mCOPD: Mobile Phone Based Lung Function Diagnosis and Exercise System for COPD

[†] Wenyao Xu, [†]Ming-Chun Huang, [†]Jason J. Liu, [‡]Fengbo Ren, [‡]Xinchen Shen,
[‡]Xiao Liu, [†]Majid Sarrafzadeh
[†] Wireless Health Institute, University of California, Los Angeles, California, 90095, USA
[‡] Electrical Engineering, University of California, Los Angeles, California, 90095, USA

ABSTRACT

COPD (Chronic Obstructive Pulmonary Disease) is a serious lung disease that causes difficulty in breathing. COPD patients require lung function examinations and perform breathing exercises on a regular basis in order to manage and be more aware of their health status. In this paper, we designed and developed a mobile-phone based system for lung function diagnosis, called mCOPD. Besides enabling accurate COPD examinations at home, the mCOPD system also offers a video-game based guidance system for breathing exercises. We evaluated mCOPD in controlled and uncontrolled environments with 40 subjects. The experimental results show that our system is a promising tool for remote medical treatment of COPD.

Keywords

COPD detection, Android, Spirometer, Wireless health

Categories and Subject Descriptors

J.3 [**Health and Medical information systems**]: LIFE AND MEDICAL SCIENCE

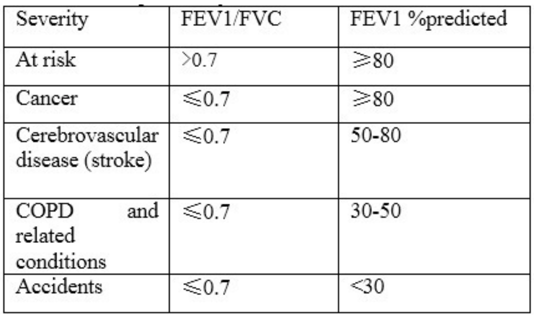
General Terms

Design, Economics, Reliability, Experimentation

1. INTRODUCTION

1.1 COPD Introduction

Chronic obstructive pulmonary disease, although incurable, is a treatable illness that affects both lungs and other important body systems. The leading cause of COPD is smoking, and COPD has become more prevalent during the past twenty years [1]. It is reported that COPD and related conditions are the fourth leading cause of death in United States, after heart disease, cancer and stroke [2]. More specifically, COPD kills more than 126,000 Americans annually [3]. The mortality rate of COPD and related conditions rose nearly 40% from 1979 to 2009, and may surpass stroke to become the third leading disease worldwide by 2020 [4].



Severity	FEV1/FVC	FEV1 %predicted
At risk	>0.7	⩾80
Cancer	⩽0.7	⩾80
Cerebrovascular disease (stroke)	⩽0.7	50-80
COPD and related conditions	⩽0.7	30-50
Accidents	⩽0.7	<30

Figure 1: Spirometric classification of chronic obstructive pulmonary disease (COPD) [5]

Spirometry is the most common and effective instrument for diagnosis of COPD. In fact, spirometry is as important in diagnosing COPD as blood pressure measurements in the diagnosis of hypertension. Spirometry is a simple test to measure the amount of air a person can breathe out, as well as the amount of time taken to do so. There are three important parameters in spirometry testing: forced expiratory volume in one second (FEV1), forced vital capacity (FVC), and the ratio of the previous two features (FEV1/FVC). FVC indicates the maximum volume of air that can be exhaled during a forced maneuver. FEV1 is the volume exhaled in the first second of maximal expiration after a maximal inspiration. This parameter is an indicator of how quickly the lungs can be emptied. FEV1/FVC, the ratio of the above two features, gives a clinically useful index of airflow limitation. By analyzing these three features, physicians can track changes in patients' lung functions. As shown in Figure 1, FEV1/FVC ≤ 0.7 can confirm non-reversible airflow limitation.

Spirometric classification has proven to be useful in various areas of COPD [5]. The major areas in which we are interested are predicting health status [6, 7] and mortality [8]. It has been proven that spirometry is not only useful for initial diagnosis but also for long term monitoring. It is also one of the motivations for a long term COPD monitoring system.

