TIPTEKNO'19
TIP TEKNOLOJİLERİ KONGRESİ
MEDICAL TECHNOLOGIES CONGRESS
3-5 Ekim 2019
Kuşadası / Aydın

Immersive Virtual Reality Games for Rehabilitation of Phantom Limb Pain

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***Abstract*—Serious games mostly associated with rehabilitation systems with state-of-the-art virtual reality hardware and software products. This approach benefits from gamification that improves the participant's engagement and makes cybertherapy sessions fun and interactive. This paper describes four different serious games for the rehabilitation of phantom limb pain (PLP) syndrome. Each immersive virtual reality game is designed to overcome the negative effects of PLP for different amputation regions including below-elbow, above-elbow, below-knee and above knee. We aimed to propose a low-cost, effective rehabilitation system that can be used at home instead of hospital-oriented physiotherapy routine. We used the Kinect sensor, a wearable surface electromyography (sEMG) sensor, and the Oculus Rift virtual reality headset to provide a longer therapeutic interaction between the patient and the cyber-therapy environment. Alpha test results of a pilot study with unimpaired healthy participants reveal the proposed system works practically in the home environment.**

***Index Terms*—Cyber Therapy; Gamification; Phantom Limb Pain; Serious Games; Virtual Reality**

I. INTRODUCTION

Phantom limb pain (PLP) is a common sequelae of amputation characterized by feeling pain in the amputated body part [1]. Reports point out that 80-85% of amputees suffer from severe pain episodes with symptoms such as throbbing, burning, stabbing, tingling, squeezing, shocking and cramping throughout the missing limb [2]. The onset of PLP is commonly early however it can occur months or even years after amputation [3]. PLP is primarily localized in the distal parts of the amputated limb such as palms and fingers for upper limb amputations and ankle and toes for lower limb amputations [2].

Chronicity of phantom pain affects quality of life negatively and leads to limitations in activities interacting with the social and professional environment [4]. This chronic condition is an important health care issue due to patients with PLP have increased incidence of obesity, cardiovascular disease, sleep disorder, chronic joint pain, and low back pain [3]. PLP does not respond to typical analgesic treatments and constitutes a significant medical problem [5]. Although there are many different interventions to treat patients with phantom pain, none has yet proven to succeed efficacy [6].

The most common therapeutic approach used in the treatment of PLP is mirror therapy (MT) [7]. MT uses the reflection of voluntary movements performed by the intact limb through a mirror and involves creating an illusion of non-painful movement on the phantom extremity. By using imaginary movement of the missing limb, its projection in corresponding motor and sensory corticies is restored and provide pain reduction resulting from the breaking-off of sensory information [8]. However, MT has some clinical and methodological limitations [9]. Spatial dimention of the MT is restricted within the mirror surface and patient remains in a fixed position to perform movements with mirror box. The illusion is temporary and rely on reflected image as opposed to moving anatomical extremity. Also, MT can only be applicable for unilateral amputations [10], [11].

Given the chronic nature of PLP, effective approaches are needed that can reduce PLP in a sustainable way. Researches about PLP suggest that visual therapies based on same principles which accomplish the inherent problems of the MT may reduce PLP. Immersive virtual reality based rehabilitation approaches have the potential to create a more advanced form of MT and may allow patients to continue exercising outside the clinic. The aim of the current study is to develop immersive virtual reality (IVR) serious games for alleviating PLP and improve the quality of life by reducing the negative effects of the pain.

II. BACKGROUND

IVR is an interactive computer-generated experience taking place within a simulated environment which makes possible to create artificial experiences in real time. First, Kuttuva et al. (2005) developed a virtual environment that allows people with upper extremity amputation to manipulate virtual objects such as balls within them. After the development of this virtual environment for amputees, some researchers developed similar systems for the treatment of PLP [12]. Murray et al. (2007) used IVR environment to treat three patient with PLP (two with an upper limb amputation and one with a lower limb amputation) in between 3-5 session

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along 3 weeks. All participants stated a decrease in PLP at least one of the sessions [13]. Mercier and Sirigu (2009) used virtual visual feedback to alleviate PLP resulting from upper limb amputation or brachial plexus avulsion for 8 week and 2 times per week. Participants reported 38 percent decreasing in pain after the intervention according to visual analog scale (VAS) [14]. In the initial studies about VR, virtual images of the missing limb movements were obtained by filming the intact limb while performing different actions and then digitally inverted and projected on a computer screen. Thus, VR mirror box therapy based on MT were applied according to data from the intact extremity.

