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

A thesis submitted in partial satisfaction
of the requirements for the degree
Master of Science in Electrical Engineering

by

Xiao Liu

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Abstract of the Thesis

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

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Master of Science in Electrical Engineering

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Professor Majid Sarrafzadeh, Chair

COPD (Chronic Obstructive Pulmonary Disease) is a serious lung disease which makes people hard to breathe. The number of people who have COPD is on the rise. COPD patients require lung function examinations and perform breathing exercises on a regular basis in order to be more aware of their lung functions, get diagnosed early, and control the shortness of their breaths. In order to help people with COPD, we developed mCOPD which is a smartphone based Android application made especially for COPD patients. COPD patients can do breathing test on mCOPD. mCOPD will automatically record test results and send data to doctors via the phone, assisting them in making diagnostic decisions. A novel game based breathing exercise system is also offered by mCOPD. We evaluated mCOPD in controlled and uncontrolled environments with 40 subjects. Deviation between the test results of using mCOPD and using a digital spirometer is about 10%. The experimental results show that this mCOPD system is a promising application for remote medical treatment of COPD.

The thesis of Xiao Liu is approved.

Mario Gerla

Lei He

Majid Sarrafzadeh, Committee Chair

University of California, Los Angeles

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To my parents . . .

who—among so many other things—

support my overseas study and life

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CHAPTER 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 [NMO98]. It is reported that that COPD and related conditions are the fourth leading cause of death in United States, after heart disease, cancer and stroke [NMO98]. This has raised to the third position in 2007 [Ass07]. More specifically, COPD kills more than 126,000 Americans annually [Nie98]. Even though the mortality rates with other common diseases such as stroke have been decreased over the past 30 years, the mortality rate from COPD and allied conditions raised nearly 33% from 1979 to 1991 [Nie98]. It has been estimated that COPD will be the fifth severe disease all over the world by the year 2020[ML96].

1.2 mCOPD Mobile Phone based Solution

A new mobile phone based system called mCOPD, that is both economic and accurate, is proposed and designed for daily COPD evaluation and treatment guidance. In contrast to traditional COPD diagnostic devices, the mCOPD system can be entirely integrated in the mobile phone. Due to the rapid development of smart phones, lots of smart mobile phones have gained strong performance. The performance gap between mobile phones and normal personal computers have significantly reduced. Actually, smart phones could handle most of the signal processing and data analysis operations without any difficulty. On the other side, smart phones have unique portability and better data transmission network. Patients could access their records and obtain guidance at most places. By leveraging the built-in microphone, we developed efficient computational model to estimate lung functions through both sound signals and airflow noise signals.

1.3 Benefits of mCOPD Solution

The mCOPD combines the smart phone with spirometer function in a novel way. It brings several attractive benefits compared to the existing spirometers. The mCOPD system will dramatically reduce the cost of spirometry system with even more function extension. By using the smart mobile phone, patients no longer need to buy new devices. Their own smart mobile phone could be used as the spirometer controller. Moreover, the novel sound-based and direct airflow sensors greatly reduces the cost of the whole system. The sound generator will be simply based on harmonica.

Second, the portability of smart phone makes it ideal for daily COPD monitoring and long term reporting. With mobile phone network, patients could upload their COPD related data at most places and could get possible feedback in real time. Patients do not need to take any other monitor devices other than their mobile phone. This will increase their interest on using the system in long term.

Third, the extension features of smart phone make it easier for us to update the functions in the future. According to the demands of physicians and patients, the system could be easily personalized for better monitoring the status of COPD.

Fourth, novel guidance could be implemented on the mobile phone. More specifically, the mCOPD will implement one or more games to help patients do breathing exercises in their treatment stage. This will be a unique feature compared to off-the-shelf products.

1.4 Thesis Structure

The remainder of this thesis paper is organized as follows. Chapter 2 gives a brief background introduction on the COPD related knowledge. It also discusses existing solutions and related research work on the instruments for COPD diagnosis. Chapter 3 gives the whole image of the system architecture in our mCOPD system. Chapter 4 presents, in detail, the design of the two important types of mCOPD diagnostic subsystem structure. Chapter 5 elaborates the novel phone-based breathing exercise gaming for COPD treatment. Chapter 6 discusses the experimental evaluation of the mCOPD system. The future work and conclusion are concluded in Chapter 7 and 8.