The Global initiative for Obstructive Lung Disease (GOLD) classifies COPD into four stages: mild, moderate, severe, very severe. These stages are classified based on the value of FEV1/FVC. There are some common ways that can alleviate the symptoms such as smoking cessation, healthy nutrition and exercise. Another way to greatly improve the condition is to change the way we breathe. There are several

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useful breathing exercises: pursed-lip breathing, diaphragmatic breathing, comfortable breathing, and forceful coughing [9]. For most of the exercises, patients need to breathe as smoothly and slowly as possible. This requirement illustrates the need for an assisted method [10, 11] to guide people in performing the correct breathing exercise.

1.2 Our Contribution

In this paper, a new mobile phone based system that is both economic and accurate is proposed and designed for daily COPD evaluation and treatment guidance. In contrast to traditional COPD diagnostic devices, our mCOPD system can be entirely integrated in the mobile phone. By leveraging the built-in microphone, we developed efficient computational modeling to estimate lung functions through sound signals.

There are four major advantages of mCOPD compared to the traditional COPD diagnostic instruments. Firstly, the mCOPD system will dramatically reduce the cost of spirometry systems since it is only based on the existing smart phone platform without any extra sensors. Secondly, the portability of smart phone makes it ideal for daily COPD monitoring and long term reporting for lung function. With the mobile phone network, patients can upload their COPD related data anywhere and get evaluation results and feedback effectively. It will increase their interest in using the system in long term due to the convenience. Thirdly, the extensible features of smart phone [12] technology make it easier to update the functions in the future. According to the demands of physicians and patients, the system can be easily personalized for better status monitoring of COPD. Finally, novel guidance can be implemented on the mobile phone. More specifically, the mCOPD system has been integrated with one or more games [13, 14] to help patients with breathing exercises during their treatment stage. It will be a unique feature different from the traditional COPD treatment.

The remainder of this paper is organized as follows. Section 2 discusses existing solutions and related research work on the instruments for COPD diagnosis. Section 3 introduces the system architecture in our mCOPD system. Section 4 presents, in detail, the design of the mCOPD diagnostic subsystem structure. Section 5 elaborates the phone-based gaming for COPD treatment. Section 6 discusses the experimental evaluation of the mCOPD system. The future work and conclusion are concluded in Section 7.

2. BACKGROUND AND RELATED WORK

2.1 Existing Products and Solutions

In the current market, there are a variety of different spirometers. Most of them are not designed exclusively for COPD detection but they can all be used to detect FEV1 and FVC. Here we classify the current products into three categories: traditional spirometers, portable spirometers, and computer-aided spirometers.

2.1.1 Traditional Spirometers

Traditional spirometers are capable of accurately measuring more than 50 different spirometric features. They are often purchased by hospitals for professional diagnosis of different kinds of lung disease. The advantage of this kind of traditional spirometer is the accuracy and range of functionality. However, the trade off is size and price. This kind of system is far from affordable to the average person. Moreover, it is apparently not suitable for regular monitoring by patients and are usually stand alone devices.

Figure 2: Current examples of existing spirometers. From left to right: Traditional, Computer-aided, and Portable Spirometers

2.1.2 Portable Spirometers

This kind of spirometer is in a dominant position in today's home-based COPD lung function detection and monitoring market. Portable spirometers are handled easily. Compared with the traditional spirometer, many unused functions are not implemented, leaving just the core features like FEV1 and FVC. This greatly simplifies the design and cost of the system. With a simple processor and circuit, typically it can not process and record data after measurement. Most of the portable spirometers are also stand alone systems. This restricts the applications in the future, especially in long term monitoring. Moreover, it has some guidance features to help patients in treatment stage.

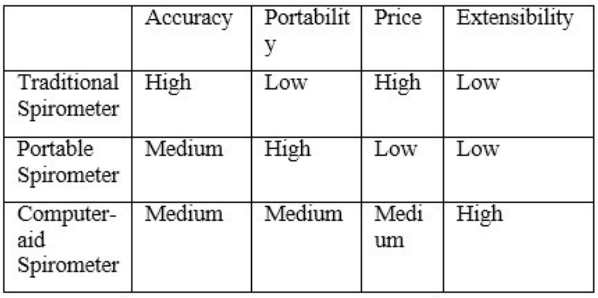
2.1.3 Computer-aided Spirometers

Computer-aided spirometers are the newer models on the market. This kind of spirometer commonly utilizes the USB interface of a computer to transmit the sensor data onto the computer. Unlike the portable spirometer, USB spirometer can use high-performance computers to do complex data analysis, data collection, date management, and data sharing. The main problem of this kind of device is that it is still not convenient to move from one place to another. Even though the cost has been greatly reduced, the spirometer and software is still quite expensive. We need a more economical and general solution.

