender a eficácia e eficiência durante a execução dos movimentos em conjunto do feedback visual proveniente da realidade virtual com o uso dos EMGs.
2. Avaliação do impacto do paradigma de EMG com feedback em RV na redução da Dor fantasma.

METODOLOGIA

PARADIGMA: A instalação consiste em um computador portátil que processa em tempo real os dados EMG da actividade muscular do utilizador, enviando comandos de controlo para o computador que os executa no ambiente virtual, sendo gerada uma correspondência visual para o utilizador.

Appendix A.2 SESARAM protocol – ReLiPh intervention (Portuguese)

B ReLiPh Intervenção

O estudo consiste em 8 sessões de 20 minutos, com a duração de 4 semanas, no qual os participantes poderão sair a qualquer momento.

O doente é imerso no sistema virtual numa perspectiva em primeira pessoa. O membro inferior amputado é apresentado como íntegro através de um avatar. A execução de tarefas pelo membro inferior são desencadeadas pela ativação muscular detectado por eléctrodos de superfície colocados sobre o coto. A ativação muscular desta forma ativa movimento do membro inferior virtual.

C Avaliação Clínica

A avaliação será feita pelo Jean-Claude Fernandes ou outro médico escolhido pelo SESARAM no início, duas semanas, quatro semanas e quatros semanas após término do estudo.

1. Escala numérica da dor: atual, mínimo da semana anterior, máximo da semana anterior
2. Avaliação subjectiva da dor ou sensação: melhor, pior ou igual
3. Frequência da dor ou sensação: Constante, algumas vezes por hora, algumas vezes por dia, algumas vezes por semana
4. Duração da dor ou sensação: dias, horas, minutos, segundos
5. Descrição da sensação da dor

Appendix A.3 SESARAM protocol - Inclusion and exclusion criteria (Portuguese)

CRITÉRIOS DE INCLUSÃO

1. Doente com dor ou sensação fantasma;
2. Idade: ≥18;
3. Doente em programa de reabilitação no SESARAM
4. Doentes refratárias a tratamento farmacológica da dor fantasma
5. Capaz de ler e escrever;
6. Motivação para participar no estudo;
7. Capacidade cognitiva e motora suficientes para executar as tarefas propostas.

CRITÉRIOS DE EXCLUSÃO

1. Doentes com défices cognitivos que possam interferir com a compreensão e execução da tarefa
2. Doentes com feridas que impeçam colocação de eletrodos de superfície
3. Doente com cotos em fase de cicatrização.
4. Compromisso grave da visão.
5. Grávidas e puérperas

Appendix A.4 SESARAM protocol – Informative document for patient (Portuguese)

I. DOCUMENTO DE INFORMAÇÃO PARA O PARTICIPANTE

Documento de informação para o participante

NOME DO ESTUDO: Validação do tratamento da dor fantasma do Membro Inferior com sistema de feedback baseado em EMG e realidade virtual

RESPONSÁVEIS: Sergi Bermúdez Badia, Carlos André Freitas Costa, Jean-Claude Fernandes

INVESTIGADORES: Sergi Bermúdez Badia, Carlos André Freitas Costa, Jean-Claude Fernandes

Foi-lhe pedido para participar num estudo de investigação a decorrer no SESARAM, em parceria com a Universidade da Madeira. Estará envolvido na recolha de informação para ajudar a compreender técnica para com intuito de inovar as terapias, no controlo de uma personagem virtual integrada num mundo virtual como complemento da terapia convencional, em pacientes que, sofrem de dor ou sensação fantasma dos membros inferiores

QUAL É O OBJETIVO DESTE ESTUDO?

O objetivo deste estudo é a avaliação dos benefícios de um sistema de feedback baseado em EMG e realidade virtual no tratamento de dor fantasma

O QUE É QUE ESTE ESTUDO ENVOLVE?

Todos os pacientes seguirão o tratamento de reabilitação habitual, adicionalmente ao tratamento proposto, com o objetivo de obter a máxima recuperação possível. Na admissão, os pacientes serão propostos que:

Além da avaliação clínica habitual, todos os pacientes serão avaliados no início, duas semanas, quatro semanas e quatros semanas após término do estudo sobre as características da dor ou sensação

A QUEM É PEDIDO PARA PARTICIPAR NESTE ESTUDO?

