Augmented Reality Treatment for Phantom Limb Pain

Francesco Carrino[1], Didier Rizzotti[1], Claudia Gheorghe[1], Patrick Kabasu Bakajika[2], Frédérique Francescotti-Paquier[2], and Elena Mugellini[1]

[1] University of Applied Sciences and Arts Western Switzerland, Switzerland
{francesco.carrino,elena.mugellini}@hes-so.ch,
{Didier.Rizzotti,claudia.gheorghe}@he-arc.ch
[2] CHUV – Centre Hospitalier Universitaire Vaudois, Lausanne, Switzerland
{Patrick.Bakajika-Kabasu,Frederique.francescotti}@chuv.ch

Abstract. Mirror therapy is used from many years to treat phantom limb pain in amputees. However, this approach presents several limitations that could be overcome using the possibilities of new technologies. In this paper we present a novel approach based on augmented reality, 3D tracking and 3D modeling to enhance the capabilities of the classic mirror therapy. The system was conceived to be integrated in a three steps treatment called "Graded motor imagery" that includes: limb laterality recognition, motor imagery and, finally, mirror therapy. Aiming at a future home care therapy, we chose to work with low-cost technologies studying their advantages and drawbacks.

In this paper, we present the conception and a first qualitative evaluation of the developed system.

Keywords: Augmented Reality, 3D tracking, 3D modeling, phantom limb pain treatment, mirror therapy.

1 Introduction

In this paper we introduce a system based on augmented reality for the treatment of the phantom limb pain. The expression "phantom limb" describes the sensation of abnormal persistence of a member after an amputation or after that it became unresponsive due to some others reasons (as a stroke). Even if people suffering from this phenomenon are aware that this feeling is not real, usually they experience painful sensations in their amputated limb known as "phantom limb pain". The reason for these symptoms is not entirely clear and several theories coexist trying to explain the mechanisms underlying this syndrome [1].

To appreciate the importance of the phenomenon, in statistical terms 90-98% of people after an amputation report experiencing a sensation of phantom limb, about 85% of cases are accompanied by uncomfortable or painful sensations, physical limitation and disability. In 70% of cases, the phantom sensation is painful even 25 years after the loss of a limb [2].

The main treatment methods described in the literature for phantom limb pain are mirror therapy, motor imagery and graded motor imagery. All these treatments would recreate a correct cerebral representation of the missing limb for reducing phantom

R. Shumaker and S. Lackey (Eds.): VAMR 2014, Part II, LNCS 8526, pp. 248–257, 2014.

limb pain. In this paper, we focus on the mirror therapy. The mirror therapy was invented by V. S. Vilayanur Ramachandran [3] to help relieve phantom limb pain, in which patients can "feel" they still have the lost limb. In particular, the patient hides the stump behind a mirror (see Fig. 1) and, using the reflection of the good limb, the mirror creates the illusion that both limbs are present. The illusion persists while the patient tries to perform symmetric movements. Several experiments [4, 5] have shown that the mirror approach contributed to reduce the phantom limb pain, even if, currently, there is no general consensus regarding the real effectiveness of the mirror therapy [6].

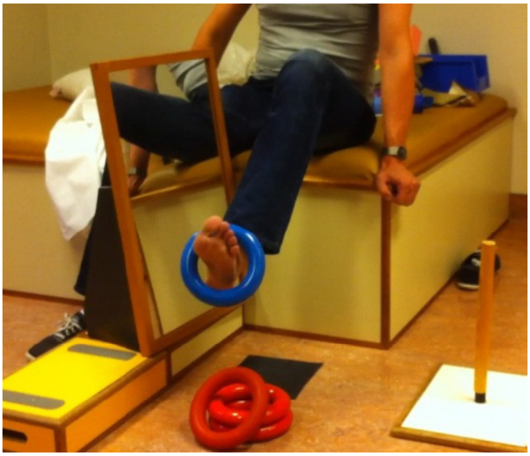

Fig. 1. Example of use of the mirror box by a healthy person. We tested the mirror therapy in order to get a better understanding of its limitations.

Starting from these assumptions, the goal of this project is to exploit the capabilities of the new technologies to develop an "augmented reality mirror therapy" capable of increasing the *immersion* and the engagement of the patient while removing some constraints related to the classic mirror therapy (i.e., restrained patient's movements, limited number of exercises, etc.). We want to study the feasibility of integrating an "augmented reality mirror therapy" within a treatment of occupational therapy for patients that suffered a lower limb amputation.

