Therapeutic Virtual Reality for Chronic Pain Treatment

Department of Mechanical Engineering
ENP120: Final Report
SPRING 2019

Prepared by:
Rhea Montgomery-Walsh rhea.montgomery_walsh@tufts.edu
Ryan Biette ryan.biette@tufts.edu

Prepared for: Sami Durrani, James Intriligator

Table of Contents

Introduction

Background/Problem Statement

Complex Regional Pain Syndrome (CRPS) is a condition that affects one or more of the limbs. It is believed to be caused by impairments of the peripheral and central nervous system, distorting the body's perception of pain. Patients suffer from extreme discomfort, swelling, skin discoloration, and changing temperatures in the affected area. To treat patients, clinicians use a technique known as "mirror therapy".

To perform this technique, the clinician places a mirror at the centerline of the patient's body, blocking the affected limb from the patient's sight. This result is a reflective illusion of the affected limb, tricking the patient's brain into thinking movement is occurring without pain. This technique has been proven to reduce pain symptoms and improve motor ability.

CRPS currently has limited therapy options. While graded motor imagery is effective for some, for others it may present problems such as difficulty in creating a convincing illusion using a mirror, the need to be stationary, and the effectiveness from limb to limb may vary.

The purpose of this project is to create a tool for therapists to test whether the treatment of chronic pain through graded motor imagery therapy is effective in virtual reality. The system is composed of an immersive experience for the user and a control interface for the therapist to lead the therapy session. This was done using Unity, the Oculus Rift VR system, and a web application.

Team

Evgeni Dobranov and Brian Djerf are seniors studying computer science in the school of engineering at Tufts University. Rhea Montgomery-Walsh and Ryan Biette are seniors studying human factors engineering in the school of engineering at Tufts University. Together, this team worked to create a cohesive research system for Dr. Nancy Baker. In addition to being the sponsor of the project, Dr. Baker was a rich resource of information for the team.

Solution Space

The team desired to integrate virtual reality technology with medical realm. Dr. Nancy Baker, a professor in the Tufts University Occupational Therapy Department, had previously conducted research in preliminary virtual reality treatments for chronic pain. Seeing the opportunity, Dr. Baker sponsored a capstone project dedicated to creating a research tool that will allow her and others to explore the effectiveness of graded motor imagery therapy (mirror therapy) in virtual reality. Preliminary results show vast improvement in the mobility of patients' appendages and decreased pain levels in the initial testing group. Encouraged by the results, but limited by technical abilities, Dr. Baker contracted our team to create a tool for her to test her hypotheses.

For our project, we will deliver a virtual reality experience based on current chronic pain treatments. The product has two sides: a patient-facing experience and a clinician-facing experience. The patient side administers treatment. The clinician side allows for monitoring and control of the treatment progression.

Document Overview

The following document summarizes the year of work the team put in to create the final version of the system. This document does not focus on the programming side of the solution, but rather the testing, human factors analysis and research methods used. A usability report, task analysis, requirements list, and a summary of results are included. Furthermore, recommendations and project reflections are also contained within this report.

Summary of Work

The team created many work items throughout the year. In this section, a usability report, user needs and product requirements list, and task analyses are included. The full usability report is included in the appendix (section 1). This report covers the findings from testing the system with students and one clinician. The user needs and product requirements are comprehensive and can be found in the appendix (section 2). The task analyses section is composed of two analyses. The first covers the clinicians task of running a session and the second covers a patient's task of completing a treatment session.

Usability Report

See Appendix Section 1

User Needs and Product Requirements

See Appendix Section 2

Task Analysis

See Appendix Section 3

Summary of Design and Results

User Research

Our team spent the first few months conducting research. The first step was to survey the literature on Complex Regional Pain Syndrome, mirror therapy, and using virtual reality in clinical settings. Next, we conducted structured interviews with the two user groups: CRPS patients and CRPS clinicians.