Você foi selecionado para participar neste estudo pelo facto de apresentar um determinado quadro clínico de sensação fantasma ou dor fantasma.

EXISTEM RISCOS NESTA PARTICIPAÇÃO?

Não existem riscos para a sua saúde pois os procedimentos consistem na interação com um computador e na realização de inquéritos de avaliação. Pode apenas sentir fadiga ou dores de cabeça devido ao aumento da sobrecarga mental exigida pelos exercícios no computador.

EXISTEM BENEFÍCIOS POR PARTICIPAR?

Este é um projeto de investigação em que os resultados podem de alguma forma beneficiar o processo de reabilitação. Contudo, o impacto é imprevisível e é possível que não haja melhorias da dor. No entanto, a informação recolhida neste estudo beneficiará, no futuro, pessoas de problemas semelhantes.

QUEM TERÁ ACESSO À MINHA INFORMAÇÃO?

O seu nome não será identificado em quaisquer relatórios ou base de dados. Todos os relatórios e materiais pertencentes a este estudo serão mantidos confidenciais. Contudo, não podemos garantir confidencialidade absoluta. A sua informação pessoal poderá ser revelada se solicitada pelas vias legais. É também possível que os resultados deste estudo sejam divulgados e/ou publicados no futuro. Neste caso, a sua identidade será confidencial e não será revelada na divulgação.

Este estudo obedece a regulamentos nacionais e internacionais aplicados à investigação com seres humanos. Todas as pessoas envolvidas neste estudo respeitarão a intimidade e privacidade do paciente. O processo clínico é confidencial. O nome e outros dados pessoais não serão partilhados ou distribuídos a não-autorizados (Diretiva 95/46/EC, Lei 67/ 98 – Lei da Proteção de Dados Pessoais).

EXISTEM CUSTOS ENVOLVIDOS?

A sua participação não envolve quaisquer encargos ou despesas da sua parte, com exceção do tempo necessário para a participação no estudo.

QUAIS SÃO OS MEUS DIREITOS?

A sua participação neste estudo é inteiramente voluntária. Pode recusar participar neste estudo ou desistir em qualquer altura. Se decidir não participar, isto não afetará o seu futuro tratamento ou direitos de saúde e direitos legais.

QUEM POSSO CONTACTAR SE TIVER ALGUMA QUESTÃO OU PREOCUPAÇÃO?

Se tiver alguma dúvida sobre os seus direitos como participante pode contatar um dos membros da equipa de investigação:

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Hospital Dr. Nélio Mendonça, SESARAM

Appendix A.5 SESARAM protocol - Informed Consent Document

I. DOCUMENTO DE INFORMAÇÃO PARA O PARTICIPANTE

Documento de informação para o participante

NOME DO ESTUDO: Validação do tratamento da dor fantasma do Membro Inferior com sistema de feedback baseado em EMG e realidade virtual

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Foi-lhe pedido para participar num estudo de investigação a decorrer no SESARAM, em parceria com a Universidade da Madeira. Estará envolvido na recolha de informação para ajudar a compreender técnica para com intuito de inovar as terapias, no controlo de uma personagem virtual integrada num mundo virtual como complemento da terapia convencional, em pacientes que, sofrem de dor ou sensação fantasma dos membros inferiores

QUAL É O OBJETIVO DESTE ESTUDO?

O objetivo deste estudo é a avaliação dos benefícios de um sistema de feedback baseado em EMG e realidade virtual no tratamento de dor fantasma

O QUE É QUE ESTE ESTUDO ENVOLVE?