A comparison between different off-the-shelf spirometers is summarized in Figure 3.

2.2 Related Work

Mobile phone based COPD detection is a relatively new application. However, our work gains motivation from some previous work. SpiroSmart [15] provides a good approach for mobile phone based lung function detection. It also tries to utilize the internal microphone for lung capacity detection. Moreover, the sound based medical sensing is developed in several other related areas. [16,17] did wide research



	Accuracy	Portabilit y	Price	Extensibility
Traditional Spirometer	High	Low	High	Low
Portable Spirometer	Medium	High	Low	Low
Computer-aid Spirometer	Medium	Medium	Medi um	High

Figure 3: The comparison among different kinds of spirometers

on coughing sound and breath detection. Wheeze detection for asthma diagnosis has also lead to positive results [18,19].

Compared to the above work, the mCOPD system provides a different way in audio based lung function sensing. Moreover, the game based rehabilitation system is novel for this application.

3. SYSTEM ARCHITECTURE

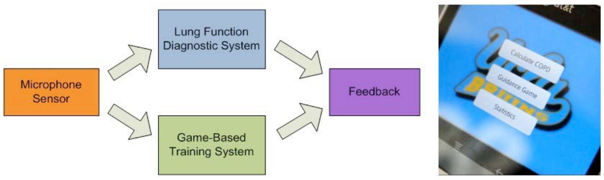


Figure 4: System Structure and the User Interface

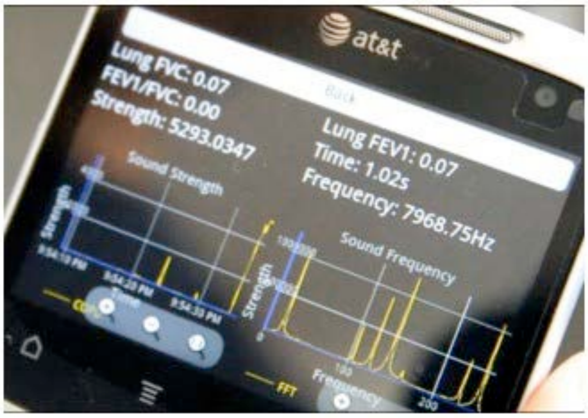
There are two functions in the mCOPD system: COPD diagnostic system and COPD gaming treatment system, as shown in Figure 4. The system can support two major operations: lung function measurement and exercise game guidance. Patients are able to create their own records based on their name, height, age and sex. The record of lung function information can be transferred to doctors for diagnosis.

From a user's point of view, there are three parts in mCOPD. 1) The COPD diagnostic system mainly focuses on calibration of FEV1, FVC and other related medical parameters. These parameters can by calculated by capturing the input airflow signal from internal mobile device microphone. 2) COPD gaming treatment system provides a novel way for patients with COPD to finish their daily treatment exercise. A video game is developed and implemented in the system in order to increase the patients' interest in rehabilitation exercise. In this way, the patient compliance can be improved. 3) A stand-alone statistics module is also implemented in the phone. This part can visualize the history data, which benefits both patients and physicians to be easier in tracking the diagnostic and exercise history.

4. DIAGNOSTIC SYSTEM DESIGN AND IMPLEMENTATION

4.1 System Overview

The COPD diagnostic system is the most important part in the mCOPD system. As mentioned above, our system detects the airflow based on air noise sound. Figure 5 shows the COPD diagnostic system user interface. It contains two major parts: the signal chart and the data presentation. For the data presentation part, three major features FVC, Lung FEV1 and FEV1/FVC are shown. Time field indicates the total time of a patient's exhalation at the current detection. The strength value shows the direct sampled microphone value. This is an important index for determining the airflow value.



Lung FVC: 0.07
FEV1/FVC: 0.00
Strength: 5293.0347
Lung FEV1: 0.07
Time: 1.02s
Frequency: 7968.75Hz

Figure 5: COPD Diagnostic System User Interface

The COPD diagnostic system consists of four procedures: sensing, signal pre-processing, modeling and calculation, and signal post-processing. The sensing part serves as the input collection of the system. As shown in Figure ???, the airflow signal is captured by microphone membrane and then transformed into an analog signal. In the signal pre-processing procedure, the analog signal is sampled at 2.4kHz. The sampled signal will then be converted into 8-bit digital signal via internal ADC. In order to analyze the frequency domain features, 64-point FFT is performed tho the signal. This choice balances the resolution requirements of the analysis and the performance of the current mobile device. The transformed frequency signal will also need to go through low-pass filters to eliminate noise. In the modeling and calculation procedure, two different machine learning regressions are used on the low-frequency signal. As a result, the low-frequency signal will be matched into specific airflow speed. This instant airflow speed will then be transmitted into the final stage. In the signal post-processing procedure, the airflow speed is integrated via certain cross section area. The medical parameters will then be obtained and output for future use.

