Augmenting Breath Regulation Using a Mobile Driven Virtual Reality Therapy Framework

Ahmad Abushakra and Miad Faezipour, Member, IEEE

Abstract — This paper presents a conceptual framework of a virtual reality therapy to assist individuals, especially lung cancer patients or those with breathing disorders to regulate their breath through real-time analysis of respiration movements using a smart-phone. Virtual reality technology is an attractive means for medical simulations and treatment, particularly for patients with cancer. The theories, methodologies and approaches, and real-world dynamic contents for all components of this virtual reality therapy (VRT) via a conceptual framework using the smart-phone will be discussed. The architecture and technical aspects of the offshore platform of the virtual environment will also be presented.

Index Terms — Breathing movement classification, lung capacity estimation, virtual therapy, visualization.

I. INTRODUCTION

A. Motivation

Lung cancer is considered as the number one leading cancer-caused death in the United States. In addition, according to [1], 1/4 of all types of clinically diagnosed cancers include the lung organs. For this reason, research on lung cancer prevention and treatment has received much attention across the medical fields as well as various systems/engineering research aspects.

One of the most challenging tasks for lung cancer patients is concerned with breathing, as the lungs are responsible for respiration. Lungs distribute oxygen to the entire body through blood flow via blood cells [2]. Hence, any form of exercise that regulates the respiratory system, improves the lung functionality in providing oxygen to the rest of the body, and as a result, can degrade lung cancer symptoms. Furthermore, several researches have proven that inducing relaxation responses improves the efficiency of the immune system, while stress retards it [3-4].

Lung cancer patients and those with breathing disorders are also subject to serious attacks in which the patient's lung capacity is significantly reduced. This can even lead to severe shortness of breath and may require emergency treatment [5]. Therefore, post-operative breathing exercises can decrease lung problems by encouraging the patient to take deep breaths [6].

B. Background

In the recent years, Virtual Reality Therapy (VRT) has been explored by many researchers to a large extent [7-8].

Virtual Reality (VR) through simulation, has the potential of assisting in breath regulation, especially for those with breathing disorders, e.g. lung cancer patients [9]. VR is defined as “an experience in which a person is surrounded by a three-dimensional computer-generated representation, and is able to move around in the virtual world, see it from different angles, reach into it, grab it and reshape it” [10]. The interactive immersive features of a virtual environment would provide a rich interactive and contextual setting to support experiential and active therapy. Another attractive advent is that smart-phone devices are nowadays becoming increasingly popular in several aspects of our daily lives [11], and the usability: especially the effectiveness and acceptance of smartphone applications by patients has become an appealing matter [12]. As virtual reality using smart phones has also evolved rapidly in the scale and scope of developing virtual reality applications for medical purposes [13], applying virtual reality therapy to assist lung cancer patients via smart phones appears to be a remarkable area under investigation, yet very challenging.

In this paper, the conceptual framework of a smart-phone-based VRT is presented that monitors breathing movements and assists users by encouraging them to regulate their breath and increase the oxygen percentage in their blood via an interactive platform. The overall framework is shown in Figure 1. The paper will first discuss the underlying theories and recent research work on virtual reality environments for therapy purposes. The conceptual framework for the implementation of our VR platform will then be presented. The paper will also present the basic architecture and the technical aspects of the virtual environment platform. The overall full-fledge implementation and test plan, however, is left as a future plan.

Manuscript received April 4, 2013, revised July 30 2013, accepted September 5, 2013.

A. Abushakra is with the University of Bridgeport, Bridgeport, CT 06604, USA (e-mail: aabushak@bridgeport.edu).

M. Faezipour is with the University of Bridgeport, Bridgeport, CT 06604, USA (phone: 203-576-4702; fax: 203-576-4765; e-mail: mfaezipo@bridgeport.edu).

U.S. Government work not protected by U.S. copyright.
C. Contribution

In this paper, we describe the conceptual framework of a virtual reality therapy environment to aid individuals by monitoring the breathing movements and motivating them to perform breathing exercises through computer aided visions to increase oxygen intake in their blood. The individual's breathing sound is used as an interfacing signal between the user/patient and the smart-phone-based VR framework. The framework analyzes the patient's breath in real-time and provides virtually real animations of the lungs as the inhalation and exhalation take place. The lung capacity is computed simultaneously as the patient is breathing and the patient is encouraged to take the next coming breath deeply if the previous one was not sufficient. For lung cancer patients, the framework animations also show cancerous cells diminishing virtually as the patient's breath is being regulated. This, in turn, may have the potential to virtually boost the immune system, decrease lung cancer symptoms and increase the chance of survivability of patients with cancer.

