HOLOLIMB

Advanced User Interfaces

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Professor: Franca Garzotto

Tutors: Francesco Vona, Alberto Patti, Luca Pieri

Abstract

Nowadays Mixed Reality (MR) has been introducing several applications in the rehabilitation of people with physical diseases. The main advantage in the context of therapies is the possibility to maintain a physical and psychological relationship with the surrounding environment while experiencing customized multimedia content and tasks that are characteristic for the needs of these specific users. The target of this work is to apply a MR solution in the case of patients with an upper-limb amputation in order to mitigate or eliminate the pain or discomfort caused by Phantom Limb Sensations (PLS). *Hololimb* application, is developed for Microsoft HoloLens 2 and offers a non-invasive procedure providing two main modalities: a *Free Mode* and a *Therapy Mode*. Furthermore, it implements different questionnaires through which therapists and researchers can gather data and feedbacks to see possible benefits and develop new treatments. This paper discusses the design and technology features that characterize *Hololimb* application.

Keywords

Mixed Reality, Phantom Limb Sensation, Therapy, Human-Computer Interaction

The Team:

Carlo Leopoldo Reinotti

- carloleopoldo.reinotti@mail.polimi.it
- +39 3665335693
- Human-Computer Interaction & Design (EIT Digital)

Enrico Sarneri

- enrico.sarneri@mail.polimi.it
- +39 3661656355
- Computer Science and Engineering

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1. Introduction

Recent scientific and technological advances have seen Mixed Reality (MR) taking a central role in the treatment application of several disorders, thanks to its capability to improve visualization of real-world images, to add viewpoint flexibility as well as the possibility to render customizable objects for the needs of the user and to completely involve the user in an immersive experience. But before continuing, what is MR? Let's try to define it.

MR is defined as a blend of real and virtual words to produce new environments and visualizations, where both digital and physical objects co-exist and interact in real time: in this way it unlocks natural and intuitive 3D human, computer, and environmental interactions, as we can figure out from Figure 1. MixConsequently, thanks to the combination of these three essential elements we set the stage for creating true mixed reality experience. As we move to through the physical world, out movements are mapped in a digital reality. Physical boundaries influence mixed reality experiences, such as games or task-based guidance in a manufacturing facility, in the digital world. With environmental input and perceptions, experiences start to blend between physical and digital realities.

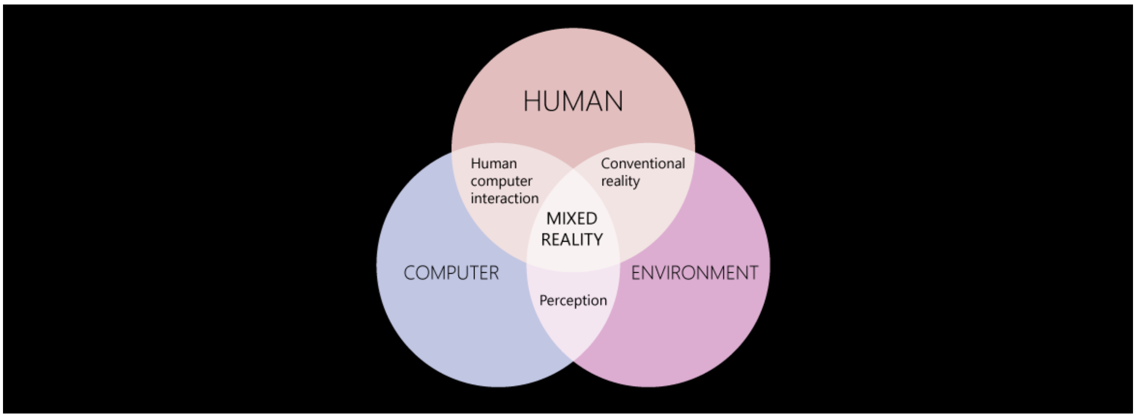


Figure 1. Mixed Reality environment.

Indeed, differently from Virtual Reality (VR), which immerges the users in a fully virtual world without the awareness of the physical reality around them, and Augmented Reality (AR), where users remain present in the physical world, with information or objects added virtually like an overlay, MR acts in a different way. It unifies these two concepts bringing all the user experience to a next level with the introduction of environmental understanding (spatial mapping and anchors), human understanding (hand-tracking, eye-tracking, speech-input), spatial sound, locations and positioning in both physical and virtual space and collaboration on 3D assets in mixed reality spaces. In Figure 2. Virtuality Continuum.we can observe the so-called *virtuality continuum*, a spectrum where we have the subjects taken in consideration in the previous lines which aims at clarifying how they are integrated between each other.

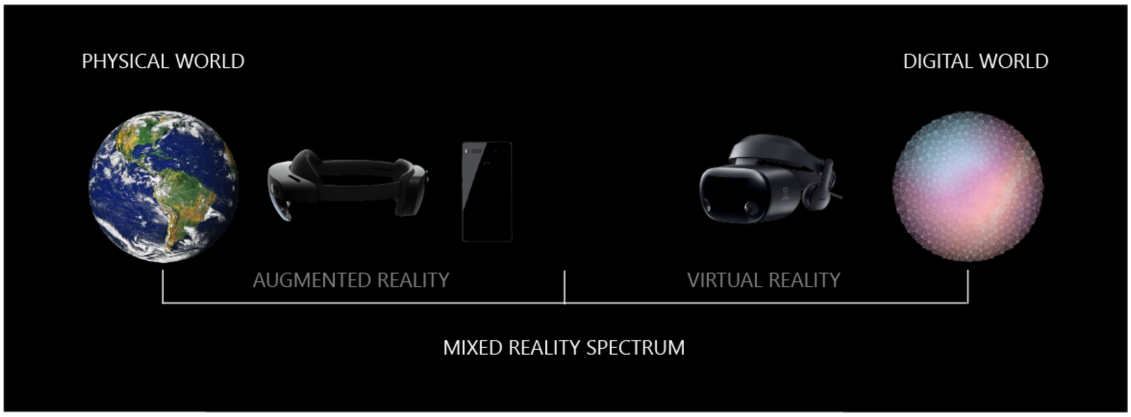


Figure 2. Virtuality Continuum.

Thanks to these specific characteristics, MR has recently seen its application also in healthcare field, leading to several advantages. First, it enhances the patient experience enabling individualized treatment plans, accelerated clinical diagnosis, and improving outcomes. It also empowers doctors and clinicians to rapidly share imaging results, better contextualize physician-patient conversations, and drive more informed patient decision-making, improving quality of care and the patient experience. Secondly, we can provide faster and better care at lower costs by deploying it before, during, and after procedures. We can also enable innovative telehealth solutions to improve care coordination, expand provider access, and address skill shortages. Moreover, we can facilitate continuous learning and widespread knowledge sharing. Doctors, nurses, technicians can train and practice using simulated training, ensuring the entire organization keeps pace with advances in science and technology. Finally, it will strengthen care teams allowing them to collaborate remotely and conduct virtual patient consultations with real-time spatial information to accelerate diagnosis and reduce time-to-treatment.