Some other studies used signals obtained from the residual limb by using myoelectric pattern recognition to predict motor volition while providing real-time feedback to the patient in VR environments and phantom motor execution is accomplished by using this system. Cole et al. (2009) captured motion data from patient stump and transform that into goal directed virtual motion enacted by an avatar in a VR environment. After VR intervention, patients with upper and lower extremity amputation reported pain reduction as well as improved virtual arm sensation [15]. Chau et al. (2017) developed an interactive three dimensional kitchen environment based on mirror therapy and used myoelectric control of a virtual hand as well as motion-tracking control in this setting for five therapy sessions [16]. Zanfir et al. (2017) evaluated the effectiveness of an IVR intervention program in participants suffering from PLP and stated a significant pain relief in patients in the IVR group compared to those in the kinesiotherapy group [17]. Ambron et al. (2018) utilized low-cost IVR with custom games. Two cases with lower limb amputation were included in the study and both patients experienced pain relief after sessions and pre-session pain levels reduce gradually over time [18].

Previous studies have shown that the virtual environment was not diversified according to the level of amputation and treatment with gamification was rarely used. Our study differs in terms of comprising various rehabilitative IVR based games for all included level of amputation.

III. MATERIALS AND METHODS

In this section, we detailed our VR-based therapy system by explaining its architecture and modules. Our proposed interactive therapy system [19] consists of 4 main parts; a wearable sensor to collect sEMG data, real-time classifier to recognize phantom movements, virtual reality-based therapy games and web services to communicate different modules of the system.

IVR based serious games were created by using Unity 3D platform for the treatment of PLP. Unity 3D is a game engine that allows developers to create games for various platforms including popular VR devices. IVR based system consists of a Kinect sensor and a head mounted display (HMD).

A. Real-time Motion Data Transfer to The Human Model in Unity 3D by Kinect Sensor

Kinect is a sensor that can detect human motion by using joint position data obtained from camera, infrared, depth sensor and temperature sensor and create physical image of the person on the monitor. Success rate of motion detection is high because it blends the data received from many sensors. For this reason, Kinect was used to transfer the movements of the participant to the virtual reality environment. Kinect studio was used to get data from Kinect. The integration of Kinect into Unity 3D was achieved through the Software Development Kit (SDK) that Microsoft shared for Kinect. In order to prevent inconsistencies between the movement of the participant and the movement of the human model seen on the screen, the angle between the joints was calculated and transferred to the 3D human model in the game.

In Unity 3D, calculation process of the joint angle was performed as the following.

- The position data of the two joints from the Kinect sensor was extracted from each other.
- The found vector was normalized.
- The normalized vector of the Unity 3D rotation class was converted to Quaternion format with the Euler function.

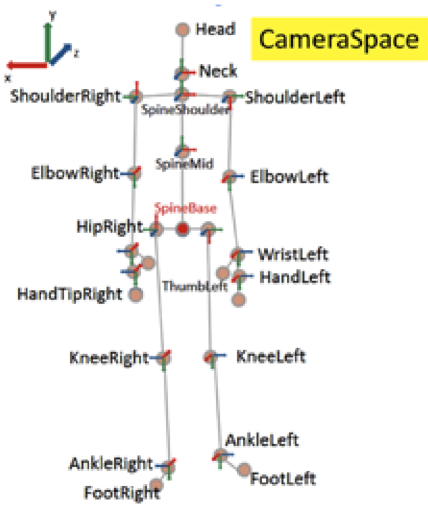


Fig. 1: Joints from Kinect Sensor and Reference Vectors of the in-game 3D Model

Kinect sensor sends 4-5 frames per second (FPS), but a minimum of 30-60 FPS is required to get a fluent image in the game. We used Linear interpolation (Lerp) to streamline and modulate hybrid data obtained many sensors of Kinect. Lerp is simply a process of obtaining data fluency by linearly passing intermediate data of two digital data. Kinect can also receive incorrect data from extremities such as the hand and foot. At this point, the Kalman filter, which is a method extracting meaningless data that disrupts data integrity, was used.