Todos os pacientes seguirão o tratamento de reabilitação habitual, adicionalmente ao tratamento proposto, com o objetivo de obter a máxima recuperação possível. Na admissão, os pacientes serão propostos que:

Além da avaliação clínica habitual, todos os pacientes serão avaliados no início, duas semanas, quatro semanas e quatros semanas após término do estudo sobre as características da dor ou sensação

DOCUMENTO DE CONSENTIMENTO INFORMADO

Entendo que toda a informação derivada do estudo **"Validação do tratamento da dor fantasma do Membro Inferior com sistema de feedback baseado em EMG e realidade virtual"** é, propriedade da equipa de investigação responsável. Dou o meu consentimento para que dados anónimos a meu respeito (resultados, imagens e vídeos) possam ser guardados e processados para fins de avaliação científica. Li (foi-me lida) a informação mencionada acima. Entendo o significado desta informação, e as minhas perguntas foram satisfatoriamente respondidas. Tive tempo suficiente para decidir sobre a participação neste estudo. Venho por este meio consentir a minha participação e consentir na recolha, uso e revelação de informação. Irei receber uma cópia deste documento de consentimento informado assinada e datada.

____ ____________

Assinatura do participante ou representante legal Data

____ ____________

Assinatura do Médico responsável Data

__________________________________ ____________

Assinatura do Investigador Data

Appendix A.6 SESARAM Consent – letter of consent for the ReLiPh project

SESARAM

(CES & CCI do SESARAM, EPE)

Autorizado. Informar os proponentes do Parecer

PARECER nº 28/2019

Sobre o Pedido/Estudo:

"Caso piloto do tratamento da dor fantasma do membro inferior com sistema de feedback baseado em EMG e realidade virtual."

A – RELATÓRIO

A.1 A Comissão de Ética para a Saúde (CES) e a Comissão Científica para a Investigação (CCI) do Serviço de Saúde da Região Autónoma da Madeira, EPE (SESARAM, EPE), analisou o documento Nº 49 de 2019, pedido submetido pelo **Dr. Sergi Bermudez i Badia,** Professor Auxiliar da Universidade da Madeira, para realização do trabalho de investigação "***Caso piloto do tratamento da dor fantasma do membro inferior com sistema de feedback baseado em EMG e realidade virtual"***. Trata-se de um estudo que pretende avaliar a eficácia e eficiência dos movimentos em conjunto com o feedback visual proveniente da realidade virtual com uso dos EMGs.

A.2 O documento em análise é constituído por: ofício enviado ao Conselho de Administração do SESARAM, EPE, (EE919964) datado de 22 de Julho de 2019, que inclui questionário de submissão, projecto do estudo, informação da direcção do serviço e termo de responsabilidade dos orientadores. Acresce email do proponente datado de 31 de Julho de 2019, que inclui revisão do questionário de submissão e projecto do estudo.

A.3 Trata-se de um estudo que pretende compreender a eficácia e eficiência dos movimentos em conjunto com o feedback visual proveniente da realidade virtual com uso dos EMGs, bem como avaliar o impacto do paradigma de EMG com feedback em RV na redução da dor fantasma. O doente será recrutado através do Serviço de Medicina Física e Reabilitação, a equipa clínica que acompanha o doente irá informar adequadamente e antecipadamente o participante para o objectivo, a relevância e os detalhes do estudo. O estudo consiste em 8 sessões de 20 minutos, com duração de 4 semanas, no qual o participante pode sair a qualquer momento. A avaliação clínica inclui escala numérica da dor, avaliação subjectiva, frequência e duração da dor ou sensação e descrição da dor.

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SESARAM EPE
Serviço de Saúde da RAM EPE

B – IDENTIFICAÇÃO DAS QUESTÕES COM EVENTUAIS IMPLICAÇÕES ÉTICAS

B.1 Serão salvaguardados ao longo do estudo, os princípios éticos relativos ao mesmo, nomeadamente no que se refere ao anonimato do doente.

B.2 Reconhece-se o interesse prático nos resultados, sendo que a metodologia utilizada salvaguarda o direito do doente.

C – IDENTIFICAÇÃO DAS QUESTÕES COM EVENTUAIS IMPLICAÇÕES CIENTÍFICAS

C.1 Serão salvaguardados os princípios básicos da investigação clínica, no que respeita a clareza de exposição dos objectivos e hipótese subjacente, interesse e inovação, metodologia e desenho do estudo.