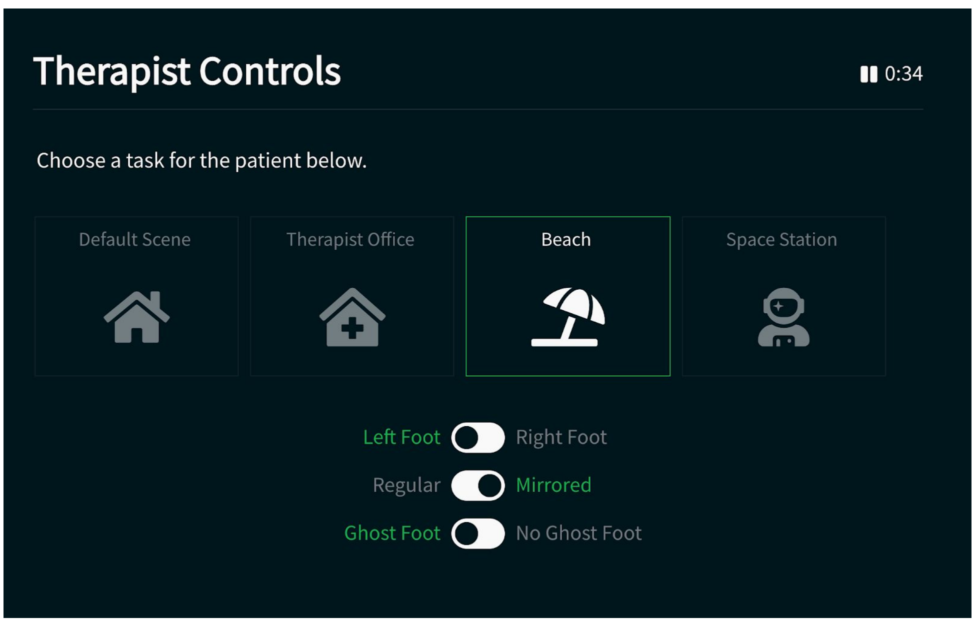
Through interviews with clinicians, we gained insight on the progression of treatment. To Megan, a Philadelphia-based occupational therapist specializing in CRPS, the most important thing during treatment is making the patient feel in control. Pace and progression of treatment is dictated by the patient, not the clinician, and retreating to more basic tasks is not a failure. The therapy experience must be graded, starting with low-risk tasks and slowly progressing to more challenging ones. Additionally, Megan mentioned that CRPS patients typically have anxiety, so it is important to introduce new tasks and environments in a cautious and gradual manner.

Through interviews with patients, we learned about the patient's experience with mirror therapy. Amber, a CRPS patient, revealed to us that she often feels nauseated after her sessions, as mirror therapy can be an incredibly intense experience. Typically, she sits in an OT office along with six to seven other patients during sessions, and she expressed her wish to be alone when she is completing treatment since the tasks take maximum concentration.

System Design

We integrated findings from interviews into the design of the virtual environment (patient interface) and the design of the web-based control portal (clinician interface).

Our team structured the virtual reality application so that the clinician facilitates the patient's experience rather than completely controlling it. One window of the clinician interface shows the patient's view through the oculus, along with a second window providing controls for graded motor imagery and scene selection.



For the patient interface, in the virtual environment, we played the isolating nature of VR to our advantage. In a room full of other individuals, the patient can still have a private experience during treatment. To ensure the treatment experience does not trigger anxiety, our team created a "home base" environment with minimal visual stimuli. From there, upon the patient's approval, the clinician can trigger alternate scenes such as an occupational therapy office or beach.

User Testing

During our user testing, our team tested three different types of users. Our testing population included one clinician with expertise in the areas of CRPS and occupational therapy (OT), four OT students with significant CRPS experience, and four laypeople with little to no experience with CRPS. Most of the individuals we tested also had limited to no exposure to virtual reality.

While testing the clinician interface, the participant was able to accurately and efficiently transition between scenes. However, the participant wished that there were options to have more control over the graded motor imagery aspect of the treatment. Since then, we have added toggles the the interface to grant the user more control.