Using augmented reality (AR) to improve the classic mirror offers several advantages. First of all, AR makes possible for the patient to make more varied movements or even actions impossible to perform with a simple mirror such as movements that pass the center of the body (otherwise limited by the mirror), interaction with virtual objects to play games or perform more or less complex exercises. These new possibilities could allow enhancing the participation of the patient to the therapy presenting more entertaining scenarios. Then, the scenarios can be adapted to the different patients' needs or interest, for instance going in the direction of *gamification* for younger patients or providing more guidance to patients that need it. Furthermore, the therapist will be able to choose the more appropriate exercise scenario in relation to the physical possibilities of the patient, which can be extremely different from person to person, depending on various factors such as age, amputation type, etc.

2 Background and Related Work

Many works tried to improve the classic mirror therapy using approaches based on virtual reality (VR) or AR aiming at providing a more immersive and interactive experience for the patient.

Murray et al. [7, 8] analyzed the use of VR as a treatment for the phantom limb pain. The authors presented a test protocol focused on the quantification of the pain perceived by the participants before and after the sessions with the mirror box in VR. Three actual cases were analyzed for a period of three weeks and several sessions. The three participants expressed a decrease in pain in at least one of the sessions.

Two systems for the hand movement rehabilitation based on VR and AR were compared in [9]. The study showed that the AR approach provided better results, especially in terms of realism of the simulation.

Desmond et al. [10] presented a mirror therapy approach based on AR and tested it with three patients comparing the results with the classic mirror box. Instead of using a head-mounted display (HMD) for the AR, they used a simple screen with a consequent loss in terms of immersion. They observed similar results from the two approaches with the exception of a rather vivid sensations experienced by patients when the AR was used to display unexpected or abnormal movements.

In [11], the authors developed an AR prototype consisting of a Head-Mounted Display (HMD) and a stereo camera system. This system allowed recording images of the healthy patient's hand, processing the images in real-time to create a reproduction of the missing hand, and finally displaying the virtual hand at the place of the missing one. Unfortunately, the authors did not present any study concerning the use of their system with patients.

3 Methods

Similarly to [11], our work aims to develop an AR system using a HMD to improve the immersion of the classic mirror therapy. However, our approach aims to extend previous works under several aspects that will be highlighted in this section. First of all, we focused on the treatment of patients with amputations in the lower limbs. We chose to move in this direction because of the high incidence of patients with an amputation at a lower limb (that statistically represents the great majority [12]) and also because most of the previous works focused only on the upper limbs. However, our approach can be easily extended to track and modeling the patient's arms.

Due to the growth of the life expectancy, in the next years the need of medical attention will be larger and larger putting "Home Care" in a role of primary importance. For this reason we chose to adopt low-cost technologies available on the market following the idea of possibly bringing in the future the therapy directly in the patients' homes. However, this first study will be held in a hospital, directly under the supervision of occupational therapists. After analyzing several options, we chose the following devices (Fig. 2):

- Microsoft Kinect for the tracking of the present limb and to animate the 3D model of the missing limb.
- NaturalPoint TrackIR 5 with TrackClip PRO for the head-tracking.
- Vuzix Warp 920AR for the visualization.

Fig. 2. The devices used in the system: (from left) Microsoft Kinect, Vuzix Warp 920AR and NaturalPoint TrackIR 5

In order to conceive exercises as useful as possible for the patient, we designed the exercises with the aid of occupational therapists taking inspiration from the exercises that they usually perform with amputated patients.

Finally, our system will be used and evaluated within a medical research project with amputated patients, as part of a therapy including also limb laterality recognition tasks and motor imagery ("Graded motor imagery").

From a technical point of view, our approach is based on three main pillars:

Augmented Reality. Aiming at improving the immersivity, the realism and the interactivity of the mirror therapy, we chose to create a system in mixed reality in which the patient has the possibility to watch his real, healthy leg together with a virtual model of the missing leg replacing the stump. Moreover, augmented realty provides the possibility of integrate exercises with virtual objects that would be impossible with the classic system and that could help to motivate the patient to practice rehabilitation exercises.

3D Tracking. The present limb is continuously tracked in real time, in order to animate de virtual model of the missing limb, in particular we use information about hips, knees and ankles movements and rotations. Moreover, we track the patient head orientation to know continuously the patient point of view and therefore mix consistently virtual objects and real objects (for instance, to place the virtual limb in the right spot in relationship to the amputation and the patient's point of view).

3D Modeling. A virtual model of the missing limb is reconstructed using information of the present limb. For instance, we used parameter such as calf diameter, leg length and skin color to create a realistic 3D model of the missing leg. In our case, the skin color assumes a particular relevance since the exercises are often performed with a naked leg. Moreover, we added physical constraints to avoid abnormal movements of the model when the tracking data are noisy or imprecise. We developed four legs models to take into account amputations at the hips or knees level (see Fig. 3).