CHAPTER 2

BACKGROUND AND RELATED WORK

2.1 Basic facts about COPD

Chronic obstructive pulmonary disease, which was paid less attention by the public, had quick expansion during the past twenty years.

National Heart, Lung, and Blood Institute has continuing tracking the leading cause of death in the past 30 years, as shown in Table 2.1 [NMO98]. Stated in the introduction chapter, COPD is now the thrid leading cause of death in America and is expected to be the fifth severe disease worldwide. Historically, COPD has been a disease that has occurred more frequently in men. This is because men smoke more than women generally. However, since 2000, more women than men have died each year of COPD [Ass07]. COPD also increases with age. It predominantly occurs in people who are more than 40 years of age. This increases the mortality rate because older people tend to be frailer to different conditions.

2.2 Diagnosis and Treatment of COPD

As shown on the National Heart Lung and Blood Institute website [NMO98], people with several symptoms including coughing coustantly, excessive sputum, hard breathing and breath shortness should be considered having COPD. Moreover, smoking people and people in highly polluted environment will be more risky.

Table 2.1: Leading Causes of Death in United States, 1996 [NMO98]

Cause of Death	No. of Deaths
Heart disease	733,834
Cancer	544,278
Cerebrovascular disease (stroke)	160,431
COPD and allied conditions	106,146
Accidents	93,874
Pneumonia and influenza	82,579
Diabetes	61,559

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 Table 2.2, FEV1/FVC 0.7 can confirm non-reversible airflow limitation.

Spirometric classification has proven to be useful in various areas of COPD [CM04]. The major areas in which we are interested are predicting health status [Fer97] and mortality [AWH86]. It has been proven that spirometry is not only useful for

Table 2.2: Spirometric classification of chronic obstructive pulmonary disease (COPD)

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

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

2.3 Existing Products and Solutions

In current market, there are lots of different spirometers available. Also most of them are not designed exclusively for COPD detection; they could be used to detect FEV1 and FVC. Here we classified the current products into three categories: traditional spirometers, portable spirometers, and computer-aid spirometers.

2.3.1 Traditional spirometers

As shown in Figure 2.1, Traditional spirometers are usually large in size. They are capable of accurately measuring more than 50 different spirometry features. They are often purchased by hospitals for professional diagnosis of different kinds of lung disease. The advantage of this kind of traditional spirometers is that they are accurate and professional. However, this sacrifices the size and the price. This kind of system is far from affordable to avergae people. Moreover, it is apparently not suitable for regular monitoring by patients. The system also lacks the ability to transmit data via network.

2.3.2 Portable spirometers

This kind of spirometers is in a dominant position in todays home-use COPD, lung function detection and monitoring market. As shown in Figure 2.2, portable spirometers are handled easily. Compared with the traditional spirometers, it eliminates a lot of unnecessary functions, with just core features like FEV1 and FVC. This greatly simplifies the design and cost of the system. However, this kind of spirometer has its own disadvantage. With a simple processor and circuit, it could not process and record data after the detection. It can be said that most of the portable spirometers are isolated systems. This restricts the applications in the future, especially in long term monitoring. Moreover, it hardly has any guidance features to help patients in treatment stage.

Figure 2.1: BTL-08 MT Plus Spiro Pro System [Equ13]

2.3.3 Computer-aid spirometers

Computer-aid spirometers are the newer models off the shelf as shown in Figure 2.3. This kind of spirometer often utilizes the command interface of a computer like USB to transmit the sensor data onto computer software. Unlike the portable spirometer, USB spirometer could use high-performance computers to do complex data analysis, data collection, date management, and data sharing. The major 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 mouth piece with the software is still quite expensive. We need a more cheap and general solution. The comparison between different off-the-shelf spirometers can be seen in Table 2.3.