We will discuss the details of each part in the remaining part in this section.

4.2 Sensing Procedure

There are three kinds of off-the-shelf sensors which are widely used for lung function instruments: pressure sensor, mass air flow sensor and air volume sensor.

There are special requirements on the mCOPD system. In order to achieve maximum compatibility, we tend to choose the internal sensors based on performance, price and availability. The mobile device MEMS microphone would be a good choice. The MEMS microphone has a similar structure as the electret microphone, as shown in Figure 6, the membrane on the microphone will vibrate with the coming air pressure. The vibration will then be transformed into a voltage signal.

Several related work have shown that there are two major components in the wind noise: Natural flow turbulence in the wind and turbulence generated during the interaction between the microphone membrane and wind. [20] The natural flow turbulence can be well eliminated via specially selected wind generation. The interaction turbulence will then serve as the main source of voltage output from microphone. This makes the direct airflow sensing possible in theory.

Research has shown that a decreasing function of frequency can be obtained in the recorded wind noise. [21] Most of the energy will be conserved in the low frequency area. Thus, the airflow coming from the mouth will perform as a low frequency sound pressure. This sound pressure measurement will present as noise in the output sound signal. Richard et al. [22] have shown that this wind noise on the bare microphone could be approximated well by fluctuating stagnation pressure. The stagnation pressure is the pressure measured at the sphere's zero velocity position. The one-dimensional model has proved to be effective:

$$p(t) = (1/2) * \rho * v + \rho * V * v(t) + (1/2) * \rho * v(t)^2 \quad (1)$$

where ρ is the ambient density, V is the average flow velocity, and v(t) is the fluctuating velocity magnitude. The MEMS microphone is suitable also because of its low price and widely availability. No more extra accessories need to be bought for the basic mCOPD system. This will greatly extend the system accessibility.

4.3 Signal Pre-Processing Procedure

Frequency domain computational model is established based on the MEMS microphone. Frequency domain analysis has certain advantages compared with time domain analysis in airflow calibration. First, the time domain analysis leads to saturation problems. Unlike the sound pressure, the airflow will easily saturate the membrane vibration. This leads to maximum output from microphone in the time domain. In practical, most of the variational characteristics will be lost in the time domain. The frequency domain analysis overcomes this limitation. Due to the feature of airflow, most of the frequency components lie in the relatively low frequency area, specifically below 1.2kHz. A low-pass filter could be applied to eliminate the background noise. Moreover, the resolution requirement of the system is also relatively low. A 64-point FFT is sufficient in practical application. This requirement could be satisfied in most of today's mobile devices.

The output of the computational model will first be the airflow speed. The output serves as the basic component for computing expected medical requirements like FEV1 and FVC. Post processing will be applied in the later stage.

4.4 Modeling and Calibration Procedure

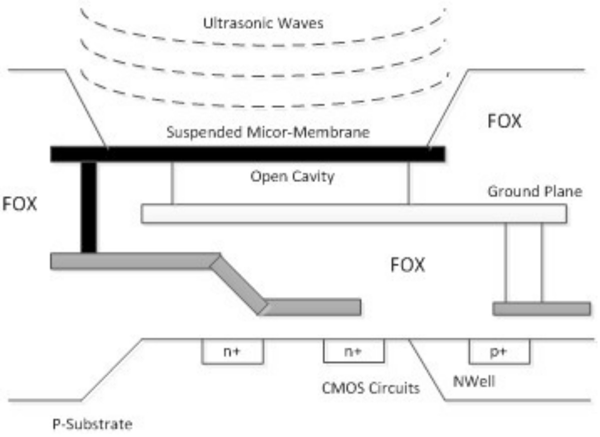


Figure 6: MEMS Microphone Structure[17]

Two machine learning regressions are applied for solving the computational model. Frequency response will serve as the feature selection component.