In this project, we applied MR to one family of physical disorders that could benefit the most from this innovation process: patients with an upper limb amputation. Upper limb amputation is the removal of any part of the upper extremity by surgery, trauma, or pathology. Standard levels of amputation include removal of any part of the arm, forearm, hand, or digits. A major limb amputation is generally considered any amputation at or above the wrist. In general, men are more at risk for amputations related to trauma. Traumatic amputations most commonly are from machinery accidents, explosions, self-inflicted injury, motor vehicle collisions, assault, and work-related injuries. Other risk factors include exposure to thermal and electrical injury, frostbite, and dysvascular disease.

An important aspect is the one of the disease progressions, including natural history, disease phases and disease trajectory. All these factors influence the resulting therapy approach. Generally, traumatic amputations have an abrupt disease process, unless a period of limb salvage is attempted prior to amputation surgery. Many trauma patients are younger and without age-related comorbidities, enabling optimal recovery. However, some complications can arise including delayed wound healing, retained foreign body, infections, vascular injuries, and blood loss. Together with the above, Phantom Limb Pain/Sensation (PLS) is one of the most common associated conditions and complications that report most of the patients.

PLS is pain that is felt in the area where an arm or leg has been amputated. The exact cause of PLS is still unclear, but it appears to come from the spinal cord and brain. Many experts believe PLS may be at least partially explained as a response to mixed signals from the brain. After an amputation, areas of the spinal cord and brain lose input from the missing limb and adjust to this detachment in unpredictable ways. The result can trigger the body's most basic message that sometimes is not right: pain. Other studies show that after an amputation the brain may remap that part of the body's sensory circuitry to another part of the body. Indeed, since the amputated area is no longer able to receive sensory information, the information is referred elsewhere. For example, from a missing hand to a still-present leg. In this case, when the leg is touched, it's as though the missing hand is also being touched. Because this is yet another version of tangled sensory wires, the result can be pain.

Furthermore, it has been demonstrated that some factors may increase the risk of phantom pain. First, pain before amputation. This may because the brain holds on to the memory of the pain and keeps sending pain signals, even after the limb is removed. Secondly, residual limb pain. It can be caused by an abnormal growth on damaged nerve endings that often results in painful nerve activity.

PLS can be mild to agonizing and even disabling for some, also leading to a lifelong battle with chronic pain. Some patients are reported to experience different sensations such as tingling, cramping, heat, cold, and squeezing along with pain. A person can feel any sensation in the portion of the limb that was removed that the limb might have experienced before it was removed. It's possible to also have residual pain or "stump pain" at the actual site of the amputation, reporting cramping, burning, aching, or sensations of heat or cold in the residual limb.

Traditional treatments for this problem focus on easing symptoms and involve medications in a first moment and then may add non-invasive o more invasive therapies. More innovative, but still exploratory, approaches use VR and AR mirror therapy treatments in order to mitigate PLS sensation providing an immersive experience for the amputee. However, there is not currently a consensus on the efficacy of VR and AR therapies.

Our research addresses this aspect suggesting a MR non-invasive approach based of visual feedback that creates a 3D virtual embodied holographic model stemming from the stump to substitute the missing upper limb, making the model gradually disappear. The advantages obtained from this specific treatment are the non-occlusion of the visual field (the user remains in a real context) that allows to focalize only on the 3D model, greater realism and tracking of the model with respect to AR/VR approaches, and possibility to interact with the hologram adapting and modifying it following personal sensations. In addition, we proposed two different pain questionnaires which have the purpose to gather useful data and feedbacks for the therapists and researchers in order to infer statistics and develop new treatments.

The rest of the paper is organized as follows: we will firstly address the State of the Art. Then, in Chapter 3 we will see the main requirements. In Chapter 4 and 5 we will introduce the solution from the UX Design and the implementation. Finally, in Chapter 6 we will argue the value proposition as well as our future work.

2. State of the Art

Despite many years of studies and research, most approaches to treatment over the past two decades have not shown consistent symptom improvement. Usually, doctors begin with medications and then may add non-invasive therapies, such as acupuncture. More-invasive options include injections or implanted devices, while surgery is left only as a last resort. Although no medications specifically for PLS exist, some drugs designed to treat other conditions have been helpful in relieving nerve pain. No single drug works for everyone, and it's not sure that medications could bring benefits. A specific patient may need to try different medications to find one that works.

A list of possible medications utilized in PLS treatment is the following:

- Over the counter (OTC) pain relievers
- Antidepressants
- Anticonvulsants
- Opioids
- N-methyl-d-aspartate (NMDA) receptor antagonists
- Over-the-counter medicine
- Beta blockers
- Muscle relaxers

However, medicine alone may not provide enough relief, so the doctor may recommend other treatments as well. In this case non-invasive medical therapies come to the aid and, as well as the previous case, there's not a general solution universal valid, it's a matter of trial and observation. Here is a list of possible techniques that may relieve PLS for some people:

- Mirror Box Therapy: It is a therapeutic intervention, which has been shown to affect motor and sensory processes through the relative dominance of the visual input it provides. The effect is created by viewing a reflection of the intact limb, through a mirror placed where the amputated limb would have existed. Most of the evidence for this intervention come from case studies and anecdotal data with only a couple of well controlled studies. While mirrored movements may expose the cortex to sensory and motor input, the therapeutic effect is magnified if cortical networks are gradually activated using limb recognition, motor imagery and finally, mirrored movements.
- Transcutaneous Electrical Nerve Stimulation (TENS): It is a therapy that uses low voltage electrical current to provide pain relief. The device delivers electrical impulses through electrodes on the surface of the skin. The electrodes are placed at or near nerves where the pain is located or at trigger points. The idea is that it can interrupt pain signals before they get to the brain.
- Spinal Cord Stimulation: The doctor will put tiny electrodes inside the body of the patient along the spinal cord and send a small electrical current through them.
- Brain Stimulation: It works similarly to the previous case, but here the electrodes send the current to the brain instead. A surgeon will place the electrodes in the right spot in the patient brain.
- Acupuncture: In this case, a skilled practitioner will insert a very thin needles into the patient skin at specific places. This can prompt the body to release pain-relieving chemicals.