Figure 2.2: MicroLab Spirometer [Med13]

Table 2.3: The comparison among different kinds of spirometers

	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

2.4 Related work on mobile phone based breath analysis

2.4.1 Couch and Breath Detection

Couch and breath detection is a relative active topic in recent years. In mCOPD system, one of the approach is to use microphone to collect sound generated by breathing. This may be similar to some of the couch and breathe detection appli-

Figure 2.3: USB Spirometer [Sal13]

cations already published.

[Jir08] tends to collect acoustic signal generated by the airflow through the trachea. This is done by directly attaching the microphone on the tissue. Inspiration and expiration will then fall into different signal patterns. [Eri11, AQW01] focus on mobile phone-based couch detection based on frequency domain analysis of couch sound signal. The couch signal is directly gathered by mobile phones internal microphone. [HHC09] applies non-acoustic approaches for breathing detection and monitoring in Kinesitherapy.

2.4.2 Spirometer

Mobile phone based COPD detection is a relatively new application. However, our work gains motivation from some previous works regarding the design and algorithm of spirometer. SpiroSmart [Eri12] 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. [GMR10] did wide research on cough sound and breath detection. Wheeze detection for asthma diagnosis has also leaded to positive results. [AQW01, HF04]. [BCL12] proposes an interesting mobile phone platform for real-time lung function assessment in asthma application. The peak expiratory flow is measured by differential pressure sensor. Data is collected in real-time by an electronic interface and then is transmitted to the mobile device. [Viv08] specifies three main methods to measure spirometry: volume measurement by piston, flow rate measurement by hot wire element, and pressure measurement by differential pressure element. Sound measurement as a novel way is not listed here. It proposes a MEMS-based pressure sensor in its low cost spirometer system. An embedded web server is also implemented for real-time monitoring. [Jer09] implements another flow rate measurement based spirometer. Similar to the commercial model, it uses some propeller-shape sensor. No sound related element is applied in this application. [Sid11] aims to find solutions for part of the similar problems we are facing, that is to wireless monitor the lung function based on mobile phone. It also uses the traditional pressure measurement for related lung function parameters. A pneumotachometer is used to collect data and then digitalized by a microcontroller. The digital data is then transmitted to android phone via Bluetooth. [Ole10] provides a similar frequency domain analysis of the wheezing sound for asthma monitoring. More importantly it proposes an asthma monitoring system architecture which consists of smart phone platform, medical doctor monitoring platform and related database. Unlike others, [K S97] tends to find the indirect way of measuring air flow by sound. In its system, this is achieved by generating turbulence. An internal microphone is used to collect the sound generated by the turbulence.

There are also several portable spirometer products that exist on the market. SpiroTube Mobile Edition by THORMED [THO] is a pulmonary function diagnostics and monitoring device which is suitable for screening COPD and asthma. The device can be used with mobile phones and PDAs with wireless connection. The respiratory diagnostic software runs on the mobile phone. The patient blows into the SpiroTube Mobile Edition device and the results appear on the mobile phone in real time.

Figure 2.4: SpiroTube Mobile Edition [THO]

COPD telemonitoring developed by fifthplay[fif] is another similar product. The patient receives a spirometer that is linked via a bluetooth mobile phone with the VitalCare platform. VitalCare plots out the pulmonary data, generates and sends reports and statistics to the doctor by letter, e-mail, SMS or fax. He can remotely analyse ,interpret the values and add comments or considerations.

MobiPulse [Mob] offers a simple, low level, easy to adopt, mobile phone based Wireless Health Monitoring System. MobiPulse helps Patients to keep track of location based vital sign data such as Blood Pressure, Blood Oxygen level, Blood Glucose level, Heart Rate and ECG reports accurately from anywhere, anytime. It is an platform that integrates different Bluetooth enabled medical monitoring devices. MobiPulse uses a spirometer in COPD detection and sends test results to the mobile platform via Bluetooth. The software running on mobile phones acts as an integrating platform that displays all the data received from different Bluetooth enabled medical monitoring devices.

Most of the related research stated above falls into traditional measurement. For those novel ones like [K S97], it bases on different sound measurement theorem compared with mCOPD. Moreover, most of the system did not fully make use of the mobile phone platform. Compared to the above works, mCOPD system provides a different way in both audio based and direct airflow based lung function sensing. Moreover, the game based rehabilitation system is novel in related area.

