Using Mr. MAPP for Lower Limb Phantom Pain Management

Kanchan Bahirat
The University of Texas at Dallas
Richardson, TX, USA
Kanchan.Bahirat@utdallas.edu

Yu-Yen Chung
The University of Texas at Dallas
Richardson, TX, USA
Yu-Yen.Chung@utdallas.edu

Thiru Annaswamy
VA North Texas Health Care System
Dallas, TX, USA
Thiru.Annaswamy@va.gov

Gargi Raval
VA North Texas Health Care System
Dallas, TX, USA
Gargi.Raval@va.gov

Kevin Desai
The University of Texas at Dallas
Richardson, TX, USA
Kevin.Desai@utdallas.edu

Balakrishnan Prabhakaran
The University of Texas at Dallas
Richardson, TX, USA
bprabhakaran@utdallas.edu

Michael Riegler
Simula Metropolitan Center for
Digital Engineering
Oslo, Norway
michael@simula.no

ABSTRACT

Phantom pain is a chronic pain that is experienced as a vivid sensation stemming from the missing limb. From traditional mirror box to virtual reality-based approaches, a wide spectrum of treatments using mimic feedback of the amputated limb have been developed for alleviating phantom limb pain. In our previous work, Mixed reality-based framework for MAnaging Phantom Pain (Mr.MAPP) was presented and used to generate a virtual phantom upper limb, in real time, to manage the phantom pain. However, amputation of the lower limb is more common than that of the upper limb. Hence, in this paper, on top of demonstrating the reproducibility of the Mr.MAPP framework for upper limb, we extend it to manage lower limb phantom pain as well. Unlike an upper limb amputee, a patient with lower limb amputated is constrained to perform the training procedure in a sitting posture. Accordingly, virtual training games are designed for lower limb exercises with sitting posture such as knee flexion and extension, ankle dorsiflexion and tandem coordinated movement. Finally, the technical details of the system setup for playing the training games are introduced.

CCS CONCEPTS

• **Computing methodologies** → **Mixed / augmented reality**; • **Applied computing** → **Interactive learning environments**; • **Software and its engineering** → *Interactive games*; • **Information systems** → *Multimedia information systems.*

KEYWORDS

Mixed Reality; Augmented Virtuality; Phantom Pain Management

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1 INTRODUCTION

Phantom pain is a frequent consequence of amputation or paralyzed limbs. Patient experiences vivid sensations from the missing body part such as frozen movement or extreme pain. Research [5, 14] indicates that neural plasticity plays an important role in the patient's experience. They show that the patient's brain needs time to learn that his/her limb is paralyzed or amputated.

Our Mr.MAPP framework [2] is an approach used for upper limb phantom pain management in a virtual environment. The system uses RGB-D camera (Microsoft Kinect V2) to capture and generate a 3D model of the participant in real-time. A virtual phantom upper limb is generated by replicating the intact counterpart. Along with the 3D mesh, the generated model contains skeleton based colliders which are used to interact with the virtual objects. The entire 3D model, along with the phantom limb are rendered, say on an HMD such as Oculus Rift. In this paper, we extend the Mr.MAPP framework for lower limb phantom pain management. The phantom limb is controlled by the intact counterpart, same as before. The patient is immersed into virtual gaming environments tailored for 3 different training games - knee extension and flexion, ankle dorsiflexion and tandem movement. The patient sits on a chair, wearing an HMD, and plays the 3 games which are developed to help relieve upper or lower limb phantom pain. The pipeline of the Mr.MAPP framework is shown in Figure 1.

2 RELATED WORK

Many approaches have been developed for alleviating phantom limb pain. Table 1 shows a summary of these approaches based on different characteristics such as display device used, source of

Source	Year	Display Device	Illusion Source	Target Limb	Merge with rest of the body	Interact with Virtual Object	Device Worn	Control Limb	Point of View
Ramachandran et al. [14]	1996	mirror box	mirror reflection	upper	yes	no	no	intact limb	first
O'Neill et al. [9]	2003	screen	pre-built 3d model	upper	no	no	sensing glove	intact limb	first
Desmond et al. [4]	2006	screen	camera	upper	no	no	sensing glove	intact limb	third
Mercier et al. [7]	2009	screen	camera	upper	no	no	no	intact limb	first
Cole et al. [3]	2009	screen	pre-built animation	both	no	no	sensing electrodes	stump	first
Murray et al. [8]	2010	HMD	pre-built 3d model	upper	no	yes	sensing glove with tactile feedback	intact limb	first
Ortiz-Catalan et al. [10, 11]	2014, 2016	screen	pre-built 3d model	upper	yes	yes	sensing electrodes	stump	third
Sano et al. [15, 16]	2015, 2016	HMD	pre-built 3d model	upper	no	yes	sensing glove with tactile feedback	intact limb	first
In et al. [6]	2016	screen	camera	lower	yes	no	no	intact limb	first
Bahirat et al. [2]	2017	HMD	RGB-D camera	upper	yes	yes	no	intact limb	third