Furthermore, newer approaches to relieve PLS include VR and AR, as discussed in (Justin Dunn) and (Thomas Rutledge, 2019) .In these cases the use of VR and AR technologies for the treatment of PLS reported improvements in pain severity resulting from both brief and repeated VR/AR treatment protocols, along with low rates of adverse effects, although the strength of these findings was limited by small samples, old technologies and lower-quality study designs. Like other chronic pain conditions, VR/AR treatments could benefit patients with PLS through general therapeutic mechanisms for pain and through PLP-specific neurological mechanisms. VR and AR work simulating the same limb illusion provided by mirror therapy using virtual environments. They can also incorporate gaming elements into PLS treatment to theoretically increase patients' enjoyment of the experience, potentially improving adherence, and can be configured to multiple kinds of amputations (e.g., upper body, lower body, bilateral amputee populations).

Despite the fact that both VR/AR approaches proved to have advantages for individuals with PLS, thanks to their increasing levels of immersion, customizable environments, and decreasing cost, there are some limitations. First of all, the two approaches are characterized by a lack of a total or partial vision of the surrounding, the scope of vision is not full, only partial at most. Then, the experiences are isolating and individual without integrate or involve other figures as the medical staff. Moreover, the technology should also be equipped with a better understanding of natural body movements, ensuring that the displays get lighter and thinner. Finally, all the studies were confined purely to case studies and case report series. No studies of higher evidence have been conducted, thus considerably limiting the strength of the findings.

These points will be addressed by the application we are going to present in this paper, *Hololimb*, which will supply those limitations adopting a MR approach. The interaction logic of *Hololimb* is simple as well as the user interface that is easy and minimal so that it can be utilized and understood by the largest possible number of heterogeneous users. Still, the experience has been explicitly designed to stimulate both self-trained therapy and sanitary operator-interactions during the guided mode, where the operator will suggest different parameters to put in input during in the auto-faded transparency process. Interaction requirements are really minimums, and the application favors visual feedback as well as a data collection useful for future research. The current version of *Hololimb* is presented in the current paper through the following sessions, but several future developments and integration will be effectuated in order to refine the technique and improve the quality of the approach.

3. Requirements

3.1. Stakeholders

The final users of the application are **patients** with an upper-limb amputation and PLS and **sanitary operators** of private clinics. The first ones will be the primary subjects for the treatment and those directly involved in the MR experience, while the second ones will have the role to supervise the entire therapy session helping the patient wearing the equipment and configuring it, suggesting him the right parameters to put in input during the "Therapy Mode", assisting him in case of troubles, and collecting feedback and data from the patient himself and from the questionnaires provided. The secondary stakeholders for this work are **researchers** and **private clinics**. The first ones, through the gathering and the study of feedback and data questionnaires, will have to infer statistics and provide conclusions and discussions about the possible advantages and disadvantages of such therapy. Private clinics, from the other side, will be directly involved in all the process since their role of is fundamental in order to test experimental approaches and modalities and discover possible future benefits from treatments.

3.2. Needs

The primary need for the **patients** is to eliminate or decrease discomfort caused by PLS and try to receive benefits from the new MR approach. The **clinic sanitary operators** need help the patients to undergo the treatment and provide them support in terms of physical and knowledge assistance. The **researchers** need to gather data and feedback from the questionnaires to which the patients are submitted at the end of the session. The **private clinics** need to offer useful and result-oriented treatments to the patients in order to reduce PLS.

3.3. Goals

The main goals the application wants to achieve are the following:

1. Provide a treatment based on visual feedback
2. Replace the lost arm with a 3D virtual model
3. Give the impression to the patient that the model of the arm is disappearing
4. Provide a way to collect and store feedback during the sessions
5. Enable the sanitary operator to guide the patient during the sessions

3.4. Context

Our application will be used during therapeutic sessions in private clinics for patients with an upper-limb amputation. The session will be taken inside the clinic's structure, will be supervised by a sanitary operator that will assists the patient for every need. In order to reach possible results and benefits a single session won't be enough with all the probabilities. As a consequence, several repeated sessions will be scheduled by the sanitary operator according to what he considers most appropriate in order to reach results and benefits for the patient himself.

3.5. Constraints

- **Time Constraints**: Our target was to deliver the project by the end of the first semester of A.Y. 2021/2022. We started to develop our application at the beginning of the first semester. Developing, experimenting, testing and creating documentations took roughly 4.5 months. We started tutor sessions in mid-October 2021 and complete the project in February 2022. The team is composed by two people with both solid Java and C-like languages knowledge but little experience in Unity and Mixed Reality design, thus we had to dedicate some time to learn and to be familiar with the environment.
- **Space Constraints**: The patient must sit on a chair and stay still in order to receiving benefits from the therapy. What he has to do is trying to fit his amputated upper limb to the 3D hologram model in order to have the feeling that the arm is completely present.
- **Technological Constraints**:
    1. The experience involves only the patient and not the sanitary operator, since only one device was available. In this case the operator cannot see the 3D model and must base his advice and suggestions only on what the feedback from the patients are. A shared MR experience would favor the interaction between the two stakeholders and would provide several advantages from both sides.
    2. Delay in the streaming of what the patient is seeing from the MR experience.
    3. Microsoft HoloLens 2 has a spatial mesh limit. If for example the user is simply walking around and scanning the rooms, then downloading the mesh via 3D view, only a portion of the room is scanned, resulting in an incomplete final mesh.
    4. Microsoft HoloLens 2 battery duration.
    5. Loss of connection. In order to receive the feedbacks from the questionnaires, the application will output a .json file on the Windows Device Portal (WDP). The process is allowed thanks to Wi-Fi connection. In case of loss of connection this feature won't be available and the data from the questionnaires won't be reachable.

3.6. Functional Requirements

In this section we list the general requirements necessary to the correct behavior of the application. The application has to be comprehensible by as many people as possible, so we decided to use English as the main language of the application.

1. The application has to start with an initial screen from which to begin the session.
2. The application has to offer the possibility to choose which arm utilize for the session.
3. The application has to display the correspondent 3D model of the selected arm.
4. The application has to display a main menu from which to choose the main functionalities (Configuration, Free Mode and Therapy Mode).
5. The Configuration menu has to offer the possibility to modify the size of the arm model.
6. The Free Mode has to offer the possibility to modify the positions of the arm model joints.
7. The Free Mode has to offer the possibility to modify the arm model transparency.
8. The Therapy Mode has to offer the possibility to choose starting and ending levels of arm model visibility.

9. The Therapy Mode has to offer the possibility to choose the time duration of fading process.
10. The Therapy Mode has to apply the input parameters and perform the auto-fading process.
11. The application has to offer the possibility to choose between two kinds of questionnaire.
12. The questionnaires have to display the single questions.
13. The single questions have to offer the possibility to move sliders and select correspondent parameters.
14. The application has to offer the possibility to save the resulting values of questionnaires inside Windows Device Portal.

3.7. Non-Functional Requirements

Below we are listing some requirements that are necessary in general to guarantee a functional application.