Nearest neighbour matching is first used to match the input frequency response to wind speed. The training samples are first collected via our test platform. These training samples will be stored in the system as a reference table. Both the geometric and average distance between the input frequency response and different sets of reference points will be calculated. The reference set with the nearest distance will be chosen as the output wind speed. Nearest neighbour matching will be a good alternate when mathematical analysis is not available. The resolution of the result depends on the quality of the training samples. In practice, the resolution can be reduced to 0.2m/s in certain controlled environments. However, the input frequency response can not exceed the maximum and minimum value of the training samples. This leads to high quality requirements of collecting procedure.

Mathematical Analysis is the second and better method for the frequency response wind speed model. A second-order mathematical regression model is established based on the training samples and historical research. The input frequency response will then serve as the input of the mathematical model. The mathematical regression overcomes the limitation of nearest neighbour matching. After the mathematical relation is established, the output wind speed can be well predicted.

4.5 Signal Post-Processing Procedure

After wind speed is obtained through computational model regressions, post processing is needed to obtain the actual required medical features. In mCOPD, we assume that the interface area of the mouth when doing the lung capacity test is the same. Integration of wind speed via certain fixed area will be done in the final stage. FEV1 will first be obtained in the first second. After that, a threshold will be set to calculate the FVC.

5. COPD BREATHING EXERCISE GAME

5.1 Exergaming and Design Criteria

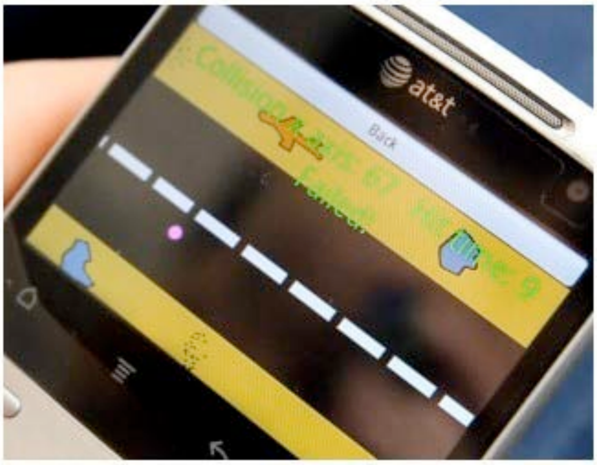


Figure 7: Game Exercises for COPD Patients

Exergaming, short for exercise games, is a recent development in entertainment gaming. The goal of today's video games is not only to have fun, but also to provide benefits to your health. Based on this concept, we designed an interesting game which not only provides fun, but also includes rehabilitation exercises while playing it.

COPD patients are required to do certain kinds of rehabilitation exercises in order to learn how to get the most air out of every breath. Dyspnea, or shortness of breath, is a result of air hunger that causes people to feel like they cannot catch enough breath. It is primarily due to the lack of oxygen in the bloodstream and directly related to disturbances in the lungs caused by COPD. Using pursed-lip breathing technique could slow their exhalations and make their breaths longer and using diaphragmatic breathing technique could increase the amount of inhaling and exhaling air.

Pursed-Lip Breathing is a breathing technique designed to help control dyspnea, the hallmark symptom of COPD. The following demonstrates the simple technique of pursed-lip breathing: patients need to draw the lips together as if they were going to whistle and blow out through pursed lips slowly and evenly, and try to make the exhalation time longer than the inhalation time. Practicing pursed-lip breathing on a daily basis 3 to 4 times a day will allow patients to use it effectively during times of need, especially when their shortness of breath worsens [23].

Diaphragmatic Breathing is a breathing technique slightly more complicated than pursed-lip breathing. Diaphragmatic breathing helps strengthen the diaphragm and the abdominal muscles allowing more air to move in and out of lungs without tiring the chest muscles [24].

Our gaming challenges are designed based on these breathing criteria. Users need to follow one of these two breathing techniques to pass some of a day's challenges and follow the other to pass the rest.

5.2 Key components in the game

In this designed exergaming, user controls the movement of a colored ball through blowing to the microphone. The ball moves vertically high or low proportionally to the strength of exhalation. COPD patients are required to using Pulsed-Lip Breathing to exhale into the microphone slowly and evenly in order to generate stable sound signal. We require players to try their best to control their breath and make the colored ball move in the range of the background road. It is especially hard for people with chronic lung disease to continuously provide a strong enough airflow at the latter stage of one exhalation. If patients can't control their breathing during this set of period, which means they probably will either make a very strong exhalation at the first half stage or only can provide a very weak airflow coming to an end, the colored ball will either hit the upper bound of the road or falls below the lower bound. Both situations will lead to the failure of the game. The speed of the ball moving from screen left to the right is configurable. Since the speed is a reflection of the length of expiration time, players can set the speed at the beginning of the game according to their current ability.