CHAPTER 3

SYSTEM ARCHITECTURE

There are two main systems in the mCOPD system: COPD diagnostic system and COPD gaming treatment system, as shown in Figure 3.1. The system can support two major operations: lung function measurement and exercising game guidance. Patients are able create their own records based on their name, height, age and sex. The record of lung function information can be transferred to doctor for diagnosis.

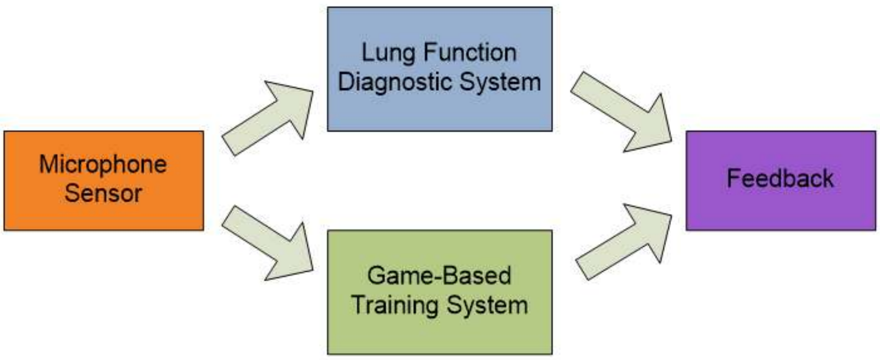

Figure 3.1: System Structure

From users point of view (see Figure 3.2), there are three parts in mCOPD. First, 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. Second, 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 interests in rehabilitation exercise.

In this way, the patient compliance can be improved. Third, a standalone 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 exercising history.

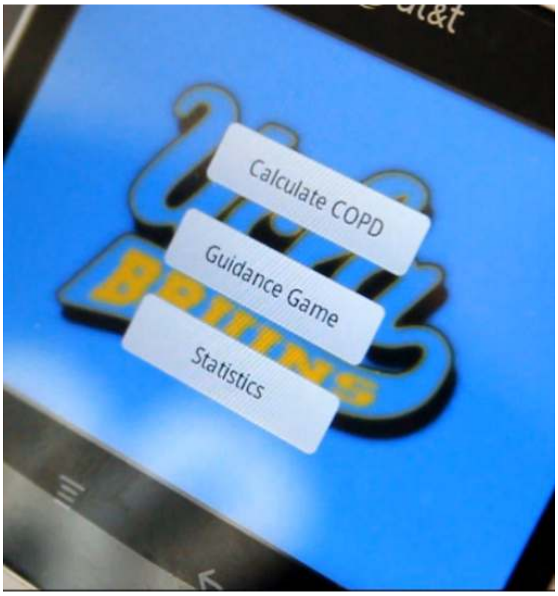

Figure 3.2: mCOPD User Interface

In the following chapters, the diagnostic and exercises parts will be discussed in details.

CHAPTER 4

COPD DIAGNOSTIC SYSTEM DESIGN AND IMPLEMENTATION

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. Two different approaches are applied in the diagnostic system. In the sound-based diagnostic approach, a special sound signal generator is built to transform the airflow signal into sound signal with certain frequency. This approach has less strict requirement for the surroundings. In the direct airflow-based diagnostic approach, air speed is measured directly by the mobile microphone. This approach eliminates the need of add-on devices. The overview of two diagnostic system approaches are shown in Figure 4.1.

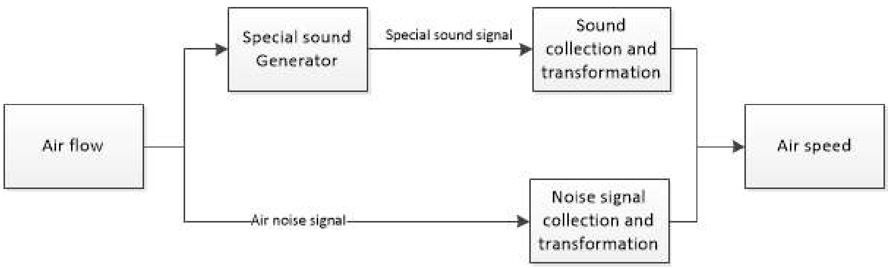

Figure 4.1: mCOPD Diagnostic System Overview

Figure 4.2 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 blow at the current detection. The strength outputs the direct sampled microphone value. This is an important index for determining the airflow value. Frequency domain result is also shown. It shows the frequency value with highest weight in the total output value. In the signal chart, both time-domain signal chart and frequency-domain signal chart are shown here. This gives people a direct feeling of the output value.