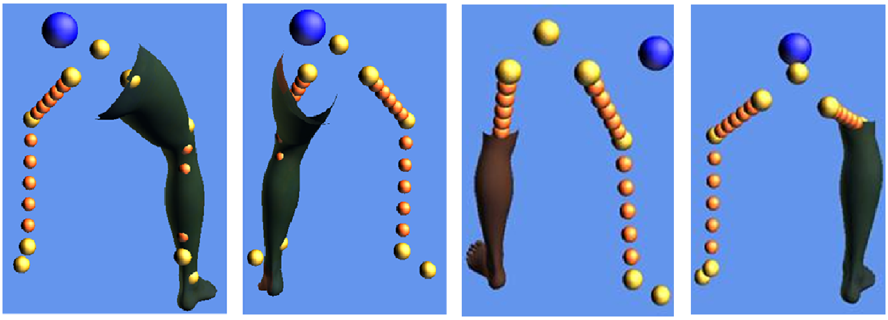

Fig. 3. The four leg models (without the skin texture)

The next section will present the use case of the application.

4 Use Case Scenario

The research project that included the development of the prototype presented in this paper proposes an occupational therapy session composed of three steps ("Graded motor imagery"): limb laterality recognition tasks, motor imagery and, finally, mirror therapy with augmented reality.

The first step "Limb laterality recognition" involves having the patient correctly identify pictures of right and left hands/legs in various positions. The second step, "Motor imagery", involves asking the patient to mentally represent movement with amputated leg. The **whole** process is important for the patient's rehabilitation; however, since this paper focuses mainly on the conception and development of a prototype for an AR mirror therapy, the scenario presented in this section will focus on this latter step.

The therapy will takes place over several sessions. The first session requires an additional step to getting started with the system so, also in the home care scenario, the first session will be held in a hospital under the supervision of occupational therapist. During the first session the system will record the patient data: the patient sits in front of a camera in a well-defined position, in a controlled environment (i.e., determined room illumination, uniform background color). Given the distance of the patient from the camera and the camera parameters, we are able to automatically measure the leg's parameters such as the legs' dimensions (e.g., calf diameter, length of the thigh, etc.) and the skin color (Fig. 4).

These parameters are stored along other patient's personal information (such as age, type of amputation, etc.) and then assigned to the 3D leg model in order to match the characteristics of the present limb and the amputation level. This setup phase is needed only the first time for a new patient. Starting from the second session, the data related to a particular patient can be simply reloaded into the system. In the case of an important change on the color of the patient skin (for instance due to a new, intense tanning) a new model can be created.

Fig. 4. Example of picture used to calculate the leg's parameters (left) to assign to the 3D leg model (right)

The following steps are common to every session, while the first session will be directed by the therapist, from the second session on the patient will be able to follow the therapy autonomously in her/his home.

Once the leg model is ready (recorded or reloaded), the occupational therapy session can begin: the patient takes place into the exercise area (i.e., inside the Kinect and Track IR field of view). The setup is depicted in Fig. 5.

Initially, a short phase of automatic calibration detects the body position and the head orientation. The leg's 3D model is then visualized attached to the patient body in the correct position accordingly with the tracking information provided by Kinect and the stored information about the patient's amputation level. The model is then animated accordingly with the movement of the healthy leg.

Depending on the exercise chosen by the therapist, the virtual limb can perform either symmetric movements or replicate the same movements of the healthy limb.

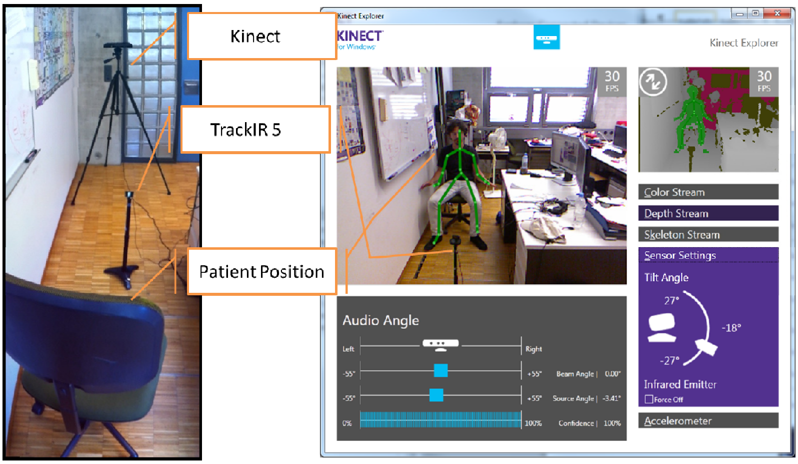

Fig. 5. Example of the setup of the exercise region

Finally, the patient can interact with virtual objects present on the scene using the virtual limb as well as the real limb (see Fig. 6). The coherence between the user perspective and the virtual objects on the scene (virtual leg, objects for the exercise, etc.) are constantly assured by tracking the user's head position and orientation.