- **Portability**: The application should be extended to different MR devices in order to be used by the possible largest number of clinics in several contexts.
- **Stability**: The application should always be available at any time it is needed. Failures of the system and server-side crashes must be avoided in order to guarantee a correct and fluent process.
- **Availability**: The system must always be ready to be used even during a failure period. A backup facility must be present in order to do so.
- **Reliability**: Data must be reliable, so the remote repository where the questionnaire data are stored must be secure to satisfy this requirement.
- **Efficiency**: The application needs to use the least number of resources possible. Algorithms and data structures should be used as efficiently as possible to do so.
- **Extensibility**: The application should allow further extensions in the simplest way, without modifying the core functionalities.
- **Maintainability**: The application code should be well written, reliable, and well documented, making easier to be changed or extended by future programmers.

4. Solution – UX Design

4.1. General Approach

The solution proposed by the application exploits the usage of MR through the wearing of Microsoft HoloLens 2 device. Our application can be considered an enhanced environment app thanks to MR's ability to let users place digital information or content in the current environment. This approach is popular for those applications where the contextual placement of digital content in the real world is paramount and keeping the user's real world environment present during their experience is key. Users can also move between real world digital tasks with ease. This lends even more credence to the promise that the mixed reality apps the user sees are truly a part of the environment.

Now we'll see the main interaction paradigms the patient can do in our application. Firstly, we have a **Start Gesture**, that is a hand gesture used to invoke the Start Menu through a one-hand gesture. Holding out the hand with the palm facing ourselves, looking at the start icon on our inner wrist and pinching our thumb and index finger together we are able to start the application. Then, the entire application is based on **Hands and Motion Controllers** together with **Eye Tracking and Head Gaze**. This builds a consistent UX across tracking and 6Dof controllers. Thanks to hands and motion controllers the patient will see a hand mesh a fingertip affordance or hand/controller rays and will see grabbable handles, or bounding box appears when the hands are near the object. Thanks to head-gaze the patient will see a cursor in the center of the field of view and will see a progress indicator when he dwells on an interactable object.

The application will allow both direct manipulation with hands together with point and commit with hands. Thanks to the first modality, we are able to directly touch holograms and interact with them. The idea behind this concept is that objects behave just as they would be in the real world. We will have **Collidable Fingertip** to implement the idea of touching holograms, a F**ingertip Cursor** (fingertip cursor far, fingertip cursor near, fingertip cursor contact), **Bounding Boxes** (hover far, hover near, contact begins, contact ends) with proximity shader, **Pressable Buttons** (finger is far away, finger approaches, contact begins, press down), **2D Slate Interaction**, **3D Objection Manipulation** (move, rotate, scale). The second modality, from the other side, empowers patients to interact with holograms in a distance. It enables patients to make the best use of surroundings. They can place holograms anywhere and still access them from distance thanks to **Hand Rays** (hand ray that shoots out from the center of the user's palm) and **Transition Between Near and Far** (when an object is within arm's length, the rays are turned off, encouraging near interaction, and vice versa).

The principal contents the patient will have to interact with are the following. An initial **Button Choice** through which select the desired arm. A M**ain Menu** through which to choose the desired modality among **Free Mode**, **Configuration**, and **Therapy Mode.** The 3D M**odel of the Arm** to manipulate, change in size, transparency, and joints positions. A **Therapy Settings Menu** through which to select the correspondent values for the guided and automated process of transparency fading with sliders. Two different slate panels characterizing **Pain Questionnaires** with which the patient will provide personal feedback and sensations useful for post-therapy analysis and evaluations. This process will be allowed thanks to the interactions with sliders and dialog panels.

4.2. User workflow

The following Flow Diagram describe at high level a typical interaction the patient can have with the application together with linked activities and tasks.