D. Paper Organization

The rest of this paper is organized as follows. Section II glances at earlier work related to virtual reality therapy frameworks. In Section III, our proposed conceptual framework is presented and the VRT framework components are elaborated. The developmental framework of our virtual reality therapy system is explained in Section VI. The conclusions and recommendations for future work appear in Section V.

II. Related Work

It is noteworthy to mention that the connection between the brain and body is comprehensible, with a powerful belief that visualizing something in the brain encourages the body to make it happen [2]. This appealing fact motivated many researchers to work along this path.

The computer visualization and imagery techniques to build a virtual reality application for cancer patients has been presented in [3][5]. These work present facts showing the effectiveness of using self-imagery to stimulate the immune system in order to enhance its efforts to protect the body from the disease. Moreover, while stress has been shown to retard the immune system, relaxation has the opposite effect. In [5], this was the motivation to develop a virtual reality visualization tool called Staying Alive for cancer patients. The system offers a motivation for users to relax while instantly visualizing their immune systems fighting against their diseases. White and red blood cells and malignant cells populate the virtual environment. The user navigates a white blood cell through the blood stream and "digests" malignant cells found along the way. In this virtual environment, the user, free of wires and other such encumbrments, engages the system by sitting in a room, practicing certain gestures to virtually fight against the disease .

Computer vision techniques are applied to monitor the user's hands and head in 3-D and a Hidden Markov Model framework is applied to identify the motions in real time.

Virtual reality systems have also been presented in [14] in order to stimulate the patients while receiving their treatment. The authors stated that VR systems improve the patients' state of mind, thereby improving their immune system. Their work involves studying the factors of VR in increasing pain tolerance for chemotherapy. The authors also introduce the advantages and difficulties of using VR as an added therapy to reduce pain. Their work is based on the fact that diversion from unwanted feelings such as pain and stress is one of the most effective therapy techniques in dealing with such feelings/diseases.

In [15], the authors present the development and design of a breathing interface and video game to promote compliance with post operative breathing exercises. An interactive spirometer was introduced to motivate patients to perform post-operative breathing exercises. The work, however, mostly described the early progress of an interaction device, game design, initial play testing and the usability of the game.

In [16], a virtual reality therapy system was introduced for the treatment of acrophobia and therapeutic cases with the objective of developing an affordable and more realistic virtual environment to perform visual therapy for acrophobia. The visualization was a PC-based framework using a virtual scene of a bungee-jump tower in the middle of a big city. The overall system has proven that VR therapy environments are successful, realistic, and at the same time very fascinating.

III. Proposed Conceptual Framework

According to many research investigations, and based on true numbers; Virtual Reality Therapy has proven to increase the chances of survivability of patients with cancer by 56% [5]. This type of therapy relieves the patient in a better and healthier virtual world, which directly increases their level of hope, and empowers the immune system. Similar to how stress can adversely affect any pain or disease in general, and increase the growth of cancer cells in particular, soothing and relaxing treatments, even in a fictitious world, has been a very effective method for treatment and recovery [17-18]. Moreover, breathing therapy is an established and serious supplementary treatment method for lung cancer [6]. Thus, the presented VR approach has the potential to further optimize breathing therapy for patients with lung cancer and in general.

With this motivation, the development of a virtual environment is proposed here which is intended to aid any user in general, and lung cancer patients in particular, by monitoring the user's breathing movements and motivating them to perform interactive regulative breathing exercises and simultaneously providing quantitative measurement of the progress and compliance. The framework includes 3-D computer animations of the human body, surfing through various tissue layers and cells, and eventually landing on the lung organ and cells. For patients with cancer, the patient is urged to diminish his/her own cancerous lung cells through certain breathing movements/interactions that he/she performs in this virtual environment.

This work introduces an on-going research of a conceptual VR framework to assist individuals regulate their breath. Capturing the breathing movements from the user through the acoustic signal of respiration is one of the major inputs of the framework. In addition to the acoustic breathing signal, the age, gender, height and the cancer stage of the patient (in case of lung cancer patients) will be other input factors of the framework. The framework will be a smartphone application (Figure 1) that will interface a breathing movement classification component, a
lung capacity estimation component and a visualization component (Figure 2). All the components will be integrated together to interact and to produce the overall framework output which includes 3-D virtual computer animations of the human lung cells moving according to the corresponding breathing movements of the user/patient. The patient will be encouraged to regulate his/her breath as he/she is observing the virtual lung organ/cell movements in real-time. In what follows, we describe the components of our VRT framework.