In this first prototype we developed a simple game in which the patient can use conjointly the healthy leg and the virtual leg to pick and move a virtual ball (see [13] for a complete video demonstration).

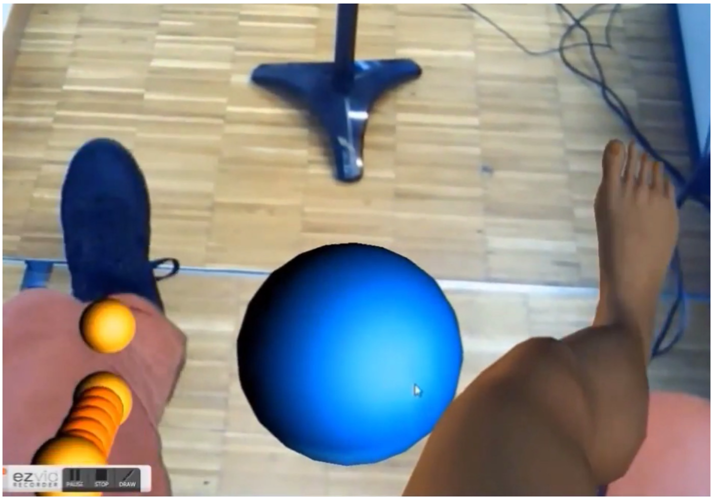

Fig. 6. Screenshot of a healthy user testing the application (from the user point-of-view)

During this preliminary study, once completed the therapy session, we asked the patient to fill a survey about the session with particular focus on the usability of the system and the realism of the simulation.

5 Discussion

The preliminary tests we performed during this study showed a series of interesting points to be analyzed and developed in future works.

Using commercial device helped us to create an application that would be easy to deploy in a user's home without the need of a long training. The Kinect is basically *plug and play* as well as the Vuzix Warp 920AR. The only problem we encountered was the setup of the Track IR for the head tracking. In fact, this device works well just in a range going from 61 cm to 152 cm from the user's head. This obliged us to put the Track IR on a support in front of the user, causing a small occlusion on the Kinect field of view. Moreover, since our exercises required the user to keep the head tilted far forward, we had to put the sensor at the knees level while setting accurately the inclination of the Track IR camera in order to detect the head movements in this very particular position. The mentioned occlusion issue did not cause many troubles. The Kinect tracking algorithm has proven to be robust enough to manage small occlusions in space and time.

Finally, Kinect and Track IR are sensible to infrared light (both technologies are based on emitters and infrared cameras); however, just avoiding placing the patient in front of a window prevented any issue related to infrared noise.

If, on the on hand, using commercial devices allowed us to build a system fairly easy to set up, on the other hand, the limitations imposed by these devices are numerous and need to be discussed.

Kinect's precision is good enough to provide a good tracking of the human body and the leg movements. However, the tracking of the ankle movements is already less precise: the *abduction/adduction*[1] movements are fairly tracked, while *plantar flexion/dorsiflexion*[2] movements are, basically, ignored. In a future application aiming at tracking more subtle movements (for instance fingers movements) another sensor or technique should be considered.

The used AR glasses have 31-degree diagonal field of view. This means that the user see in front of him a sort of "window on the real world" inside a black frame. The field of view offered to the user is good enough to perform mostly of the occupational therapy exercises involving legs (as you can see in Fig. 6), the legs are visible from the top of the knees). However, a wider field of view could facilitate the immersion for the user.

The system provides a fairly realistic representation of the missing limb adapting the 3D model to match color and size of the healthy leg. The resolution of the adopted HMD (two 640 x 480 LCD displays, 60 Hz progressive scan update rate, 24-bit true color) does not allow seeing much more details; for this reason, in this first prototype, we ignored important leg's characteristics like hairiness and muscle mass that probably should be taken into account for the higher resolution future versions.

Finally, there is a short delay between the movement of the present limb and the visualization of the movement of the virtual limb due to tracking and image processing time. In order to evaluate the impact of the lag on the therapy and how the user perceives it, deeper analyses are needed.