While testing the patient interface, participants reported that the feet were not entirely believable. When graded motor imagery was not featured in the scene, users commented that their virtual-foot-movement felt very life-like. The controllers were securely attached to the feet, and they accurately tracked foot movement. However, when graded motor imagery was incorporated into the scene, users were somewhat confused about which foot they were looking at. Most users were not convinced that the virtual right foot was their actual right foot and the virtual left foot was their actual left foot. Despite this report, a majority of the users mistakenly moved the wrong foot during motor graded imagery, which demonstrated that the motor graded imagery technique was somewhat effective. Participants also commented that certain features of the virtual scenes were unrealistic and disorienting. Particularly, participants found that the shoe's shadow in the beach scene was unrealistic and made the foot seem like it was floating and disconnected from the body. Within the beach scene, participants did not like being placed on the roof and had fearful reactions. Additionally, participants commented that in the office scene, the desk and chair were too large.

Final Product

By the end of our project, we achieved many of our goals. One of our main goals was to create a virtual reality application with both a clinician interface and patient interface. We successfully achieved this goal and were able to test both interfaces. The clinician we worked with, Dr. Nancy Baker, was successfully able to navigate through the clinician interface, changing scenes and settings within the virtual environment. She was able to open up the application, use the application, and shut the application off with ease. Within the patient interface, our team successfully created three scenes. All eight participants felt comfortable and safe within these virtual environments.

The second major goal we achieved was to track the lower extremities. Our team attached the two Oculus hand controllers to the left and right feet, tracking the user's feet movements to the virtual space. When we asked participants if the virtual feet felt life-like, all eight participants reported that they did.

Our third major goal was to incorporate graded motor imagery into the virtual reality application, allowing clinicians to use it as an alternative tool for treatment. Our team was able to track the left foot and portray it as the right foot in VR, and track the right foot and portray it as the left foot in VR. However, most participants were not convinced by the graded motor imagery, and were hesitant when reporting which foot they were looking at. When we asked participants how convinced they were that the virtual shoe was their left foot on a scale of 1 to 10, the average score was 1.6. This was asked during the office scene. When we asked participants how convinced they were that the virtual shoe was their right foot on a scale of 1 to 10, the average score was 2. This was asked during the beach scene. However, a majority of the users mistakenly moved the wrong foot during motor graded imagery, which demonstrated that the graded motor imagery technique was somewhat effective. One participant commented that the believability of the feet may increase with more exposure to the virtual environment. Two other participants commented that the feet were more believable in second scene, which could be attributed to longer exposure in the virtual environment. Based on this evidence, our goal for incorporating graded motor imagery into the virtual reality application was somewhat achieved.

Our team achieved the majority of our goals, and we look forward to passing this project along to Dr. Nancy Baker to continue testing with CRPS patients.

Recommendations

Further Product Improvements

Our team ran into a series of technical difficulties over the course of the project. At the end of the project, this prevented our team from further developing the system to encompass the findings of our first round of usability testing.

A feature that was meant to be incorporated but did not end up in the final product include the settings function in the web application. The connection from the web page to unity was fine, but the mirroring feature that our team created was not robust enough to handle and the programming team simply ran out of time. If this project is to be worked on in the future, the team highly recommends that this feature be developed and implemented. Currently, the system lacks flexibility that would greatly improve the clinicians experience.

Additionally, the team desired to add a "ghost foot" or a reference foot to the patient's view, but did not accomplish this goal. This foot would remain stationary and act like the patient's unaffected limb was being mirrored when in reality the unaffected limb is moving and the affected limb is not. This would solve the issue that some participants mentioned during testing in that the treatment scenes were not entirely realistic since there was only one foot present. This feature would ideally be a setting that the clinician would be able to change from their control panel.