Figure 8: Dyson Air Multiplier used in our experiments

Game difficulties can be increased through lowering the speed of the colored ball which requires longer stable exhaling time in succeeding the game. Game difficulties can also be increased through requiring patients to use Pursed-Lip Breathing when inhaling and use Diaphragmatic Breathing when exhaling which in another way increases their exercise tolerance.

Patients can finish daily exercise through completing certain amount of tasks in the game. mCOPD will record exercise data which includes number and type of exergames have been played and success rate and send it to doctors via internet. In this way, doctors can monitor patients' in-home rehabilitation exercise through real data.

6. EXPERIMENTS AND RESULTS

We evaluate the effectiveness of the mCOPD system for two different aspects. First, we validate the accuracy of the microphone model. Second, we test the overall performance of mCOPD while measuring lung function parameters.

6.1 Model Verification

In this part, we try to validate the accuracy of the microphone model. In order to find corresponding relations between the frequency response of microphone and different

Figure 9: Experimental Setup

airflow rate, we attached our microphone to the place near the air intake of a digital portable anemometer. Thus, the speed of air which causes sound signals on microphone is the same of that goes through the anemometer. We put the microphone together with the anemometer 10-15cm away from the air multiplier in order to catch the strongest airflow generating from it. The air multiplier as shown in Figure 8 is a blade-less fan producing speed-stable airflow with continuous airflow speed adjustment.

We did 12 training tests at the first place. Experimental setup is shown in Figure 9. The speed of wind in our training ranges from 2.1m/s to 4.4m/s with 0.2m/s increments. Experimental result shows that there exists a clear relationship between the airflow rate and the corresponding frequency responses of microphone. The frequency response of our testing microphone to airflow with speed 2.1m/s looks like this (Figure 10). Figure 11 shows all the frequency response curves of these 12 tests. We can see from Figure 11 that as the airflow rate increases, the frequency response strength increases as well. We can see the curve moves upward along with the Y axis in Figure 11. Figure 12 shows the change in response intensity at a specific frequency point with the increase of airflow rate. From Figure 12 we find that almost every frequency point within the response region increases along with the increase of airflow speed and they are of certain mathematical quadratic relation. The red curve in Figure 12 is a quadratic mathematical fitting curve we use to approach the increasing trend we get from our tests.

Frequency responses of mobile phone based microphone to various airflow rates are mainly concentrating on the lower frequency part. We pick the first 16 frequency points and got their fitting quadratic mathematical equations based on our 12 training tests. When patients use our mCOPD spirometry, we assume in a very small time interval the airflow rate is stable, so the frequency response of microphone within that time interval is also stable. We choose the responses intensity of the first 16 frequency points. Put them into their quadratic equations respectively and we get 16 predicted airflow rates in total. The mean of the 16 numbers is our predicted speed for that small time interval. The instantaneous predicted speed multiplies the cross-section area of a mouthpiece that we provide in our tests to control airflow multiplies dt is the instantaneous air volume of that time interval. At the end, we integrate all these instantaneous air volumes together then we get the total lung capacity of the user.