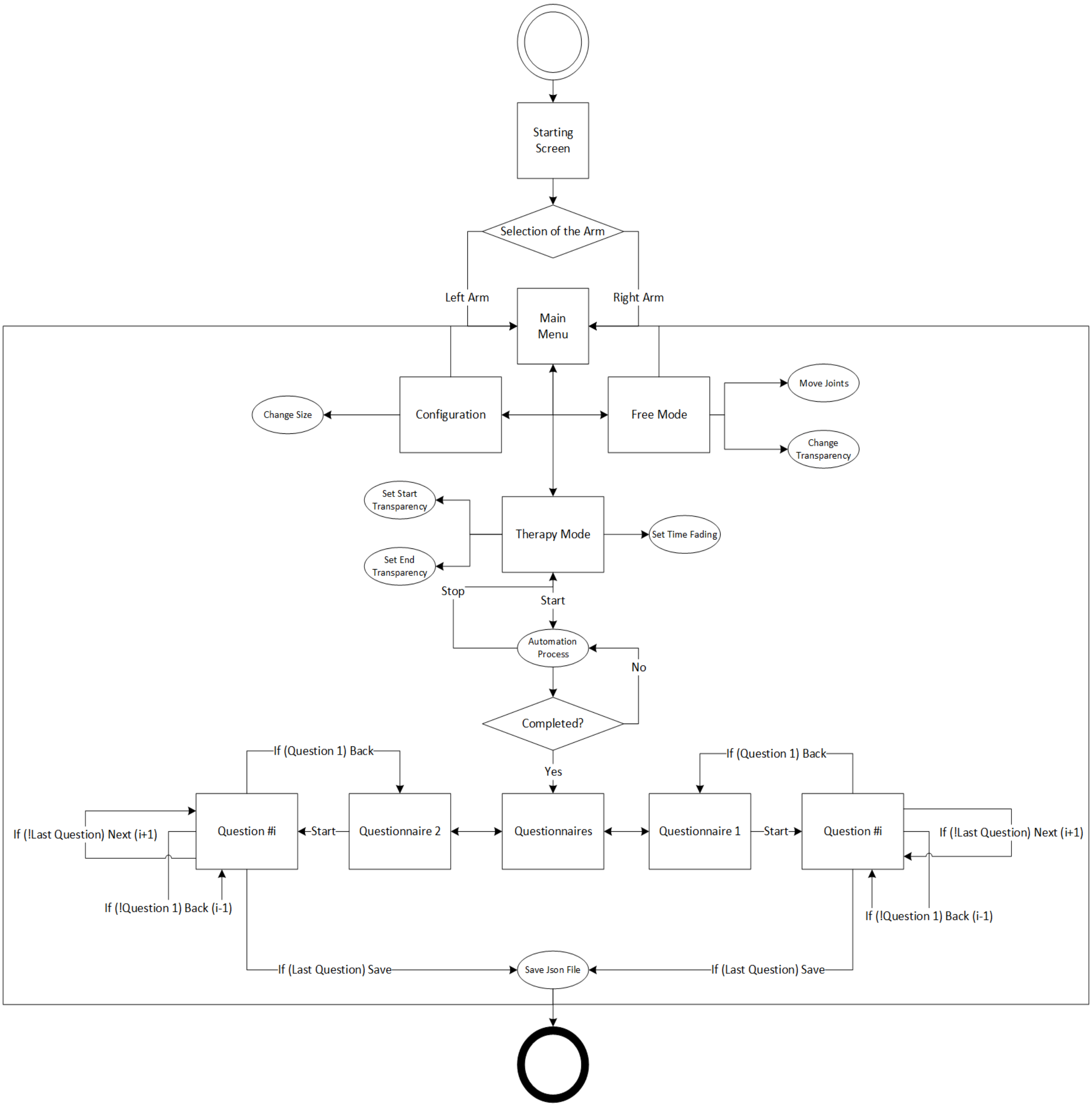


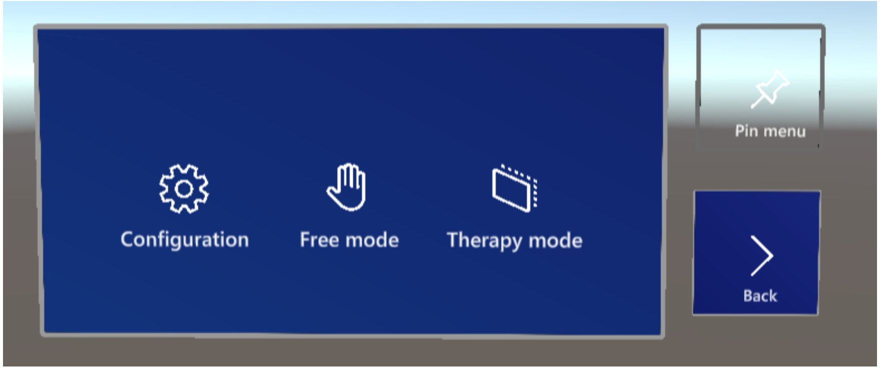
Figure 3. Flow Diagram

4.3. Scenarios

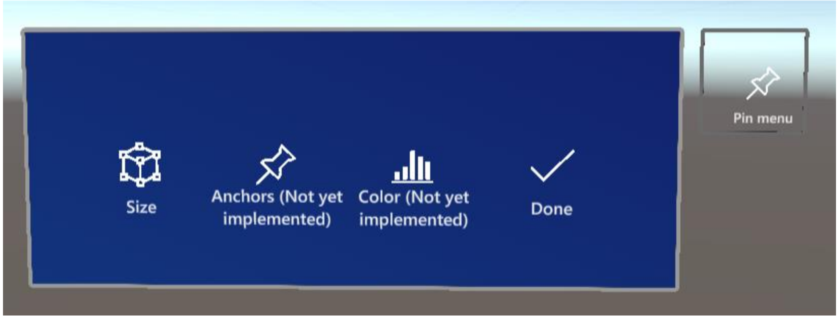
- **Starting Screen:** This screen appears as soon as the patient starts the application from HoloLens 2. Here he has the possibility to choose to begin the experience with *Hololimb.*

- **Arm Choice:** This screen appears when the patient decides to start the experience from the previous screen. In this case he will have the possibility to choose the preferred arm according to his needs. The selected arm will be kept for the entire duration of the experience unless he decides to go back to this screen and change it.

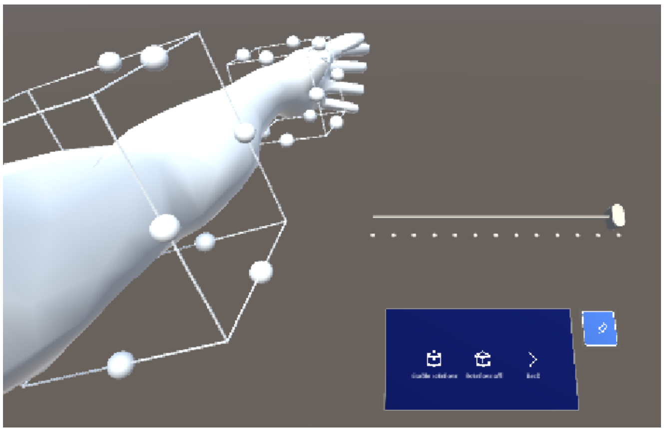
- **Main Menu:** This screen appears as soon as the patient selects the desired arm. We can see that the arm is already displayed in the reality. From this menu the patient can choose the desired functionality among "Configurations", "Free Mode" and "Therapy Mode".



- **Configuration:** This modality is activated when the patient selects the correspondent button from the previous described menu. In this case, a new options menu will be displayed together with the arm model that will remain present in the reality. Here, the patient has the possibility to modify the size of the arm thanks to the bounding box and the manual interactions that characterizes the arm hologram. When the desired size is set, the user can press the "Done" button in order to confirm the decision and be redirected to the "Main Menu".

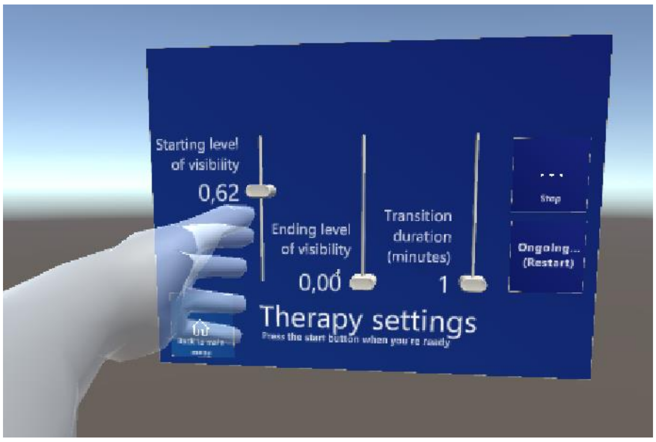


- **Free Mode:** This modality is activated when the patient selects the correspondent button from the "Main Menu". In this case, a new options menu will be displayed together with the arm model. Here, the patient has the possibility to modify the desired transparency of the arm model in order to try the sensations by himself. A confirm button will apply the set value. Moreover, the patient has the possibility to modify the positions of joints in order to reach the best possible fit for his upper limb. When the desire parameters have been set, the patient can return to the "Main Menu".