A. Lung Capacity Estimation

One of the main components of our VRT framework is the lung capacity estimation module. This component gives an estimate of the air-volume entering/exiting the lungs using the acoustic signal of respiration.

Breathing phases are divided into four different phases: inspiratory phase, inspiratory pause, expiratory phase and expiratory pause [19-20]. In this part, we identify the breathing phases and extract certain metrics of each phase to model and estimate the lung capacity. Voice Activity Detection (VAD) is one of the most effective functions that can differentiate between silence and speech phases [21]. By applying VAD on the acoustic signal of breath using a microphone and segmenting the breath cycles into inhale and exhale speech phases as shown in (Figure 3), the average time duration and energy of the breathing cycle can be computed to easily estimate the lung capacity by using the following metrics and factors:

1. **Gender and adult state**: The subject’s gender can affect the computation result, since physiologically, female lung sizes are generally different from male lungs.
2. **Age**: Subject’s age in years.
3. **Height**: Subject’s height in inches.
4. **Duration**: The duration of time which the subject blows air in the microphone.

5. **Signal Energy**: The amplitude of the acoustic speech signal through time.

The following steps show the basics of the lung capacity measurement procedure:

- First, the recorded acoustic breathing signal for each speaker/subject is split into inhale and exhale speech segments. The splitting process has been implemented using the VAD technique.
- Second, the start and end point of each speech segment (inhale and exhale duration) is marked.
- Third, the time duration between each start and end of speech segments (inhale and exhale) are computed.
- Fourth, the energy of the signal between each speech segment (considering all samples within the speech segments) are computed.
- Finally, the lung capacity, also referred to as Forced Vital Capacity (FVC), is modeled using the following equations (separate equations for male and female subjects) by substituting the five important factors: gender (m or f), age (a), height (h), breathing time (t), and energy (e). These equations were derived using empirical data and curve fitting to estimate the lung capacity:

\[
FVC_m = \frac{15e}{100} (0.1524h - 0.021a - 4.65)t
\]

\[
FVC_f = \frac{15e}{100} (0.1247h - 0.021a - 3.59)t
\]

In the above equations, the signal energy has been included in the lung capacity calculations in addition to the breathing time. Through analyzing the statistical model of lung capacity estimation, it is clear that signal energy plays an important role in lung capacity calculation, since it refers to the power of the breath signal. Essentially, this means that the actual power and depth of breath within a certain time of air blow forms the basis of lung capacity estimation [22-23].

B. Classification

Monitoring breath and identifying breathing movements via a microphone to detect and classify breathing movements is the goal of this component. Mel-Frequency Cepstral Coefficients (MFCCs) are coefficients that represent audio signal characteristics according to the human ear perception. It is based on the known variation of the human ear’s critical bandwidths with frequency. MFCCs are extracted through a series of steps that mainly include filtering, windowing, Fast Fourier Transform (FFT) and Discrete Cosine Transform (DCT) computations [24]. We employ MFCCs [24-25] along with speech segmentation techniques using Voice Activity Detection (VAD) and linear thresholding to the acoustic signal of breath captured using a microphone to depict the differences between inhale and exhale in frequency domain.

For every subject, 13-MFCCs of all voiced segments are computed and plotted. The inhale and exhale phases are differentiated using the 6th MFCC order, which carries important classification information. Experimental results on a number of individuals verify this classification methodology [25-26]. The following steps show the classification procedure:
• The recorded acoustic breathing signal for each speaker/subject is split into speech and silence segments. The splitting process was implemented using the VAD technique, as described earlier.
• The 13-MFCC layers for each speech/voiced segment of the same speaker are calculated.
• The 6th MFCC for the speech breathing segments of each speaker are further analyzed using the linear thresholding method of averages, where the inhale and exhale utterances are differentiated from being above/below the threshold (See Figure 4). These differentiated MFCCs are then related back to the speech segments to mark which segment was corresponding to inhale and which one was for exhale.