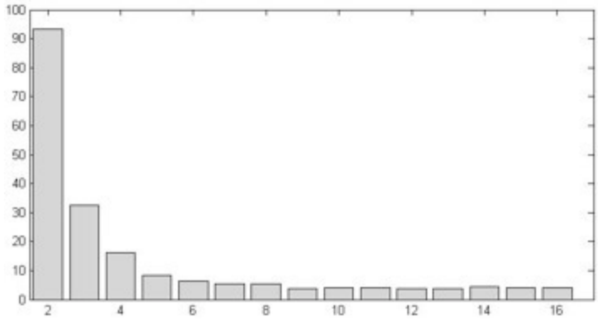


Figure 10: Frequency Response of Microphone to Airflow with Speed 2.1m/s

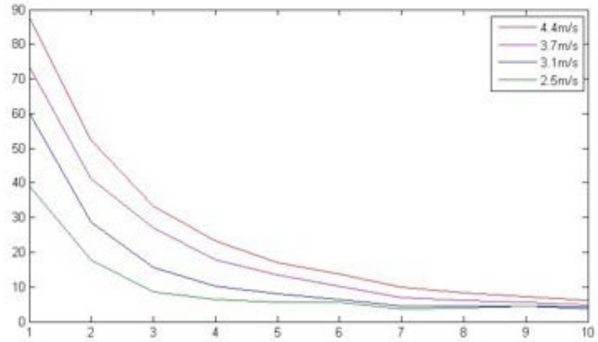


Figure 11: Frequency Response Curves on different airflow speed

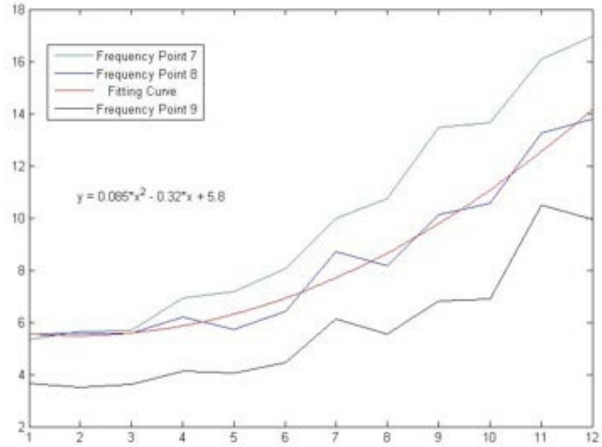


Figure 12: Change in Frequency Response Intensity with the increase of airflow speed

6.2 mCOPD Performance on FEV1, FVC Calculation

After we verified our microphone model, we transferred our mathematical model into our mobile phone application m-COPD and did 40 concurrent tests using a mobile phone and a digital spirometer. Test results (Figure 14) show that the average deviation between the data FVC tested by mCOPD and the data tested by the digital spirometer is about 6.5%; the average deviation between the date FEV1 tested by mCOPD and the data tested by the digital spirometer is about 3.6% (Figure 15); the average deviation of the data FEV1/FVC when compared to the clinical spirometer is 3.9% (Figure 16) for common measures of lung function.

Figure 13: One Subject with traditional spirometer and mCOPD

6.2.1 Test Setup and Procedure

To evaluate and inform the design of mCOPD, we find 40 volunteers to participate in our comparable test. Our custom lung function diagnosis application for Android recorded subjects' exhalation sound using the built-in microphone and provided feedback to the user based on testing data. We also obtained measurements during the same session using a standard clinical spirometer. The spirometer is a fully electronic spirometer. It measures the speed of the airflow by measuring pressure difference in the channel. Figure 13 shows the use procedure of mCOPD.

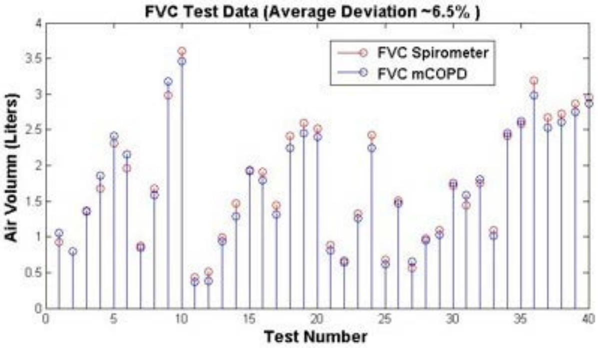


Figure 14: FVC difference between mCOPD Data and Actual Spirometer Data (average deviation is 6.5%)

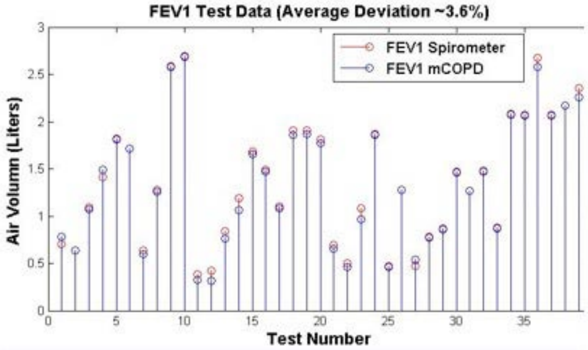


Figure 15: FEV1 difference between mCOPD Data and Actual Spirometer Data (average deviation is 3.6%)