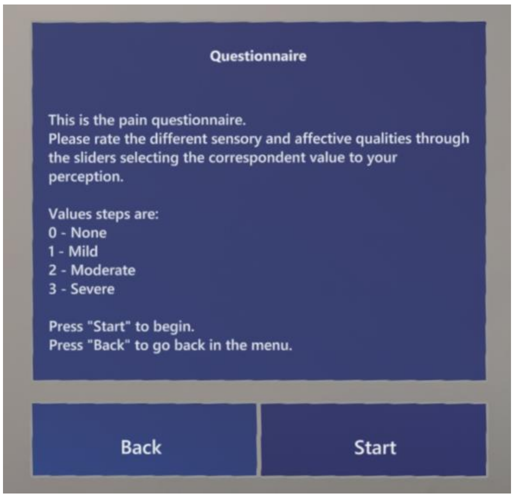
- **Therapy Mode:** This modality is activated when the patient selects the correspondent button from the "Main Menu". In this case, a new interactable menu will be displayed together with the arm model. Here, the patient has the possibility to modify different parameters. The first one is the "Starting level of visibility", an initial value of transparency for the arm model from which start the therapy session. The second one is the "Ending level of visibility", the final value of transparency for the arm model we want to reach at the end of the therapy session. The third one is the "Transition duration" in minutes, so the duration of the therapy session from which the arm model will start with the initial visibility ending to the final one. Moreover, here are also present the buttons for starting or stopping the session. The button for returning back to the "Main Manu" is still present.

- **Started Session:** Here we can see a frame taken from the started therapy session where the arm model starts to fading out reaching the final transparency.



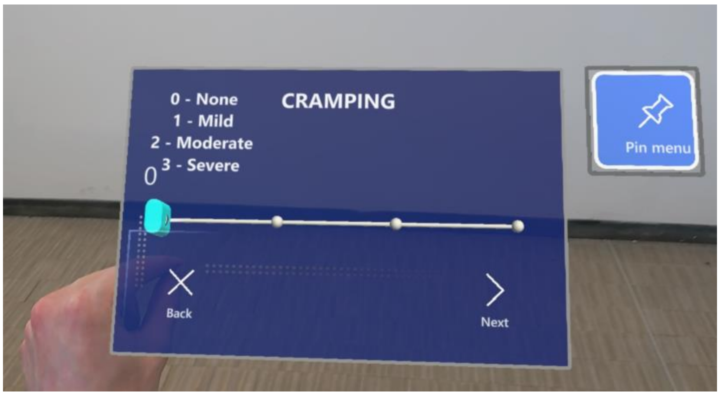
- **Questionnaires Choice**: This screen appears when the therapy session has been entirely completed. In this case, the patient has the possibility to choose the desired questionnaire among the two.

- **Mc Gill Pain Questionnaire:** This screen appears as soon as the patients select the correspondent button from the "Questionnaires Choice". In this case, we see a panel with the general descriptions of the related questionnaire together with a start button to begin the questions and the back button for going back to the "Questionnaire Choice".

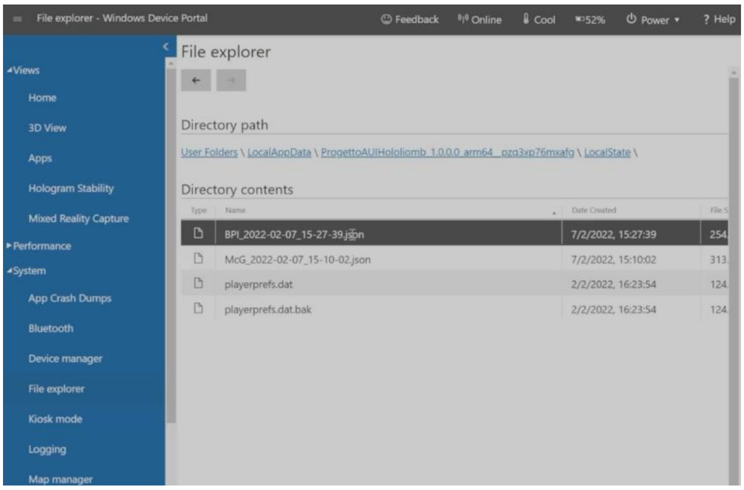


- **Brief Pain Inventory:** This screen appears as soon as the patients select the correspondent button from the "Questionnaires Choice". In this case, we see a panel with the general descriptions of the related questionnaire together with a start button to begin the questions and the back button for going back to the "Questionnaire Choice".

- **Question:** This screen corresponds to the example of one of the questions present in the questionnaires. We can see as it is characterized by a title describing the correspond parameter to evaluate and the scale for the value. The patient will have to move the slider to the desired value. The "Next" button will bring the patient to the next question while the "Back" one to the previous one.



- **Windows Device Portal:** This screen corresponds to the Windows Device Portal. The operator in this case will reach the right folder and will see the .json file that includes all the parameters the patient selected during the questionnaires. The file will be saved with a timestamp together with the name of the correspondent questionnaire. The file will be saved as soon as the patient click "Save" in the last question of each questionnaire.



5. Solution – Implementation

5.1. Hardware Architecture

In this project the main hardware device upon which the entire application is developed is Microsoft HoloLens. It refines the holographic computing journey started by HoloLens (1st gen) to provide a more comfortable and immersive experience paired with more options for collaborating in mixed reality. HoloLens 2 runs on the Windows Holographic OS, which is based on a flavor of Windows 10, that provides users, admins, and developers with a robust, performant, and secure platform. The main component is the visor, which contains the HoloLens sensors and displays and can be rotated up while wearing the HoloLens. All the technical details can be found here: (Abo).