C.2 Reconhece-se a validade científica e interesse prático do estudo proposto, cuja qualidade e rigor devem ser assegurados no decorrer da investigação.

D – CONCLUSÃO

A CES/SESARAM, EPE deliberou emitir **Parecer Favorável** por não se colocarem quaisquer questões de ordem ética.

A CCI/SESARAM, EPE decidiu emitir **Parecer Favorável** por estarem cumpridos os princípios básicos das Boas Práticas Clínicas na Investigação.

Reavaliado dia 09 de Agosto de 2019, conforme aprovado em acta do dia 22 de Julho de 2019 da CES por unanimidade.

Aprovado pela CES	Aprovado após avaliação pela CCI.
O presidente da CES/SESARAM, EPE	A responsável da CCI/SESARAM, EPE
(Ricardo Santos)	(Paula Pinto)

Região Autónoma da Madeira – Serviço Regional de Saúde, E.P.E. – Comissão de Ética

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7.2. Appendix B. System Usability Scale questionnaire (English and Portuguese)

System Usability Scale

*Obrigatório

1. **I think that i would like to use this system frequently? / Eu acho que gostaria de usar este sistema com frequência? ***

   Marcar apenas uma oval.

	1	2	3	4	5	
Disagree / Discordo	◯	◯	◯	◯	◯	Agree / Concordo

2. **I found the system unnecessarily complex? / Eu achei o sistema desnecessariamente complexo? ***

   Marcar apenas uma oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

3. **I thought the system was easy to use? / Eu achei o sistema de uso fácil? ***

   Marcar apenas uma oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

4. **I think that i would need the support of a technical person to be able to use this system? / Eu acho que eu precisaria do apoio de uma pessoa técnica para poder usar este sistema? ***

   Marcar apenas uma oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

5. **I found the various functions in the system were well integrated? / Eu encontrei as várias funções no sistema foram bem integradas? ***

   Marcar apenas uma oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

6. **I thought there was too much inconssistency in the system? / Eu pensei que havia muita inconsistência no sistema? ***

   Marcar apenas uma oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

7. **I would imagine that most people would learn to use this system very quickly? / Eu imagino que a maioria das pessoas aprenderia a usar esse sistema muito rapidamente? ***

   Marcar apenas uma oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

8. **I found the system very cumbersome to use? / Eu achei o sistema muito complicado de usar?**

Marcar apenas uma oval.

	1	2	3	4	5	
Strongly Disagree						Strongly Agree

9. **I felt very confident using the system? / Eu me senti muito confiante usando o sistema?** *

Marcar apenas uma oval.

	1	2	3	4	5	
Strongly Disagree						Strongly Agree

10. **I needed to learn a lot of things before could get going with this system? / I needed to learn a lot of things before could get going with this system?** *

Marcar apenas uma oval.

	1	2	3	4	5	
Strongly Disagree						Strongly Agree

7.3. Appendix C. Presence questionnaire (English and Portuguese)

Presence questionnaire

11. **How much were you able to control events? / Quanto você conseguiu controlar os eventos?** *

Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Completely

12. **How responsive was the envoironment to actions thet you initiated (or performed)? / Quão responsivo foi o ambiente para ações que você iniciou (ou realizou)?** *

Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Not Responsive	◯	◯	◯	◯	◯	◯	◯	Responsive

13. **How natural did your interaction with the envoironment seem? / Quão natural sua interação com o meio ambiente parece?** *

Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Artificial	◯	◯	◯	◯	◯	◯	◯	Natural

14. **How much did the visual aspects of the envoironment involve you? / Quanto os aspectos visuais do ambiente envolvem você?** *

Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Completely

15. **How natural was the mechanism which controlled movements through the envoironment? / Quão natural era o mecanismo que controlava os movimentos pelo meio ambiente?** *

Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Artificial	◯	◯	◯	◯	◯	◯	◯	Natural

16. **How compelling was your sense of the objects moving through space? / Quão convincente foi o seu senso dos objetos se movendo pelo espaço?** *

Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Completely

17. **How much did your experiences in the virtual envoironment seem consistent with your real world experience? / Quanto suas experiências no ambiente virtual parecem consistentes com sua experiência no mundo real?** *

Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Not consistent	◯	◯	◯	◯	◯	◯	◯	Consistent

18. **Were you able to anticipate what would happen next in response to the actions that you performed? / Você foi capaz de antecipar o que aconteceria em seguida em resposta às ações que você realizou?**
Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Completely

19. **How completely were you able to actively survey or search the envoironment using vision? / Como completamente você foi capaz de examinar de forma ativa ou procurar o meio ambiente usando a visão?**
Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Completely

20. **How compelling was your sense of moving around inside the virtual envoironment? / Quão atraente é o seu senso de se movimentar dentro do ambiente virtual?**
Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Not Compelling	◯	◯	◯	◯	◯	◯	◯	Compelling

21. **How closely were you able to examine objects? / Quão perto você foi capaz de examinar objetos?**
Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Closely

22. **How well could you examine objects from multiple viewpoints?**
Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Extensively

23. **How well could you examine objects from multiple viewpoints?**
Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Extensively

24. **How involved were you in the virtual envoironment experience? / Quão envolvido você estava na experiência do ambiente virtual?** *

Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Not involved	◯	◯	◯	◯	◯	◯	◯	Completely Engrossed

25. **How much delay did you experience between your actions and expected outcomes? / Quanto atraso você experimentou entre suas ações e resultados esperados?** *

Marcar apenas uma oval.

	1	2	3	4	5	6	7	
No Delays	◯	◯	◯	◯	◯	◯	◯	Long Delays

26. **How quickly did you adjust to the virtual envoironment? / Com que rapidez você se ajustou ao ambiente virtual?** *

Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Less than one minute

27. **How able interacting with the virtual envoironment did you feel at the end of the experience? / Quão capaz de interagir com o ambiente virtual você se sentiu no final da experiência?**

Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Not able	◯	◯	◯	◯	◯	◯	◯	Very able

28. **How much did the virtual display quality interfere or distract you from assigned tasks or required activities? / Quanto a qualidade do visor virtual interferiu ou distraiu você das tarefas atribuídas ou das atividades necessárias?** *

Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Not Interfered	◯	◯	◯	◯	◯	◯	◯	Very Interfered

29. **How much the control devices interfered with the performance of assigned tasks or activities? / Quanto os dispositivos de controle interferiram no desempenho de tarefas ou atividades designadas?** *

Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Not Interfered	◯	◯	◯	◯	◯	◯	◯	Very Interfered

30. **How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to performed those tasks? / Quão bem você poderia se concentrar nas tarefas designadas ou atividades requeridas, em vez de nos mecanismos usados para executar essas tarefas?** *

Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Completely

7.4. Appendix D. Intrinsic Motivation Inventory questionnaire (English and Portuguese)

Intrinsic Motivation Inventory (IMI)

31. **Interest/ Enjoyment** *

Marcar apenas uma oval.

- I thought this activity was quite enjoyable. / Eu achei que esta atividade foi bastante agradável.
- This activity did not hold my attention at all (R). / Esta atividade não me chamou a atenção (R).

32. **Perceived Competence** *

Marcar apenas uma oval.

- After working at this activity for awhile, I felt pretty competent. / Depois de trabalhar nessa atividade por algum tempo, me senti bastante competente.
- I am satisfied with my performance at this task. / Estou satisfeito com o meu desempenho nesta tarefa.

33. **Effort / Importance** *

Marcar apenas uma oval.

- It was important to me to do well at this task. / Foi importante para mim fazer bem nesta tarefa.
- I did not put much energy into this. (R) / Eu não coloquei muita energia nisso. (R)

34. **Pressure /Tension** *

Marcar apenas uma oval.

- I was anxious while working on this task. / Eu estava ansioso enquanto trabalhava nessa tarefa.
- I was very relaxed in doing this. (R) / Fiquei muito relaxado ao fazer isso. (R)

35. **Perceived choice / Control** *

Marcar apenas uma oval.