Table 1: Summary of phantom pain management approaches based on different characteristics

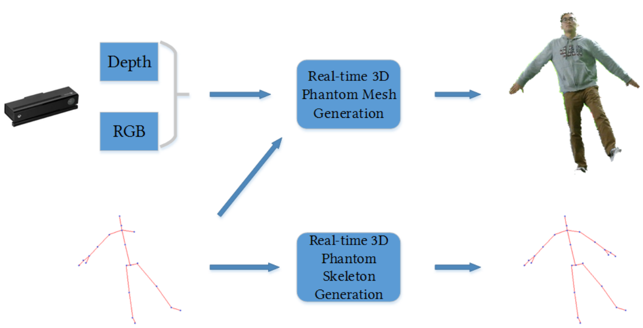

Figure 1: Mr.MAPP framework pipeline

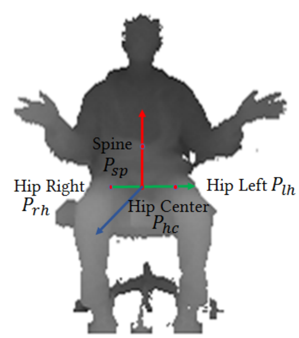

Figure 2: Skeletal coordinate system for phantom limb generation

illusion, target limb, virtual object interaction, control limb and point of view. Our Mr.MAPP framework [2] is the first method that uses RGB-D cameras to generate the virtual limb in real time.

3 EXTENDING MR.MAPP FOR LOWER LIMB AMPUTATION

Although the majority portion of the Mr.MAPP framework can be directly used, the local skeletal coordinate system to mirror the lower limb should be redefined appropriately. Because with the skeletal coordinate system defined at *spine joint* P_{sp}, the shoulder movement may result in the unnatural lower phantom limb generation. Hence, we define a coordinate system for the participant's skeleton, with origin at the *hip center joint* P_{hc} (see Figure 2) as:

$$x_s = \frac{P_{lh} - P_{rh}}{|P_{lh} - P_{rh}|}, y_s = \frac{P_{sp} - P_{hc}}{|P_{sc} - P_{hc}|}, z_s = \frac{x_s \times y_s}{|x_s \times y_s|}, O_s = P_{hc} \quad (1)$$

where P_{lh} and P_{rh} are left and right hip joint, P_{sp} is spine joint, P_{hc} is a hip center joint.

Figure 3 shows the block diagram of the lower limb mesh generation using Mr.MAPP. First, raw depth and color data streams generated from Microsoft Kinect V2 are filtered by depth to extract the point cloud of the subject in the foreground [12]. Second, the extracted point cloud is segmented based on the distance between skeleton segments and each point [13]. The distance is estimated by a Voronoi decomposition based approach [1]. In Figure 3, resulting segmentation is presented using different color. Third, to achieve a realistic illusion, points corresponding to the affected limb should be removed. Hence, the manually specified affected limb segments are removed from the segmented points. Next, the intact counterpart segments are mirrored to create an illusion mesh of the affected limb. A local coordinate for mirroring process is defined using left shoulder, right shoulder, spine and shoulder center joints in the skeleton data. After that, points in intact limb are transformed to the local coordinate and reflected in the coordinate. Then, the generated points are transformed back to the real-world coordinate to obtain the mirrored points representing the phantom limb. However, some of the data points are lost during back projection because of numerical round-off errors. Average filtering is performed as the last step, to fill these holes and obtain the final complete body mesh.

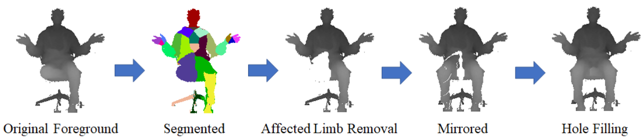

Figure 3: Block diagram for real-time phantom mesh generation

4 LOWER LIMB TRAINING GAMES

We developed 3 different training games for lower limb training, each tailored for a specific exercise - (i) knee flexion and extension, (ii) ankle dorsiflexion & (iii) tandem coordinated movement. Bubble Burst, pedal and piano are the 3 games that are developed correspondingly. In each game, the player needs to sit on a chair and face the Kinect camera ensuring that the camera can see the lower limb. For proper generation of the phantom limb, it is recommended to sit straight and keep arms slightly away from the legs.