Another feature that would improve the realism of the patient experience is adding more of the leg to the model in VR. During testing, the team heard from multiple participants that the “floating feet” would be better if the leg was attached. This presents a slight technical challenge that our team did not surmount. The leg has multiple joints, however, the Oculus Rift system only has two controllers. To map the thigh, the shin, the foot, and the toes, we would need to add additional sensors or perhaps use the existing sensors in a way we did not think of. This product feature would greatly improve the system.

Lastly, the product could be used at home in the future. Thus, creating a wider variety of scenes and providing a way to follow specific instructions given by a therapist or communicating with the therapist from home would be a wonderful addition. Currently, therapy options for CRPS patients are not easily accessible and traveling to clinician’s offices can be exhausting for some. The potential for a home system is exciting and adding these features would allow for this.

Possible Team Improvements

The team could have been better in a few ways. Namely, testing with more iterations of the system, using revision control, and having better communication.

First, one round of user testing is not sufficient for a product. We did some informal testing throughout the process, but only one formal usability test. The class that this project was completed for was a learning process and we felt that we did learn, however the team could have tested outside of when it was required and potentially gained more insight. The system was not ready for this testing until we conducted the formal usability test. If we could have had a working prototype earlier, we could have improved the product more.

Revision control was another aspect of the project that should have been implemented and was not. This is what led to most of the technical issues at the end of the project. Proper file management practices, nor revision control software were used. As a result, the team had to troubleshoot and eventually fix the system back to the level it was at before testing. If a version had been saved and then another file could have been experimented with or if GIT was used, these issues could have been avoided.

This leads to our last major project team aspect that could have been improved: communication. The capstone class was split between three departments and within our department, we had two professors. This led to conflicting and overlapping deliverables. There were weeks where the HFE team had a deliverable that had been due a week beforehand for the CS team or the deliverables were due the same week, yet had different requirements between the two departments. This led to confusion and a feeling that we were two separate teams. As a result, the CS team and the HFE team ended up being somewhat separated and could have communicated in better ways to ensure that all team members were on the same page and that we were on schedule.

Conclusion

Our results are promising but not conclusive in solving our problem statement. We sought to create a system that acts as a tool for therapists to test whether the treatment of chronic pain through graded motor imagery therapy is effective in virtual reality. We originally thought to create a two sided user interface - one for the patient, and one side for the clinician. We did meet this goal at its strict definition. We are handing a tool to Dr. Baker that can be used to test whether the enhancement of traditional mirror therapy through VR is effective in treating CRPS.

Our research in building this system has proven that VR is an immersive strategy with the majority of our study participants saying that they felt comfortable in and convinced by our virtual reality system. In fact, one participant forgot that she was not moving the foot that she was seeing. These are extremely positive results that show the potential in our system. One caveat to our research is that we did not have permission to test on actual patients and thus we do not know exactly how CRPS patients will react to our system. We talked with clinicians, patients, and students studying the disease. But without actually testing with the clinical population, we can not be confident that our system will be well received. Our task was to create a system for our sponsor so that they could complete this research, so our team is excited to hear from Dr. Baker when she starts her research in the coming months.

The system can also be seen as an early prototype that will inform future systems that can be built by occupational therapists or others in the future. Our system is not perfect and not exactly what we hoped to achieve. Yet, it does provide an opportunity for our sponsor, Dr. Nancy Baker, to test her hypothesis that VR could be an effective treatment for mitigating or even reversing the effects of CRPS. This tool also is contributing to the larger field of exploratory medical treatments using virtual reality. Mixed, augmented, and virtual reality are all relatively new tools in the engineering world. They have existed in theory for over forty years, but the world of technology has now made these modalities accessible to a wider audience of researchers. We hope our project can inform others and help those we sought to create a solution for. In our conversation with one patient, we heard the want for hope. If nothing else, our project shows that those suffering from CRPS are heard and new treatments are being researched.