- I believe i had some choice while doing this activity. /Eu acredito que eu tive alguma escolha enquanto fazia esta atividade.
- I did not realy have control about doing this task. (R) / Eu realmente não tenho controle sobre essa tarefa. (R)

36. **Value / Usefullness** *

Marcar apenas uma oval.

- I believe doing this activity could be beneficial to someone. / Eu acredito que fazer essa atividade pode ser benéfico para alguém.
- I think this is important to do because it can .... / Eu acho que isso é importante porque pode ....

37. **Relatedness** *

Marcar apenas uma oval.

- I felt really distant to this person. (R) / Eu me senti muito distante dessa pessoa. (R)

7.5. Appendix E. Phantom sensation/pain questionnaire (English and Portuguese)

Pain Sensation

38. **In the previous week, how much pain did you feel? / Na semana anterior, qual a intensidade de dor sentida?**
Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Painless / Sem dor	◯	◯	◯	◯	◯	◯	◯	Extreme pain / Extrema dor

39. **At this time, how intense is the pain felt? / Neste momento, qual a intensidade de dor sentida?**
Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Painless / Sem dor	◯	◯	◯	◯	◯	◯	◯	Extreme pain / Extrema dor

40. **How often does pain or phantom sensation happen? / Com que frequência, A dor ou sensação fantasma acontecem?**
Marcar apenas uma oval.

- ◯ Sometimes per week / Algumas vezes por semana
- ◯ Sometimes per day / Algumas vezes por dia
- ◯ Sometimes per hour / Algumas vezes por hora
- ◯ Constante / Constante

41. **How long does the pain / sensation last or could it last? / Quanto tempo dura ou poderá durar a dor / sensação?**

____

42. **How do you describe the pain / sensation felt? / Como descreve a dor / sensação sentida?**

____
____
____
____
____

43. **How do you rate sensation after the intervention? /Como classifica a sensação depois da intervenção?**
Marcar apenas uma oval.

	1	2	3	4	5	6	7	
Get worst / Pior	◯	◯	◯	◯	◯	◯	◯	Improved / Melhor

7.6. Appendix F - Patient Semi-Structured Interview (Portuguese)

Entrevista	
O que achou deste sistema de uma maneira geral?	Bom, divertido e dá entusiasmo.
Achou o sistema de uso fácil? Sentiu alguma dificuldade enquanto usava?	O sistema é fácil que até para uma criança.
Na sua opinião, o que acha que poderia ser melhorado no jogo?	Poderia ter diferentes movimentos com a perna e com a bola. Melhorar o tempo e conseguir ver o tempo parecido com a pontuação ou em vez da pontuação. Proporcionar diferentes velocidades de bola influenciada com a força ou rapidez com que a pessoa chuta a bola. Ser um jogo mais dinâmico.
Sentiu que o tempo de resposta foi rápido ou lenta quando fazia os movimentos de perna?	Dentro da média, por vezes acontecia de não chutar o que pode depender/influencia o tipo de pessoa.
Este é um jogo de futebol. Tem alguma ideia de outro tipo de jogos que poderiam ser feitos deste género, que seja necessário usar a perna?	Um jogo de bicicleta. Ter algo relacionado com música ou ter música, também ajudaria no ambiente. Experimentar algo com sons na bola ou com outro tipo de sensação/estimulo.
Acha/Pensa que um sistema deste tipo poderia ajudar na reabilitação?	Depende da maneira como a pessoa encara. É um jogo mais de passa tempo, mas não deixa de ter as suas funções a nível de estudos. Sim, em princípio seria interessante ter algo deste género. Ajuda a distrair a pessoa dando outro complemento.
Na sua opinião. Você sentiu alguma diferença a nível da dor ou sensação fantasma? Por exemplo, se sentiu alguma sensação na perna que não existe, como comichão ou dentro deste género durante estas últimas semanas?	Quando uma pessoa está a jogar fica sempre concentrada que até se esquece de tudo, isto já é um sinal bom. Em termos de sentir em casa ou fora daqui, a nível da sensação e dor fantasma até parece que melhorou um pedaço.
Sentiu ou viu algum defeito enquanto interagia com o jogo?	Não, não senti nada. Desde a primeira vez até a última correu tudo bem. Não senti nada fora do normal.
Sentiu alguma dor ao iniciar ou durante?	Não, a pessoa fica completamente abstraída e concentrada que não sente.
A nível mais pessoal, o senhor ajudou-nos e sente que o nosso trabalho pode ajudá-lo de alguma forma?	Sim, eu entretive com isto. Foi algo maravilhoso, divertido e diferente.