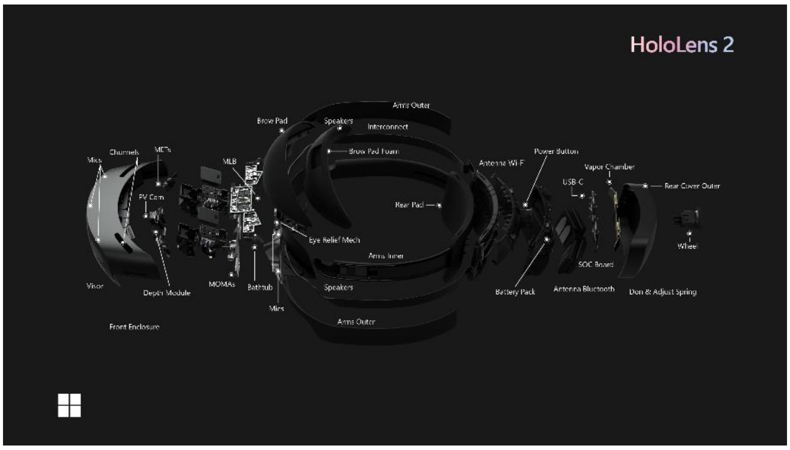
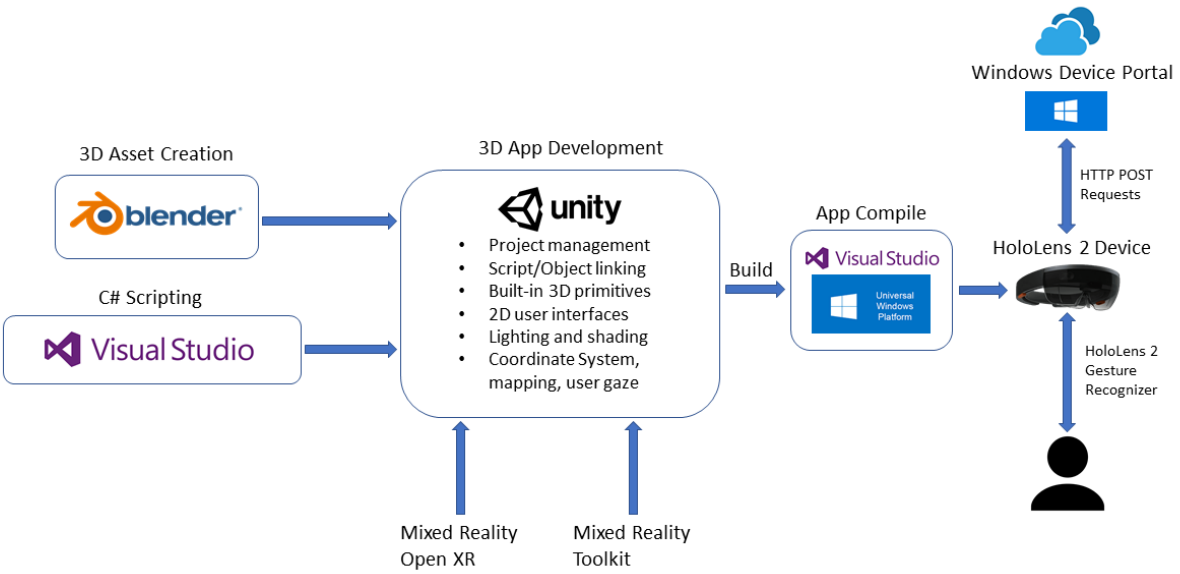


Figure 4. HoloLens 2.

Some benefits that HoloLens 2 brings are to collaborate without boundaries and act with precision to increase productivity. It allows you to stay engaged heads-up, hands free longer and more comfortably with built-in voice commands, eye tracking, and world-anchoring for continuous focus on safely completing tasks without errors.

All the developments as well as the tests and the implementations have been taken with ThinkBook 13s G3 ACN (2.30 GHz, 8 GB) and LAPTOP-6EHETA07 MateBook 14(2.90 GHz, 16GB).

5.2. Software Architecture



The 3D arm model has been designed with **Blender**. Blender is a free and open-source 3D computer graphics software toolset used for creating interactive 3D applications, VR, computer games, motion graphics etc. etc. More info can be found on (Ble).

The application has been developed with **Unity Hub** 3.0.0-beta6 and **Unity** Version 2020.3.11f1.533 Personal. Unity is one of the leading real-time development platforms on the market, with underlying runtime code written in C++ and all development scripting is done in C#. Unity also offers solutions and services for creating games, boosting productivity, and connecting with audiences including the Unity Asset Store, Unity Cloud Build, Unity Game Performance Reporting, Unity Ads, and Unity EveryPlay. For more info check (Uni).

The C# scripts as well as the deploy and debug have been done with **Visual Studio 2019**. It requires to enable the developer mode on the utilized devices, on HoloLens 2 or Windows PC if we're working with a Windows Mixed Reality headset connected to the PC. More info can be found on (Usi).

Universal Windows Platform (UWP) is the way we use to create the client application for Windows. A UWP application uses WinRT APIs to provide powerful UI and advanced asynchronous features that are ideal for internet-connected devices. More info can be found on (Wha).

Through the **Windows Device Portal** we are able to configure and manage the HoloLens device remotely over Wi-Fi. The Device portal is a web server on the HoloLens device that we can connect to from a web browser on our PC. The Device Portal offers many tools that will help to manage the HoloLens and debug and optimize the applications. In this case, we utilized it in order to store the .json file that is created when the patient concludes a questionnaire. The sanitary operator then, will retrieve it in the apposite folder through the PC to which it's connected and collecting all the data,

The main external packages we used are **Mixed Reality Toolkit** (MRTK) and **Mixed Reality Open XR**. The first one, is a Microsoft-driven project that provides a set of components and features, used to accelerate cross-platform MR app development in Unity. The main functions are the following: it provides the cross-platform input system and building blocks for spatial interactions and UI. Then, it enables rapid prototyping via in-editor simulation that allows to see changes immediately. The second one, is an open, royalty-free standard developed by Khronos that aims to simplify AR/VR and MR development by allowing developers to seamlessly target a wide range of devices. More info can be found on (Ope).

6. Value Proposition

This report described the implementation of *Hololimb* application, a customized MR application that aims at proposing a new treatment for patients with PLS. One of the factors that inspired the current work was our own prior experience with mirror therapy for PLS. Mirror therapy has been demonstrated to be effective for PLS reduction, but no more effective than a control psychotherapy condition. It also emerges the difficulties for many patients of traveling to hospital and clinics for treatment sessions, struggles adhering to the mirror therapy exercises, and practical barriers to having the mirror accessible for use during PLS episodes. These facts motivated us to consider MR technology as a means of making treatments more portable, enjoyable, and usable in natural living environments. Still, actual proposals of VR/AR implementations suffer some limitations: they lack of rendered reality and restricted vision field and are characterized by individual user experiences. With a MR approach we are able to have a non-occlusion of the vision-field, so the user will remain in a real context and will focalize on the 3D arm model. Then we get more realism and the possibility to interact with holograms, which give the user the opportunity to fit the personal dimension, testing transparency etc. etc. that will strongly increase the quality of UX and therapy itself, providing more real and effective sensations and feedback.

However, there are multiple factors contributing to the paucity of quality MR for PLS research. MR technology has been financially costly and required technical skills rarely possessed by both pain researchers and in particular sanitary operators. In this direction, successful MR studies, often necessitate collaborations between researchers and MR specialists. Furthermore, the main barrier to reach high-quality MR treatment for PLS, derives from characteristics of PLS itself rather than from the technical challenges. PLS is an intermittent and often unpredictable pain condition that varies markedly in frequency and intensity among amputees. For patients experiencing PLS symptoms that may occur a few times or for short time ranges, a MR treatment must be portable and easy to initiate in order to address the pain in real time. However, the nature of PLS makes it difficult to measure the impact of treatment in a controlled laboratory setting. The suggestions are those of using the treatment regularly, in particular when the patients experience an increase in PLS symptoms or unpleasant phantom sensation. We believe that MR treatments that can reduce PLS intensity may be particularly helpful and valuable for improving patients' quality of life, even though more research and applications have to be tackled in this direction.