APPENDIX

Usability Test Report

Team Maximum Purple

Rhea Montgomery Walsh & Ryan Biette

4/12/19

Introduction

Team Maximum Purple has sought to create create a physical therapy tool to help treat patients with complex regional pain syndrome (CRPS). This condition has symptoms including intense pain in limbs, headaches, and sensation of pins and needles or burning. CRPS patients often also suffer from depression and/or anxiety. We aimed to create a more immersive means of graded motor imagery therapy, also known as mirror therapy. To accomplish this, we utilized virtual reality (VR), specifically, to focus on foot treatment.

In this round of testing, we implemented a holistic testing strategy. Our goals were to analyze the comfort, usability, and effectiveness of our current prototype. We collected mostly qualitative data as our main goal at this stage was to make the environment and experience as immersive and realistic as possible. The data we collected and that will be presented in this report is currently being used to make changes to the product before we hand over the final version to our sponsor by the end of this month.

Testing Methods

We tested three different types of users. Our testing population included one clinician with expertise in the areas of CRPS and occupational therapy (OT), four OT students with significant CRPS experience, and four lay people with little to no experience with CRPS. Most of the individuals we tested also had limited to no exposure to virtual reality. Each user group involved different variations of testing strategies.

In testing with the clinician, the clinician user interface (UI) was the focus of usability testing. The user was asked about general impressions about the web-based UI and then asked to complete a series of tasks ranging from communicating treatment instructions with the patient and rating clarity of communication to changing the scene that the patient was experiencing. The clinician was then immersed in the VR program for themselves and asked qualitative questions about realism and what features were missing or confusing.

Testing with OT students and lay people followed the same general structure. Participants were allowed to put on the VR headset after the test moderator affixed the controllers to the participants feet and gave a brief system overview. Questions included general questions of how participants felt in the environments and if the environments and foot projections were realistic. Furthermore, participants were asked to complete a series of exercises including spelling their name using their feet. Testing of the clinician UI was not included in these testing groups. Upon the conclusion of the study, this was recognized as a shortcoming to make up for in future testing.

Results

As mentioned previously in this report, most of the data collected was qualitative rather than quantitative. Errors and issues did arise and will be summarized here.

UI Issues:

During these usability tests, there were no major usability issues within the clinician user interface. The participant was able to accurately and efficiently transition between scenes. However, the participant wished that there were options to have more control over the motor graded imagery aspect of the treatment.

A major user interface issue we found within the patient interface was that the feet were not entirely believable. When motor graded imagery was not featured in the scene, users commented that their virtual-foot-movement felt very life-like. However, when motor graded imagery was incorporated into the scene, users were somewhat confused about which foot they were looking at. When we asked participants how convinced they were that the virtual shoe was their left foot on a scale of 1 to 10, the average score was 1.6. This was asked during the office scene. When we asked participants how convinced they were that the virtual shoe was their right foot on a scale of 1 to 10, the average score was 2. This was asked during the beach scene.

Participants also commented that certain features of the virtual scenes were unrealistic and disorienting. Particularly, participants found that the shoe's shadow in the beach scene was unrealistic and made the foot seem like it was floating and disconnected from the body. Within the beach scene, participants did not like being placed on the roof and had fearful reactions. Additionally, participants commented that in the office scene, the desk and chair to the right of the user were too large.

Root Cause Analyses

One participant noted that they experienced mild nausea and headache after using our system. This shows us that one problem we currently have is that the system can be disorienting and straining to the eyes. It is not possible to know the participant's propensity for these symptoms, but it is clear that our system had a role in their occurence. The root cause of this is that our design does not include many grounding features such as a reference foot. To address this, we should increase the clarity of ground surfaces and add a reference foot option. These design changes will affect the disorientation factor of this issue, but not the headaches. The participant experienced a headache, most likely due to eye strain. To address this issue, we can build in a clause to our procedure that instructs those needing vision devices to wear contacts or glasses that can fit within the headset. Additionally, we can recommend that this system is only used in limited sessions since we are not sure of the long-term effects of VR.