7.7. Appendix G – Results from technical validation study

		Intrinsic Motivation Inventory (IMI)									
		Interest		Perceived competence	Effort	Tension		Choice		Value	Relatedness
		I1	I2*	PC1	E1	T1*	T2	C1	C2	V1	R1*
Person	p1	6	7	7	7	1	1	6	1	7	3
	p2	5	6	6	4	2	1	5	1	7	4
	p3	7	7	7	7	1	1	1	1	7	7
	p4	6	7	6	5	1	1	5	1	7	4
	p5	5	6	6	4	1	2	4	4	4	4
	p6	7	7	7	7	4	5	1	1	7	7
	p7	7	7	7	7	1	1	7	7	7	7
	p8	5	3	6	6	2	2	6	2	6	5
	p9	6	6	5	3	3	1	4	1	6	5
	p10	6	7	3	6	2	4	6	2	6	6
	p11	6	3	6	6	1	2	3	6	6	3
	p12	6	7	6	6	2	2	1	6	7	4
Mean per question		6	6,08	6	5,67	1,75	1,92	4,08	2,75	6,42	4,92
Mean per category		6,04		6	5,67	1,83		3,42		6,42	4,92
***(R) – reverse questions mean they are subtracted.**											

		Presence Questionnaire (PQ)											
		Control			Sensory			Distraction			Realism		
		C1	C2	C3	S1	S2	S3	D1*	D2*	D3*	R1	R2	R3
Person	p1	6	4	5	5	5	6	3	1	6	6	5	7
	p2	6	6	5	5	4	6	6	2	6	6	5	6
	p3	7	7	7	7	7	7	6	1	7	7	7	7
	p4	7	6	6	5	6	6	3	3	3	6	6	6
	p5	6	6	6	5	4	6	4	2	7	6	5	7
	p6	7	3	7	5	7	7	3	1	7	4	6	7
	p7	7	1	7	7	7	7	5	1	7	7	7	7
	p8	5	6	5	5	5	6	2	2	3	6	5	6
	p9	7	5	5	6	7	6	3	2	7	6	5	7
	p10	5	5	5	5	4	5	3	6	6	5	2	5
	p11	5	5	6	5	5	5	3	3	6	5	4	5
	p12	7	4	6	5	3	6	7	2	7	5	3	6
Mean per question		6,25	4,83	5,83	5,42	5,33	6,08	4	2,17	6,00	5,75	5	6,33
Mean per category		5,64			5,61			4,06			5,69		
Total Presence		4,92											
(R) – reverse questions mean they are subtracted.													

		System Usability Scale (SUS)										
		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Total
Person	p1	4	4	1	4	5	3	5	1	4	4	72,50
	p2	4	3	2	3	4	4	2	4	4	5	57,50
	p3	5	1	1	1	5	1	5	1	5	5	100,00
	p4	5	2	2	2	5	1	5	1	5	5	92,50
	p5	4	2	2	2	5	3	5	2	3	5	77,50
	p6	5	1	1	1	3	1	5	1	4	5	92,50
	p7	5	1	1	1	5	1	5	3	5	5	95,00
	p8	3	3	2	3	4	1	4	1	4	4	72,50
	p9	4	1	2	1	4	5	4	2	4	5	75,00
	p10	4	2	1	2	5	4	4	1	4	5	80,00
	p11	4	2	2	2	5	3	4	1	4	4	77,50
	p12	4	1	1	1	5	4	5	3	4	5	82,50
									Mean			81,25
									Deviation			11,99

7.8. Appendix H – Results from clinical validation study

		Intrinsic Motivation Inventory (IMI)									
		I1	I2*	PC1	E1	T1*	T2	C1	C2	V1	R1*
Session	S1	6	7	6	6	2	2	5	1	7	2
	S4	7	7	6	7	1	1	6	1	7	2
	S8	7	7	7	7	1	1	2	1	7	6
Mean		6,67	7,00	6,33	6,67	1,33	1,33	4,33	1,00	7,00	3,33
Mean by Category		6,83	6,33	6,67	1,33	2,67	7,00	3,33	6,83	6,33	6,67
*(R) – reverse questions mean they are subtracted.											