Figure 4.2: COPD Diagnostic System User Interface

4.1 Sound-based Diagnostic System Design

4.1.1 System overview

mCOPD sound-based diagnostic approach tries to maximally utilize the mobile sensors. Rather than use traditional airflow sensors, mCOPD uses the microphone to collect sound signal and to transform into airflow data. In order to generate sound signal, a special sound generator is provided to the patients. The design of the system is shown in Figure 4.3.

4.1.2 Sensing procedure

In sound-based diagnostic approach, airflow data is obtained via indirect way. We need to find the exact relationship between sound signal and airflow. Figure 4.4

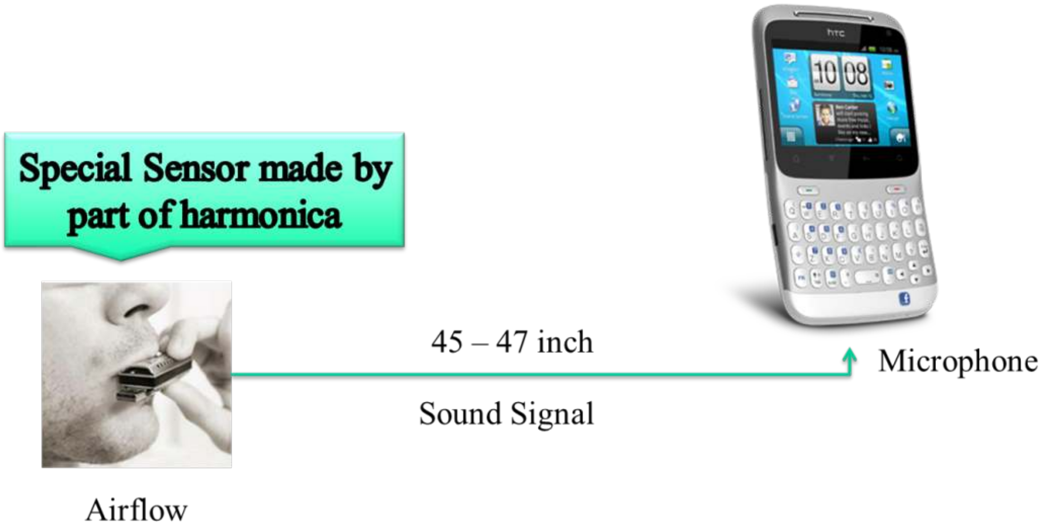

Figure 4.3: mCOPD System Composition

shows the necessary procedure to transform a sound value into airflow value.

For the sound generator the fixed reed instruments may be useful. The characterization of fixed reed instruments is that it will generate fixed frequency sound signal. The magnitude of the sound is directly related to the airflow that goes throw the gap between fixed reed and frame as shown in Figure 4.5. In the mCOPD, we made our own fixed reed sound generator by cutting the harmonica in pieces and adding an airflow tunnel to guide the airflow output from one direction. The feature of the fixed reed instrument makes it possible to implement our special airflow sensor.

After the fixed frequency sound is generated, it will be captured by the smart phone microphone. At the application level, corresponding value could be read via specific interface. In our application, we choose PCM 16bits as our analogue-digital conversion standard. The sampling frequency here is 16kHz. The sampled and quantized value will be transmitted into an application buffer. Approximately every 1/8 seconds the values be taken out of the buffer and will be processed.