Another issue that is valuable to delve into is the lack of believability in the foot, especially in the beach scene. As explained earlier, our testing was mostly qualitative. For this reason, root cause analysis is less useful. However, we can examine this issue. The foot was not believable because it did not mimic real life. It did not mimic real life because the shadow of the foot did not meet the user's perceived expectation. The shadow was out of place because the foot was not calibrated well to where the user would be sitting. By addressing the position of the foot and the resulting shadow, the realism issue can be addressed.

Subjective Feedback

The subjective feedback was the most valuable aspect of the data we collected. When first introduced to the environment, half of the participants used the word “comfortable” in their description. Generally, participants felt positively and relatively relaxed when first introduced. It is important to note that the transition period and starting the testing in a mundane environment was viewed as helpful in creating this feeling.

In the first scene, the mundane environment without motor graded imagery, all participants reported that they felt in control of their left and right feet. One participant commented that they did not like the shoelaces in the shoe model. Another participant commented that the shoes should exaggerate the differentiation between left and right feet, specifically in terms of the inner foot arch. The left and right shoes used in this usability study looked too similar. CRPS patients have a hard time differentiating left and right extremities, so it is important to exaggerate the difference in the feet.

In terms of controller placement on the feet, participants reported that the Oculus controllers remained securely attached. However, some participants commented that the initial controller placement was sometimes off, angling the virtual shoe incorrectly. Additionally, users commented that it took a long time to attach the controllers to the feet, which could detract from the session time.

When motor graded imagery was introduced, participants had a hard time believing that the virtual right foot was their actual right foot and that the virtual left foot was their actual left foot. Most participants attributed this to the fact that the legs were not visible, making the shoe seem like it was floating. All participants were able to identify that the virtual right foot was supposed to be their actual right foot and that their virtual left foot was supposed to be their actual left foot, but none of the participants thought this was believable. One participant commented that the believability increased by performing more occupational therapy tasks with their foot. Two participants commented that the more they were in the virtual environment while they were experiencing the motor graded imagery, the more believable the feet were.

None of the participants thought that the transition of scenes was too abrupt or nauseating. Just above half of the participants preferred the office environment, reporting that it was more realistic. A little less than half of the participants preferred the beach scene, commenting that they enjoyed the beach sounds and trees blowing in the wind. One participant preferred the beach scene because it was “calm”. None of the participants reacted with pure negativity toward any of the environments.

Approximately half of the participants reported that they would like to see an interactive component in the virtual scenes. For example, they wanted to be able to kick a ball with their virtual foot. These participants believed that this added element would make the virtual experience more immersive.

Recommendations

User testing unearthed some areas in which the product could be improved. Smaller changes such as fixing floating books in the office environment and altering the shadow of the foot in the beach scene are easily addressable and will be fixed for the next version. Adding documentation to account for those who are visually impaired and need glasses should be addressed. Creating a repeatable system for affixing the controllers to patient's feet in a consistent and reliable way is necessary for product success. Additionally, it is recommended that the foot models be altered by accentuating the differences between the right and left feet as CRPS patients have difficulty discerning this difference. The foot should also be extended through the calf to increase the realism and believability of the system. Lastly, adding interaction with the environments would greatly increase psychological immersion. Though CRPS patients have extreme sensitivities, adding a balloon to kick or allow for interaction with sand would increase the realism of the product.