There are some important limitations to consider in interpreting this work. Unfortunately, we didn't have the possibility to test the application on real patients due to time constraints and due to the fact that it's not so common and simple to find patients with the specific required characteristics. Consequently, a direct comparison between MR and standard mirror therapy remains a valuable scientific goal for the future to provide a clearer interpretation of the unique benefits. As such, the current use of MR for PLS treatment, while attractive due to the increasing levels of immersion, customizable environments, and decreasing cost, is yet to be completely proven and continues to need further research with higher quality studies to fully explore its benefits.

7. Future Work

Future extension and improvements have already been taken in consideration. First of all, we plan to also implement a tracking system in order to let the 3D model follow the upper limb, giving a more reality experience. In this project we didn't implement it since when the user looked away from his arm, the 3D model disappeared. For that reason, we preferred to leave a fixed model constantly present in the patient field of view avoiding brutal experiences as the sudden disappearance of the model, which would bring him worst consequences. Moreover, we plan an extension in the potential patients through the addition of more types of amputation, from bilateral to lower extremity amputation. We think that these main improvements together with a shared MR experience between the user and the sanitary operator assisting him, will bring much more benefits in the treatment.

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Annexes

In the following section we attach the two main questionnaires that we used in order to retrieve all the patient feedback and personal feelings and sensations. The first one, is the McGill Pain Questionnaire that represents a major revolution in pain research. Pain was mainly described and measured in terms of intensity, but thanks to the MPQ, the qualitative aspect of pain became an important subject in pain research. Pain descriptors were brought together and categorized in three dimensions of pain experience:

- Words that described the sensory qualities of the experience in terms of temporal, spatial, pressure, thermal, and other properties
- Words that described affective qualities in terms of tension, fear, and autonomic properties that are part of the pain experience
- Evaluative words that subjectively described the overall intensity of the total pain experience

Short-Form McGill Pain Questionnaire

Short-Form McGill Pain Questionnaire

PATIENT'S NAME: ______________________ DATE: ______________

	NONE	MILD	MODERATE	SEVERE
THROBBING	0) ____	1) ____	2) ____	3) ____
SHOOTING	0) ____	1) ____	2) ____	3) ____
STABBING	0) ____	1) ____	2) ____	3) ____
SHARP	0) ____	1) ____	2) ____	3) ____
CRAMPING	0) ____	1) ____	2) ____	3) ____
GNAWING	0) ____	1) ____	2) ____	3) ____
HOT/BURNING	0) ____	1) ____	2) ____	3) ____
ACHING	0) ____	1) ____	2) ____	3) ____
HEAVY	0) ____	1) ____	2) ____	3) ____
TENDER	0) ____	1) ____	2) ____	3) ____
SPLITTING	0) ____	1) ____	2) ____	3) ____
TIRING/EXHAUSTING	0) ____	1) ____	2) ____	3) ____
SICKENING	0) ____	1) ____	2) ____	3) ____
FEARFUL	0) ____	1) ____	2) ____	3) ____
PUNISHING/CRUEL	0) ____	1) ____	2) ____	3) ____

VAS NO PAIN |——————————| WORST POSSIBLE PAIN

PPI

0 NO PAIN ______
1 MILD ______
2 DISCOMFORTING ______
3 DISTRESSING ______
4 HORRIBLE ______
5 EXCRUCIATING ______

The short-form McGill Pain Questionnaire (SF-MPQ). Descriptors 1–11 represent the sensory dimension of pain experience and 12-15 represent the affective dimension. Each descriptor is ranked on an intensity scale of 0 = none, 1 = mild, 2 = moderate, 3 = severe. The Present Pain Intensity (PPI) of the standard long-form McGill Pain Questionnaire (LF-MPQ) and the visual analogue scale (VAS) are also included to provide overall intensity scores.

BRIEF PAIN INVENTORY

Data____/____/____ Ora____

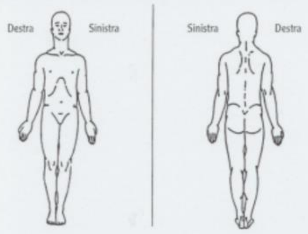
Nome/Cognome____________ ____________ ____________

Dopo Prima Intermedio

1) Nel corso della vita la maggior parte di noi ha avuto di tanto in tanto qualche dolore (come un leggero mal di testa, uno strappo muscolare e un mal di denti). Oggi ha avuto un dolore diverso da questi dolori di tutti i giorni?

1. Sì 2. No

2) Tratteggi sul disegno le parti dove sente dolore. Metta una X sulla parte che fa più male.



3) Valuti il suo dolore facendo un cerchio intorno al numero che meglio descrive l'intensità del suo dolore peggiore nelle ultime 24 ore.

0 1 2 3 4 5 6 7 8 9 10
Nessun dolore — Il dolore più forte che possa immaginare

4) Valuti il suo dolore facendo un cerchio intorno al numero che meglio descrive l'intensità del suo dolore più lieve nelle ultime 24 ore.

0 1 2 3 4 5 6 7 8 9 10
Nessun dolore — Il dolore più forte che possa immaginare

5) Valuti il suo dolore facendo un cerchio intorno al numero che meglio descrive l'intensità del suo dolore in media nelle ultime 24 ore

0 1 2 3 4 5 6 7 8 9 10
Nessun dolore — Il dolore più forte che possa immaginare

6) Valuti i l suo dolore facendo un cerchio intorno al numero che meglio descrive quanto dolore ha in questo momento

0 1 2 3 4 5 6 7 8 9 10
Nessun dolore — Il dolore più forte che possa immaginare

7) Che terapie o medicine sta ricevendo per il suo dolore?

____

____

____

(seguito)

8) Nella ultime 24 ore quanto sollievo ha ricevuto dalle terapie o dalle medicine? Faccia un cerchio intorno alla percentuale che meglio descrive quanto sollievo del dolore ha avuto

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Non interferisce — Interferisce completamente

9) Faccia un cerchio intorno al numero che meglio descrive quanto, nelle ultime 24 ore, il dolore ha interferito con:

A) La sua attività in generale

0 1 2 3 4 5 6 7 8 9 10
Non interferisce — Interferisce completamente

B) Il suo umore

0 1 2 3 4 5 6 7 8 9 10
Non interferisce — Interferisce completamente

C) La sua capacità di camminare

0 1 2 3 4 5 6 7 8 9 10
Non interferisce — Interferisce completamente

D) La sua normale attività lavorativa (include sia il lavoro fuori che in casa)

0 1 2 3 4 5 6 7 8 9 10
Non interferisce — Interferisce completamente

E) Le sue relazioni con le altre persone

0 1 2 3 4 5 6 7 8 9 10
Non interferisce — Interferisce completamente

F) Il sonno

0 1 2 3 4 5 6 7 8 9 10
Non interferisce — Interferisce completamente

G) Il gusto di vivere

0 1 2 3 4 5 6 7 8 9 10
Non interferisce — Interferisce completamente