The Kalman filter simply updates the incoming data according to a dynamically calculated threshold. Each time new data is received, the threshold value is updated according to this incoming value. Therefore, the incoming data is updated according to the characteristics of the array. Thus, more accurate data is obtained. Figure 2 shows the Kalman filter steps.

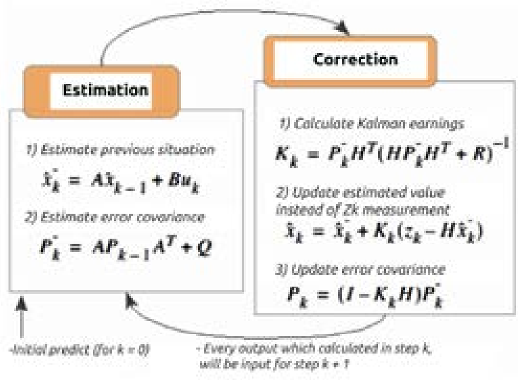


Fig. 2: Steps of Kalman filter.

X_k represents the previous prediction. This is the raw estimate before updating the incoming new value with the newly calculated threshold. Pk is the previous error covariance. (common amount of change of error). X_k and P_k are used as prior values in the Correction phase. That means these values will be input to the correction phase. Equations in the incoming value correction stage contain the actual value. This value is the value of X at time k. So it is essentially the desired value. There is also a Pk value. With these two values, the value at the next $(k+1)$ is calculated. Kalman gain is calculated because it is necessary for the next step. While this value is hidden, mysterious, it is the most important part of the equations. The values found in the correction phase are posterior values. [20]

B. *Integration of Virtual Reality Glasses into the Game on the Unity 3D Platform*

The VR headset generally consists of a wearable glasses, 2 hand controllers and 2 stations. The HMD serves as a monitor for entering in the virtual environment. Hand controllers allow the participant to control their interaction in the virtual world. The stations receive the position information from the glasses and the controllers. In this study, HTC Vive and Oculus Rift were used as HMD. In order to develop games on Unity, manufacturers share HMD-specific development kits. However, the development of glasses-specific games increases the problem that the game is not compatible with other glasses. To solve this problem, SteamVR, a library that works for all glasses, was used. In addition, SteamVR has shared a plug-in to be used in Unity 3D. The plug-in is a simple, stable, compatible with most virtual reality goggles with a size of 58 MB. We used this library for VR headset integration. The hardware and software architecture layers of the integration of virtual reality glasses are as shown in Figure 3.

C. *Rehabilitative Games*

During the IVR treatment, participants could play four games: Basketball Game, Rehab Ninja, Football Game and

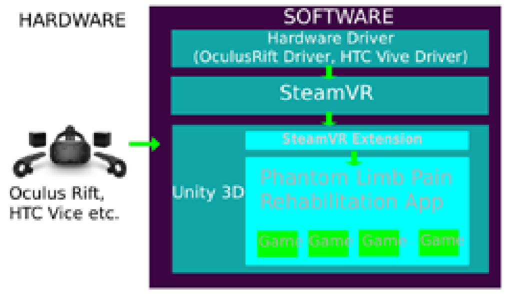
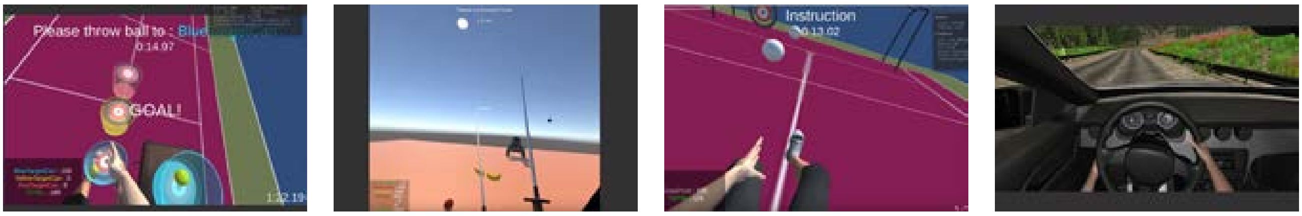