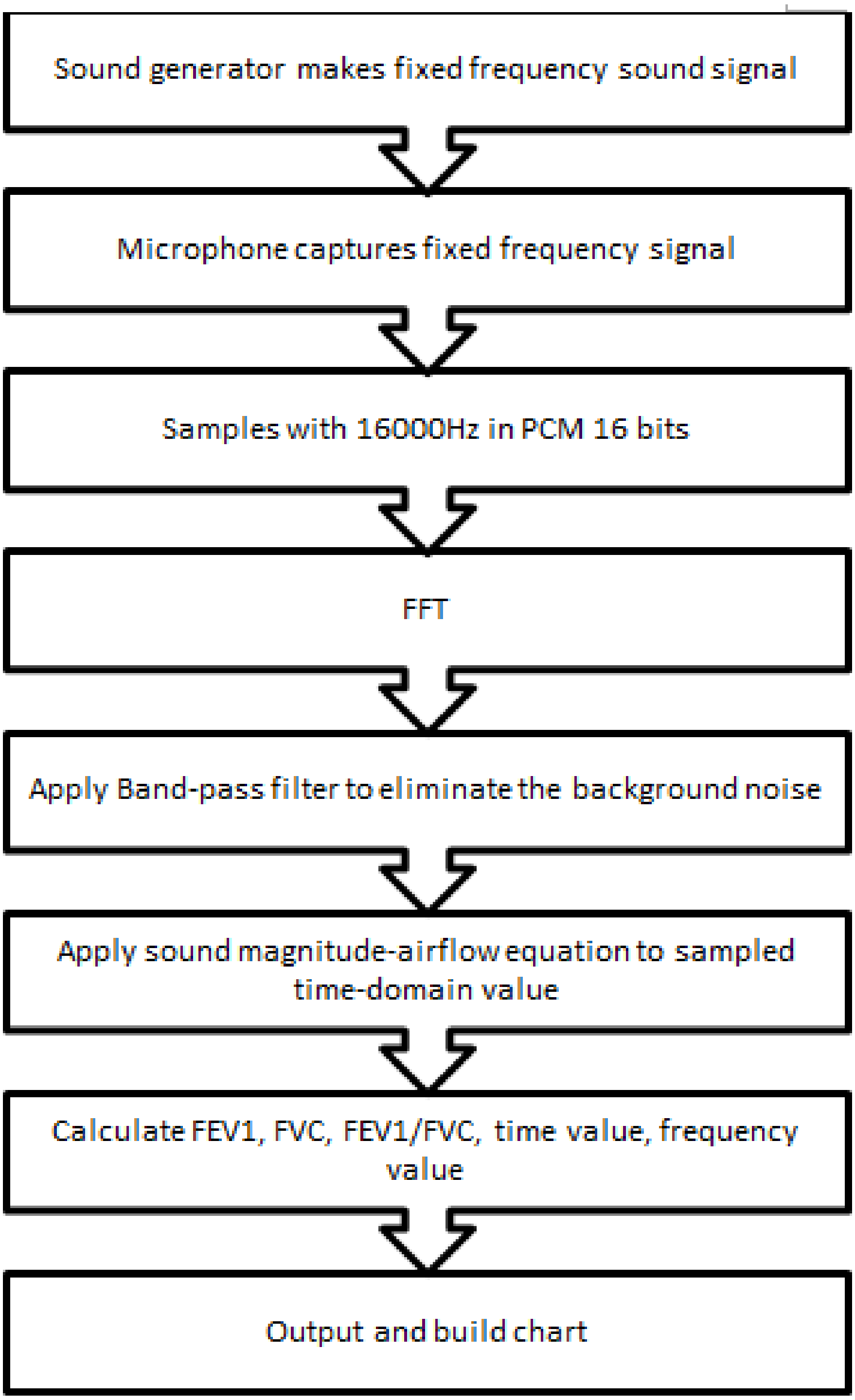

Figure 4.4: mCOPD Sound-based Diagnostic System Signal Processing Procedure

At the next stage, the sampled values will do the Fast Fourier Transformation.