C. Visualization

In this framework, the visualization component displays a virtually-real animation of the lungs in real-time that encourages the patient to regulate his/her breath (Figures 1 and 5). The patient interacts with 3-D animations that virtually resemble real lung cells [26–27]. Breath movements such as inhale and exhale are to be identified and the user is encouraged to regulate his/her breath through the framework. These movements may also virtually navigate the patient’s cancer cells to certain directions. As the patient is manipulating his/her own cancerous cells in a relaxing virtual environment, he/she is actually practicing one of the best known techniques for treating lung cancer; that is breathing treatments to increase oxygen intake [28].

The modeling and visualization of human lungs in this work will be performed using high-definition 3-D animations. In general, many different methods and techniques exist for generating high-definition 3-D animations of the human lung. These methods start with the knowledge of lung anatomy, followed by High Resolution Computed Tomography (HRCT) imaging protocols [29]. In [30], a method which consists of a symbolic description of lung anatomy and a 3-D atlas using HRCT volume data is presented for modeling and visualizing human lungs. Modeling of real-time deformations of 3-D high-resolution polygonal lung models in this work will be obtained from High Resolution Computed Tomography (HRCT) [31]. This model for the visualization component ensures high-quality animations which allows the patient experience the VRT as if it were for real.

VI. DEVELOPMENTAL VIRTUAL THERAPY FRAMEWORK

The development of our highly feasible and portable virtual reality therapy framework on a smart-phone device customized to monitor breathing movements and assist in breath regulation starts with the Application Programming Interface (API) specification intended to be used as an interface for the framework components to communicate with one another (Figure 6). The Data Source contains the patient information including the age, gender, height and the cancer stage which passes through the Data Analysis block to the Mobile Element where the acoustic breathing signal of the user/patient is captured.

The user/patient would initially enter a virtual environment by activating an application on a smart-phone that is to be developed by integrating the system components; breathing movement classification component, lung capacity estimation component and the visualization component (Figure 2). A goggle may be used to enhance 3-D visibility and to also detach the patient from surrounding distractions. As a result, the user will then observe high quality animations of the human body through the goggle. The Operations Management block manages the system operations starting from generating an avatar of the patient around the chest area, gradually penetrating through skin, muscles, and finally approaching the lungs. The framework zooms on the lung organs and also visualizes the tumor forming the cancer virtually for patients with cancer. When the patient breathes, movements are captured through the microphone of the smart-phone.

Various breath movements are to be identified/classified in this framework and each movement is to be reflected differently on the animation as the lung capacity is calculated in the Execution Environment. The Generate Environment block uses the Environment Management block to integrate the input and guarantee the run-time for the application. If there is any interruption that happens to the system, it is handled by the Function Filter block. The overall functionality will be performed by permitting patients to see a virtually real image of their lungs while they are breathing, so that when their inhale/exhale is less than normal, they will be motivated to take their next coming breath more efficiently. This, in turn, will lead to increasing the oxygen percentage in their blood.

The real-time functionality of this framework is critical to synchronize the breathing movement classification, lung capacity estimation and the animations the patient will see on the screen. This is done by splitting the captured acoustic signal into small chunks of data and storing it in the memory units of
the device (smart-phone) and then processing only small chunks at a time with a small delay (less than a portion of a second), which makes it feel as if it were functioning in real-time for the user/patient.

The state diagram in Figure 7 shows the flow of the events in the framework. The flow of events in each breathing exercise session is described as follows:

- **(S0) The Start state** is the initial state at the beginning of the breathing exercise session. The initial Lung Volume (LV) is initialized to zero \( LV = 0 \) in this state.
- **(S1) In the Capture state**, the acoustic signal of respiration of the patient is being captured via a microphone (smart-phone embedded microphone).
- **(S2) The Classification state** is the state where the breathing movements are classified into inhale or exhale.
- **(S3) Then, in the Lung Capacity state**, the amount of air that is inhaled or exhaled to/from the lungs is computed. This value is denoted as \( LV_{new} \).
- **(S4) In the Counter state**, the accumulating amount of oxygen represented in the lung is computed by summing up the lung volume values from the beginning of the breathing exercise session; \( LV = LV + LV_{new} \). If the lung volume has not yet reached the target limit (which can be predefined in each breathing exercise session), the system will return to state (S1); the Capture state, otherwise it will go to the End state.
- **(S5) The End state** is where the breathing exercise session is terminated.

Figures 8 and 9 show the screenshot of an early-phase development of our VRT on a smart-phone app. These Figures illustrate the states of the VRT for one breathing exercise session, providing quantitative measurement of the progress.