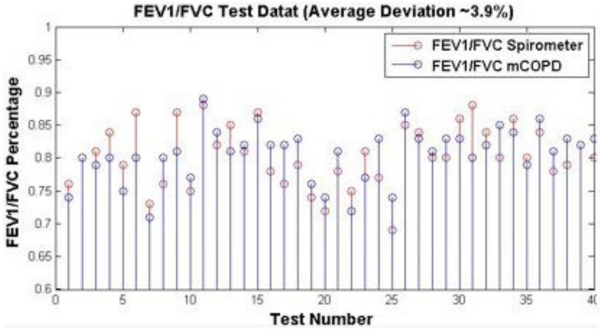
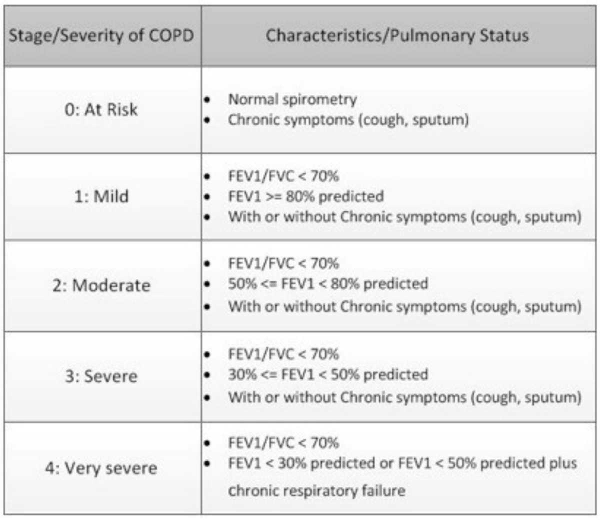


Figure 16: FEV1/FVC difference between mCOPD Data and Actual Spirometer Data (average deviation is 3.9%)

Participants hold the clinical spirometer and exhale to the mouthpiece. Since the cylindrical mouthpiece is hollow, we fix the mobile phone in front of the mouthpiece. In this way, all air going through the mouthpiece will produce signals on the built-in microphone. The distance between the mobile phone and tester's mouth is very close and there is no resistance inside the mouthpiece, so the decrease of airflow speed between this short distance is very limited. Using this set up, after one fully exhalation of tester, we can get two results simultaneously from the mobile phone and from the clinical spirometer. Spirometry measurements rely largely on effort. Each participant is coached how the test is conducted and is asked to practice using the spirometer first before we feel they are able to perform an acceptable test.



Stage/Severity of COPD	Characteristics/Pulmonary Status
0: At Risk	• Normal spirometry • Chronic symptoms (cough, sputum)
1: Mild	• FEV1/FVC < 70% • FEV1 >= 80% predicted • With or without Chronic symptoms (cough, sputum)
2: Moderate	• FEV1/FVC < 70% • 50% <= FEV1 < 80% predicted • With or without Chronic symptoms (cough, sputum)
3: Severe	• FEV1/FVC < 70% • 30% <= FEV1 < 50% predicted • With or without Chronic symptoms (cough, sputum)
4: Very severe	• FEV1/FVC < 70% • FEV1 < 30% predicted or FEV1 < 50% predicted plus chronic respiratory failure

Figure 17: Stages of COPD [25]

6.3 Diagnostic Recommendations for Different Stages

mCOPD will give out diagnostic recommendations at the end of every breathing test based on testing results (FEV1, FVC, FEV1/FVC) and existing guidelines from the Global Initiative for Chronic Obstructive and Lung Disease (GOLD) for COPD Diagnosis and Management (see Figure (Figure 17)). mCOPD will also provide different treatment recommendations for different stages. For example, after a breathing test, mCOPD detect that the tester may possibly be at stage 1 of COPD. mCOPD then gives out a list of treatment recommendations to the tester, like: quit smoking, get flu and pneumonia vaccine, take Bronchodilators, eat healthy and do daily exercise, etc.

7. CONCLUSION AND FUTURE WORK

As the third leading cause of death in United States, COPD is now gaining more and more attention by both physicians and patients. The mCOPD lung function diagnosis and exercise system successfully combines novel airflow sensing method with smart phone based exergaming which explores a new way in long term COPD monitoring and gives out a brand new method in rehabilitation exercising with high user compliance. Future extensions are also possible in either remote data transferring or adding gaming features. More research will be done in the future in order to improve calibration and network data sharing.

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