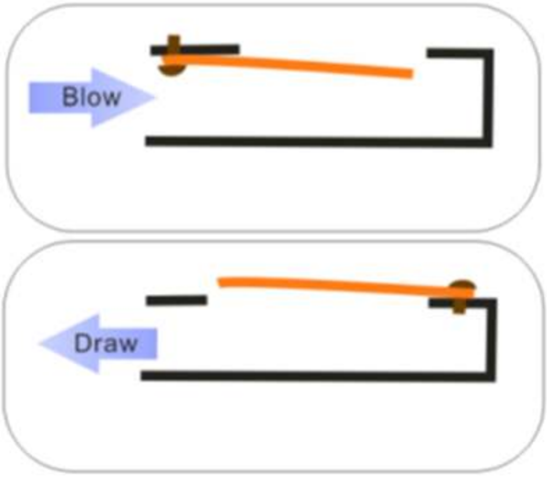

Figure 4.5: Harmonica Voice Theory [Che08]

The output of FFT is 256 points frequency domain signals. Both time domain sampled values and frequency domain values will be saved for future use.

After all the data is gathered, a simple band pass filter is implemented in the program. Since the fixed reed instrument only generates fixed frequency value, we could eliminate other noise easily. After that they will be transformed to airflow with related equations. As stated above, the sound magnitude value has a direct relation with the airflow value in fixed reed instrument. The equation and related charts are listed in the experiments and results chapter. The airflow value combined with time value will then be used to calculate related COPD characteristic values.

4.2 Direct Airflow-based Diagnostic System Design

4.2.1 System overview

The direct airflow-based COPD diagnostic system consists of four procedures: sensing, signal pre-processing, modelling and calculation, and signal post-processing.

The sensing part serves as the input collection of the system. As shown in Figure 2(a), the airflow signal is captured by microphone membrane and then transformed into analogue signal. In the signal pre-processing procedure, the analogue signal is sampled with 2.4kHz. The sampled signal will then be converted into 8-bit digital signal via internal ADC. In order to analyse the frequency domain features, 64-point FFT is performed through the signal. This choice balance the resolution requirements of the analysis and the performance of current mobile device. The transformed frequency signal will also need to go through low-pass filters to eliminate the noise. In the modelling 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.

4.2.2 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. Special requirements are placed 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 Figur 4.6, the membrane on the microphone will vibrate with the coming air pressure. The vibration will then be transformed into voltage signal. Several related work have shown that there are two major components in the wind noise: Natural flow turbulences in the wind and turbulence generated during the interaction between the microphone membrane and wind [S 03]. The natural

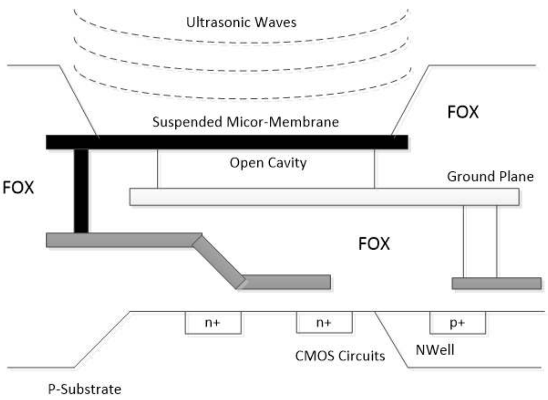

Figure 4.6: MEMS Microphone Structure [Com]

flow turbulence could be well eliminated via specially selected wind generator. 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 could be obtained in the recorded wind noise [Eli09]. 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 measurements will present as a noise in the output sound signal. Richard [RD05] has shown that this wind noise on the bare microphone could be approximately 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:

$$p(t) = \frac{1}{2}\rho V^2 + \rho V \upsilon(t) + \frac{1}{2}\rho \upsilon(t)^2 \tag{4.1}$$

where ρ is the ambient density, V is the average flow velocity, and υ(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.

4.2.3 Signal pre-processing procedure

Frequency domain computational model is established based on the MEMS microphone. Frequency domain analysis has certain advantages comparing with time domain analysis in airflow calibration. First, the time domain analysis leads to saturation problem. 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 variation characters 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.

4.2.4 Modelling and Calibration Procedure

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 set 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 practical, the resolution could be reduced to 0.2m/s in certain controlled enviroment. However, the input frequency response could not exceed the maximum and minimum value of the training samples. This leads to high quality requirenments of collecting procedure.

Mathematical Analysis is the second and better method for the frequency response wind speed model. A second-order mathematical regression model was 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 could be well predicted.