Figure 9.a. shows the personal information (age, gender, height, and cancer stage) collected from the user/patient.

Figure 9.b. shows the screenshot of the lungs in the app right before the patient starts breathing in the breathing exercise session. In this state, the air volume of the lung is in its smallest size \( (LV = 0) \).

Figure 8 shows the list of parameters calculated during the patient's breathing cycle while the system is capturing the acoustic signal of the patient's breath through the smart-phone microphone. These parameters are:

- **Current lung size**: the air volume of the current breathing cycle (S3) computed from Equations 1 or 2.
- **Lung capacity**: This is the desirable (target) air volume that the patient would like to achieve in the breathing session. It is normally set to a predefined default value based on the users goal or patient's cancer severity stage.
- **Total lung capacity**: the accumulated value of the lung volume (S4).
Lung capacity in each breathing cycle: This shows the lung volume computed in each breathing cycle of the session separated by commas.

Figure 9.c. shows the screenshot of the lungs in the app in the middle of the breathing exercise session. In this intermediate stage, it is observed that the lungs are inflated as compared to the initial stage, as the air volume has increased. The previous values and parameters are also shown in this Figure.

Figure 9.d. shows the screenshot of the lungs in the app at its maximum size at the end of the breathing exercise session. The patient continues to perform the breathing exercise until he/she has gained the intended lung capacity during the session.

Promising results (>85% accuracy) on a number of subjects (20-125 subjects) motivated us to deploy the microphone embedded within a smart-phone for lung capacity estimation and breathing movement classification [22-25].

The work presented in this paper is the conceptual framework of the intended virtual reality platform. The various components of the framework are integrated together efficiently for a high-performance real-time functionality.

V. CONCLUSIONS AND FUTURE DIRECTIONS

Lung cancer patients and those with breathing disorders (e.g. patients with asthma) usually go through severe breathing conditions. However, a customized virtual reality therapy environment which allows users/patients to virtually visit their lung organs/cells and encourages them to regulate their breath, appears to be a promising approach for any general user as well as patients to empower their immune system and eventually fight off the disease.

This paper introduced a conceptual framework of a smart-phone based virtual reality environment that deals with analyzing acoustic breathing signals in real-time to monitor respiration movements. This work suggests that if such a framework were to be fully implemented, the proposed components should be in place in order to have it functional. In continuation of this research, we intend to fully implement and test the virtual reality platform to assist users regulate their breath by integrating the proposed framework with a high quality animated application on a smart-phone. As breathing therapy is an established supplementary treatment method for lung cancer, the presented VRT has the potential to further optimize/regulate breathing for patients with lung cancer and in general by providing a daily basis estimate of their lung size using a hand-held device at home.

In the future, when fully functional, the proposed breathing VRT can be compared with other breathing therapies to measure the effectiveness of the work. However, this requires clinical trial on lung cancer patients or those with breathing disorders for a long period of time, which is clearly beyond the scope of this paper.

REFERENCES


U.S. Government work not protected by U.S. copyright.
Ahmad Abushakra received the Ph.D. in Computer Science and Engineering from the University of Bridgeport in 2013. He received his B.S. in Information Technology from Philadelphia University in 2004 and his M.S. degree in Management Information System from the Arab Academy for Banking and Finance Science in 2007. He worked for The Arab Education Forum as Web Developer until August 2008. In September 2008, he became an Information Technology Manager for The Arab Education Forum. His research interests are in the areas of smart mobile phone content information, management systems, virtual reality systems development, mobile web application systems and web technologies.

Maid Faezipour (S’06–M’10) is an Assistant Professor in Computer Science and Engineering and Biomedical Engineering at the University of Bridgeport, CT and the director of the Digital/Biomedical Embedded Systems and Technology (D-BEST) Lab since July 2011. Prior to joining UB, she has been a Post-Doctoral Research Associate at the University of Texas at Dallas collaborating with the CICS and QoLT laboratories. She received the B.Sc. in Electrical Engineering from the University of Tehran, Tehran, Iran and the M.Sc. and Ph.D. in Electrical Engineering from the University of Texas at Dallas. Her research interests lie in the broad area of biomedical signal processing and behavior analysis techniques, high-speed packet processing architectures, and digital/embedded systems. Dr. Faezipour is a member of IEEE, IEEE EMBS and IEEE Women in Engineering.