Figure 1: *Calibrating System*

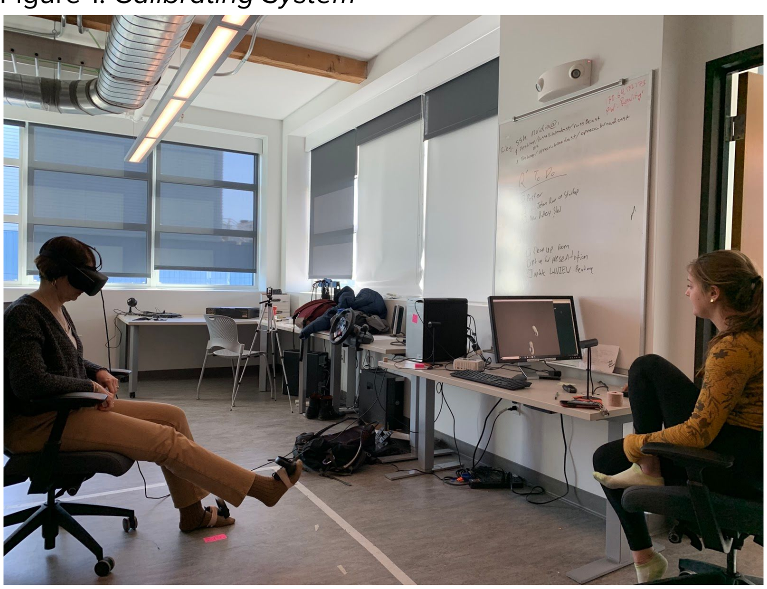


Figure 2: *Testing with Clinician*

APPENDIX - SECTION 2

User Needs and Product Requirements

User Needs

Clinician

- Ability to see the patient's virtual environment
- Ability to control the patient's experience in VR
- Ability to communicate to the patient while they are in the virtual environment
- Ability to prompt the patient to perform certain exercises

Patient

- Ability to perform physical therapy exercises while wearing the VR headset and tracking equipment
- The VR equipment does not worsen patient's pain
- Ability to stop or pause the treatment and control progress in the VR physical therapy exercises
- Ability to communicate with clinician during treatment

Product Requirements

- The product shall recreate motor graded imagery in a virtual environment
- The product shall not worsen patient's anxiety or condition
- The product shall have two distinct interfaces (clinician and patient)
- The product shall have controls in the clinician interface
- The product shall have an escape/pause button for the patient
- The product shall be able to be used while the patient and clinician communicate

APPENDIX - SECTION 3

Task Analysis

Clinician

1. Prepare room for occupational therapy session
    a. Ensure the room is tidy
    b. Review patient's files
    c. Prepare equipment for planned tasks
    d. Prepare note-taking materials
2. Welcome patient
    a. Invite patient to have a seat
3. Check-in with the patient
    a. Review the patient's long term progress
    b. Ask about the current status of the patient's chronic pain
        i. What tasks have been painful?
        ii. What tasks have been more manageable?
    c. Review goals of the current session
4. Begin occupational therapy session using motor graded imagery
    a. Place a mirror along the centerline of the patient's body
        i. Ensure the mirror blocks the patient's view of their affected limb
        ii. Ensure the mirror displays a reflection of the patient's unaffected limb
    b. Prompt the patient to perform various tasks with their unaffected limb
    c. Evaluate the patient's performance on the tasks
    d. Prompt the patient to perform more complex tasks when appropriate
5. Review the session
    a. Ask the patient what tasks went well
    b. Ask the patient what tasks did not go well
    c. Ask the patient what they would like to improve or focus on
6. Schedule the next therapy session with the patient
7. Set goals for the next session
    a. Assign patient tasks to complete at home
    b. Plan what tasks the patient will work on during the next therapy session
8. End the session
9. After the patient leaves, compile notes into the patient database
10. Prepare the room for the next patient

Patient

1. Arrive at clinician's office
2. Sit in the chair designated for the patient
3. Check-in with the clinician

    a. Review long term progress
    b. Report current status of the chronic pain
        i. What tasks have been painful?
        ii. What tasks have been more manageable?
    c. Review goals of the current session with the clinician
4. Begin occupational therapy session
    a. Allow the clinician to place a mirror along the centerline of your body
    b. Using the unaffected limb, complete various tasks prompted by the clinician
    c. Notify clinician how the tasks feel during their completion
    d. Notify clinician when ready to move on to more complex tasks
5. Review session
    a. Report what tasks went well
    b. Report what tasks did not go well
    c. Report what tasks require more focus and improvement
6. Schedule the next session
7. Set goals for the next session
    a. Work with the clinician to decide what tasks will be performed at home
    b. Work with the clinician to plan what tasks will be worked on during the next therapy session
8. Once the clinician has ended the session, leave the clinician's office