Talking about future possible ameliorations to improve the immersion provided by the system several options are open:

- Adding 3D vision. The HDM used, such as others, has two cameras and two screens (one per eye) making possible to provide a 3D vision of the real and virtual world.
- Adding shadows generated by the 3D models.
- Using sensors detecting muscular activity (such as electromyography) to trigger designated animations of the virtual limb overcoming the limit of parallel movements.

6 Conclusion

In this work we developed a system for the treatment of phantom limb pain based on augmented reality, 3D modeling and 3D tracking. We chose to work with commercial

---

1 During the *abduction/adduction* movement the tip of the foot goes left or right.

2 During the *plantar flexion* movement the tip of the foot goes down, while the dorsiflexion involves a movement of the toes upward.

devices, aiming to study the limitations of current technologies for a worth considering home care treatment of the phantom limb pain.

Despite the limitations discussed in the previous section, most of them resulting by the use of commercial devices, *entertaining* exercises should help to provide enough immersion to compensate some of the previous restrictions. Furthermore, the quick evolution of new sensors available on the market might soon close the gap with more expensive devices allowing a more accurate tracking of the body/head movements as well as a better visualization of augmented reality.

In this paper we provided also a first qualitative discussion about the capabilities and the limitations of such a system. Test with a first limited number of amputee patients will be performed in the next months.

References

1. Ehde, D.M., Czerniecki, J.M., Smith, D.G., Campbell, K.M., Edwards, W.T., Jensen, M.P., Robinson, L.R.: Chronic phantom sensations, phantom pain, residual limb pain, and other regional pain after lower limb amputation. Archives of Physical Medicine and Rehabilitation 81(8), 1039–1044 (2000), doi:10.1053/apmr.2000.7583
2. Hill, A.: Phantom Limb Pain: A Review of the Literature on Attributes and Potential Mechanisms. Journal of Pain and Symptom Management 17(2), 125–142 (1999)
3. Ramachandran, V.S., Rogers-Ramachandran, D.: Synaesthesia in phantom limbs induced with mirrors. Proceedings: Biological Sciences, JSTOR 263(1369), 377–386 (1996), doi:10.1098/rspb.1996.0058
4. Roches, S., Jucker, J., Bertrand Leiser, M.: Efficiency of mirror therapy for alleviating phantom sensations and pain: A systematic review. Ergoscience 4, 134–138 (2011)
5. Sumitani, M., Miyauchi, S., McCabe, C.S., Shibata, M., Maeda, L., Saitoh, Y., Mashimo, T.: Mirror visual feedback alleviates deafferentation pain, depending on qualitative aspects of the pain: A preliminary report. Rheumatology 47(7), 1038–1043 (2008), doi:10.1093/rheumatology/ken170
6. Moseley, G.L., Gallace, A., Spence, C.: Is mirror therapy all it is cracked up to be? Current evidence and future directions. Pain 138(1), 7–10 (2008), doi:10.1016/j.pain.2008.06.026; PMID 18621484
7. Murray, C.D., Patchick, E., Pettifer, S., Caillette, F., Howard, T.: Immersive virtual reality as a rehabilitative technology for phantom limb experience: A protocol. CyberPsychology & Behavior 9(2), 167–170 (2006), doi:10.1089/cpb.2006.9.167
8. Murray, C.D., Pettifer, S., Howard, T., Patchick, E.L., Caillette, F., Kulkarni, J., Bamford, C.: The treatment of phantom limb pain using immersive virtual reality: Three case studies. Disability & Rehabilitation 29(18), 1465–1469 (2007), doi:10.1080/09638280601107385
9. Shen, Y., Ong, S., Nee, A.: An augmented reality system for hand movement rehabilitation. In: Proceedings of the 2nd International Convention on Rehabilitation Engineering & Assistive Technology, pp. 189–192. Singapore Therapeutic, Assistive & Rehabilitative Technologies (START) Centre (2008)
10. Desmond, D.M., O'Neill, K., De Paor, A., McDarby, G., MacLachlan, M.: Augmenting the Reality of Phantom Limbs: Three Case Studies Using an Augmented Mirror Box Procedure. JPO: Journal of Prosthetics and Orthotics 18(3), 74 (2006), doi:10.1097/00008526-200607000-00005

11. Bach, F., Schmitz, B., Maaß, H., Çakmak, H., Diers, M., et al.: Using interactive immersive VR/AR for the therapy of phantom limb pain. In: Proceedings of the 13th International Conference on Humans and Computers, pp. 183–187. University of Aizu Press (2010)
12. Gregory-Dean, A.: Amputations: Statistics and trends. Annals of the Royal College of Surgeons of England 73(3), 137 (1991)
13. Project website and demonstrators, https://project.eia-fr.ch/plupart/Pages/Demos.aspx