4.1 Bubble Burst Game

The original 'Bubble Burst' game shown in Mr.MAPP [2] is modified for lower limb training. In this version, bubble generators on the floor are moved closer to the user so that they are reachable by foot. The player needs to perform knee flexion and extension movements as shown in Figure 4 (a). The game layout is shown in Figure 4 (b) & (c). As only the front two channels are easily reachable with foot, we enable bubble generation only from these two front channels. The goal here is to burst the bubbles while performing knee flexion and extension.

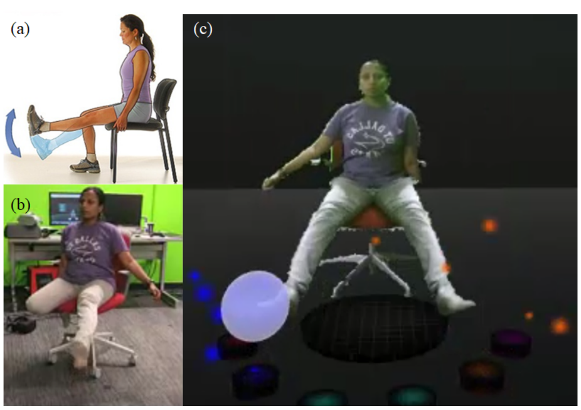

Figure 4: (a) Knee flexion and extension exercise - Picture Courtesy https://human-anatomycharts.com/v/categoryknee-extensors.asp (b) real world setup showing player with one lower limb hidden from camera (c) participant playing the 'Bubble Burst' game

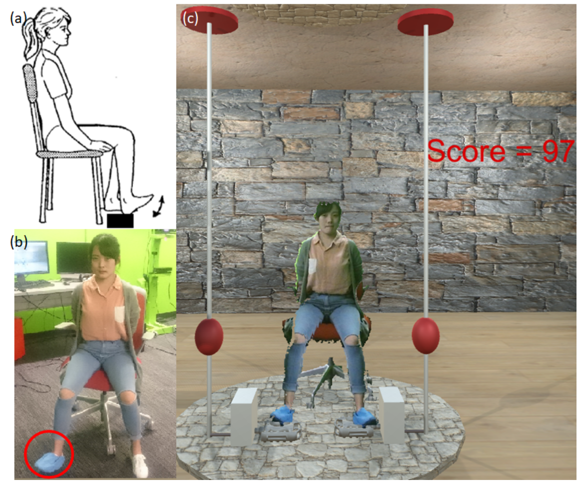

Figure 5: (a) Ankle Dorsiflexion exercise - Picture Courtesy: https://orthonc.com/uploads/pdf/Ankle_Foot_AROM.pdf (b) player wearing a blue shoe cover on the foot of the target lower limb (c) participant playing the 'Pedal' game

4.2 Pedal Game

The second game is called 'Pedal' game, which is designed to perform the ankle dorsiflexion exercise. To enhance the effect of the small motion on feet, the system will target to the blue color on the feet. That's why a blue shoe cover is required to be worn by the participant in the game, as shown in Figure 5 (b). If the feet are buried under the ground, placing a black box or step stool to elevate the foot could make it more visible to the depth camera. Figure 5 (b) & (c) show the layout of the game. The pedals in front of player's feet are the target colliders. As the patient presses and releases the pedals, the balls on both sides will start moving upwards.

4.3 Piano Game

In the 'Piano' game, the patient is asked to perform a random stomping movement while seated on the chair. There are different piano keys popping up randomly on the floor and patient must hit the popped key with stomping action. As the correct key is hit, a certain musical note will be played, and the key will disappear with sparkles. The score will increase with every correctly hit key. If any

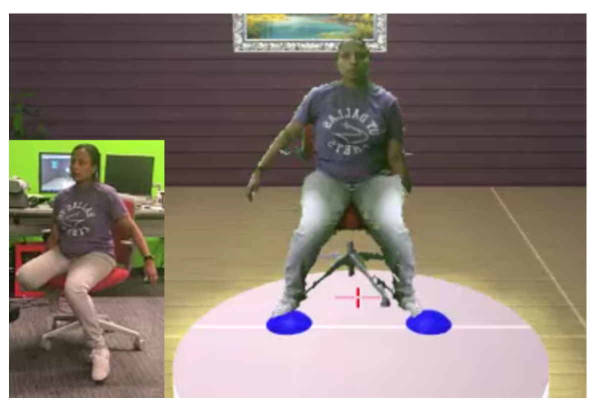

Figure 6: User playing the 'Piano' game for lower limb training

key is missed, the score remains unaltered. The game can be closed by pressing the escape key or once the time limit has exceeded. Figure 6 shows a user playing the 'Piano' game.