		Presence Questionnaire (PQ)											
		C12	C23	C3	S12	S2	S32	D1*	D2*	D3*	R1	R2	R3
Session	S1	6	6	6	6		6		1	2	6	6	
	S4	6	7	7	7		7		2	1	6	6	
	S8	7	7	7	7		7		1	1	7	7	
Mean		6,33	6,67	6,67	6,67		6,67		1,33	1,33	6,33	6.33	
Mean by category		6,56			6,67			1,33			6,33		
Total Presence		5,22											
*(R) – reverse questions mean they are subtracted.													

		System Usability Scale (SUS)										
		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Session total
Session	S1	1	4	4	2	5	1	5	1	5	5	82,50
	S4	1	4	4	2	5	1	5	1	5	5	82,50
	S8	1	4	4	0	5	1	5	0	5	5	75,00
										Mean		80,00

7.9. Instructions for setup and use the ReLiPh approach.

How to setup and use ReLiPh approach?

1 Oculus Rift Device

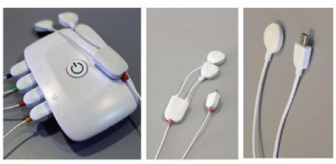
oculus

Start by connecting the oculus rift. You must connect the three USB cables to the USB 3.0 ports (indicated by blue) and the HDMI cable.

Start the oculus rift program following the instructions that appear on the screen.

*Note: If the instructions or need to do manually, select **devices** in the left menu, click on **Configure Rift**, then select **Sensor Setup**.*

2 BiosignalsPlux Device

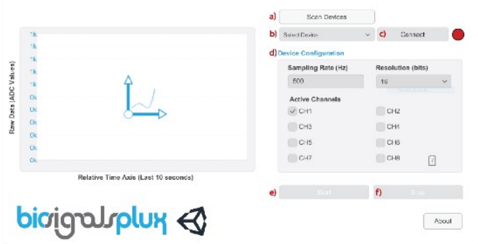


In order to use Biosignals correctly, make sure you have the device, the Eletromyography (EMG) cable(s), Ground cable and electrodes.

Connect the EMG cable(s) to the channel numbers (from 1 to 4) and the ground cable connected to the fround channels (indicated by the Arrow⬇).

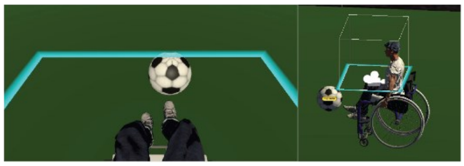
3 ReLiPh Software

Launch the ReLiPh software, your home page will have the Biosignals interface (similar to the one shown).



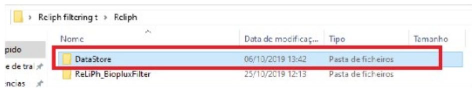
Turn on the computer's bluetooth and start the biosignals device (by pressing the button on top of the device). Next, scan (a.) dor the device.

The number corresponding to the device will be automatically filled in as soon as connected (b.), then click on Connect (c.). In the device configuration (d.), Place the Sample Rate at 300 Hz, with Resolution at 16 bits. Finally, select the channels you are using (indicated by the numbers on the device). Start by pressing start (e.).



To play switch cameras, where 1 is the biosignals interface and 2 the game camera on your keyboard.

To end the experiment, press 1 (on the keyboard) to click Stop (f.) And Disconnect (c.). Thus being able to close all applications and the game.



Note: All physiological signal files will be stored in the DataStore inside the game folder (ReLiPh filtering> ReLiPh).