Fig. 3: Hardware and software architecture layers of integration of virtual reality glasses

Driving Game. Basketball game was designed for phantom limb to move in a virtual environment and to reduce PLP by creating appropriate sensory input in individuals with limb loss after wrist disarticulation and transradial amputation. This game presents the amputees to grasp the ball with their virtual hand and throw it into the baskets with different colours. During grasping the ball with the virtual hand, it is expected that finger and wrist flexor muscles such as flexor digitorum superficialis, flexor digitorum profundus, flexor pollicis longus are activated. Activation of extensor muscles such as extensor digitorum, extensor carpi radialis longus and brevis, extensor carpi ulnaris, extensor digiti minimi are obtained while releasing the ball to the basket. Two stopwatches are used as a general stopwatch and a task stopwatch in the game. The participants are expected to throw the ball randomly into the red, yellow and green baskets. The task stopwatch run at this time. If the patient throw it in the wrong basket, the task stopwatch will reset and the display show ”Retry”. If the patient throw them in the correct basket, the stopwatch will reset and the display show “Success”. The participant get points after each successful shot and new part starts. General stopwatch demonstrates total score at the end of game.

In the Rehab Ninja, the goal of the amputee is to cut the fruits appeared on the monitor by moving the virtual arm. Patients lift two knives to cut the fruits. At that moment, phantom flexion movement of the elbow joint is expected to provide muscle activation in biceps brachii muscle. After that, elbow extension and activation of triceps are aimed to achieved while lowering the knife.There is a general stopwatch in the game. The participants try to cut the fruits and the screen displays “Successful” when they accomplished.

Football game was developed to reduce the pain in the missing leg after knee disarticulation and transfemoral amputation. In the game, the participant is presented with a virtual leg and a computer screen showing content of the football field. During the game, the amputee aims to score goals by moving the ball with virtual leg and foot that is seen on the screen. Activation of the semitendinosus, semimembranosus and biceps femoris muscles are expected with the phantom knee flexion during the preparation of the virtual leg for scoring a goal and activation of rectus femoris, vastus medialis, vastus lateralis and vastus intermedius muscles are aimed to provide during scoring the



(a) Basketball Game (b) RehabNinja Game (c) Football Game (d) Driving Game

Fig. 4: Screenshots featuring some of the Serious Rehabilitative Games

goal. Game rules and processes are same as basketball games.

The last game was Driving Game which was designed to reduce PLP in the missing limb after ankle disarticulation and transtibial amputation. We aimed to enable phantom foot movements and control their virtual foot. The upward movement of the virtual ankle to lift up for throttle or braking primarily activates tibialis anterior muscle. Plantar flexion and gastrocnemius muscle activation are executed during stepping on the gas or braking. Screenshots of all games are shown in Figure 4.

IV. CONCLUSION

In this study, we developed IVR-based serious games which overcome the limitations and disadvantages of the MT for the treatment of PLP in four different amputation region including below-elbow, above-elbow, below-knee and above knee. Our study has been different from the prior researches in terms of creating different IVR based games for each amputation level as mentioned above. In addition, using serious gamification technology would provide high motivation and participation to phantom movement execution for the people with PLP. Thus, PLP would be reduced by the obtained appropriate sensory input and motor output of the residual limb.

Despite the positive effects of the previous implementations, there are some limitations such as inconsistency of the treatment protocols between studies. We aim to investigate the effectiveness of IVR based games in the people with PLP by creating high methodological quality in the future progression of this work.

ACKNOWLEDGMENT

This study is supported by the Scientific and Technological Research Council of Turkey (TUBITAK) under grant no.EEEAG-117E579.

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