5 SYSTEM SETUP

System Requirements: To use the Mr.MAPP system, we need a MS Kinect V2 camera to capture the person, a computer for running the games and an Oculus Rift for rendering. For the Kinect to work, we need a computer having Windows 8 or newer, 64-bit (x64) dual-core processor, 2GB RAM and a USB 3.0 port. Whereas, for the Oculus Rift to work, we need Intel i3-6100 / AMD Ryzen 3 1200, FX4350 or greater processor, NVIDIA GTX 960 4GB / AMD Radeon R9 290 or greater graphics card, 8+ GB RAM, Windows 10 or newer, 1x USB 3.0 port, plus 2x USB 2.0 ports and a compatible HDMI 1.3 video output. The compatibility tool from Oculus website can be used to check the system compatibility. For our setup, we use a laptop with Windows 10, Intel i7-6700HQ x64 processor, 16 GB RAM, NVIDIA GTX 1070 8GB, 1 HDMI, 1 USB 3.0, 1 USB 2.0 and 2 USB-C ports which can be used with USB 3.0 to USB-C adapters.

Software Requirements: To capture the person, Kinect for Windows SDK 2.0 needs to be installed. The 'SDK Browser 2.0 (Kinect for Windows)' can be used to check if the Kinect is connected and able to capture the person. Specifically, one can use the Body-Basics demo to see the skeleton of the person and adjust the height and distance accordingly. The Oculus Rift Software needs to be downloaded and installed, to work with the Rift. The software provides on-screen instructions throughout the setup, to arrange the sensors at appropriate positions. Apart from the basic software requirements for the Kinect and Oculus Rift, the computer needs to have CUDA 9.1 installed. To play the games, our system also needs other library dependencies such as OpenCV 3.4.0, Eigen 3.3.4, Glm 0.9.8.5, SDL2 2.0.7 and glew. Executables for all the 3 games, along with the required pre-built dependencies, are available to download at **https://utdallas.box.com/s/9h9mbiitvbbn7jfs7hhnd9sg16xb889q**. The folder named 'HUNAD5' contains the above mentioned pre-built dependencies, which can be placed at any location on the computer. The 'setPaths.bat' needs to be run (double-clicked) to add the dependencies to the environment path variable. The folder 'Games' contains the games and other necessary executables, which can also be placed in any location on the computer. There are 3 batch files, namely 'PlayBubbleBurst.bat', 'PlayPedal.bat' and 'PlayPiano.bat', that can be run to play the corresponding games. Once any of the 3 batch files is run, the corresponding game will open, and the user can play the game as explained in Section 4.

Physical Setup: The user needs to make sure to have a clear space with enough room to move around. The Oculus setup has a 'Guardian System' that can be used to create a safe boundary area for the user to play the games. Kinect can capture the person in a range of 1-5 meters. In a typical arrangement, the Kinect is kept about 1 meter high and the chair/person is about 2.5-3 meters in front. This ensures that the person is completely detected and can be used for phantom limb generation. As mentioned in Section 4, the user needs to sit on a chair to play any of the 3 games. Once the game is on, the user needs to press the virtual 'start' button to actually play the game. This can be done using the buttons 'A' or 'X' on the touch controllers or using a mouse. However, the button should only be pressed after making sure that the entire body is visible, and that the user is ready to play the game. Even if player is not exactly on required center spot in the game, s/he will be teleported to the correct virtual location when the 'start' button is pressed. During the gameplay, the participant can refine their sitting position by slightly moving the chair, but it is recommended to not make any major movements. Once the game has started, the user needs to perform the correct exercise motion to successfully complete the task of the game.

6 CONCLUSION

In this paper, we have extended our Mr.MAPP framework [2] to be used for lower limb phantom pain management. We developed 3 different games and have made the executables, along with the library dependencies, publicly available for download at **https://utdallas.box.com/s/9h9mbiitvbbn7jfs7hhnd9sg16xb889q**

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