4.2.5 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.

$$volume = \int v(t)ds \tag{4.2}$$

As a conclusion, Figure 5-9 shows the working procedure of the entire system.

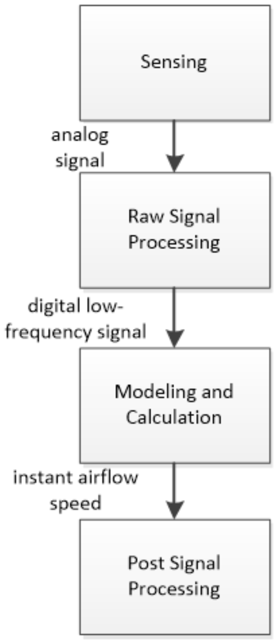

Figure 4.7: Direct Airflow-based Diagnostic System Structure

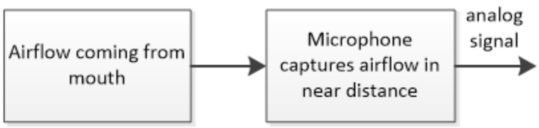

Figure 4.8: Sensing Procedure

Figure 4.9: Signal Pre-Processing Procedure

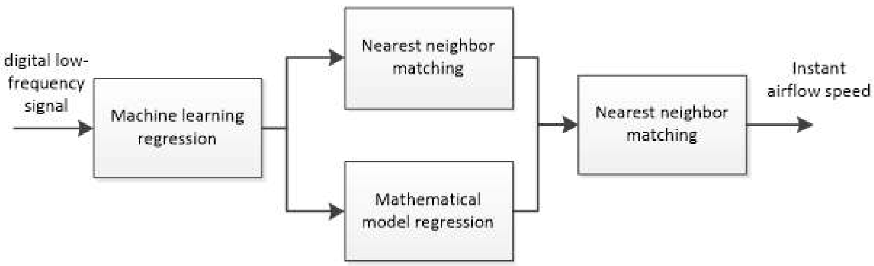

Figure 4.10: Modeling and Calculation Procedure

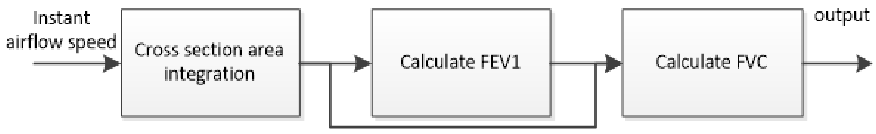

Figure 4.11: Post Signal Processing Procedure

CHAPTER 5

COPD BREATHING EXERCISE GAME MODULE

5.1 Purposes of Exergaming and Design Criteria

Exergaming, short for exercise games, is kicking the world of video games up a notch. The goal of today's popular video games is not only to have fun, but also to get you off the couch and on the way to a pulse-pounding workout.

Exercise games when used at intermediate or high intensity can indeed improve fitness and make the process easier than others. Although a set of video games will not give the user the same workout as the real thing, exergaming can be an important – and enjoyable – part of an overall aerobic exercise program. At least, it beats sitting around. Below is Table 5.1, which lists the amount of Calories burned when playing some exercise games compared to a moderate 3 mph walk which burns about 4 calories a minute, or 120 calories per half hour.

Dyspnea, or shortness of breath, is a result of air hunger that causes people to feel like they can't catch their breaths. It is primarily due to the lack of oxygen in the bloodstream and is directly related to disturbances in the lungs caused by COPD. People who have COPD or other chronic lung diseases live with this fear everyday of their lives. 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.

Table 5.1: Exergame Summary [Fri]

Exergame	Calorie burn/minute	Calorie burn/30 minutes
Golf	3.1	93
Bowling	3.9	117
Baseball	4.5	135
Tennis	5.3	159
Dancing	5.3	159
Boxing	7.2	216

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 you control dyspnea, the hallmark symptom of COPD. The following demonstrates the simple technique of pursed-lip breathing: patient needs to draw the lips together as if you were going to whistle and blow out through pursed lips slowly and evenly and try to make the time blowing out longer than when they took a breath in. Practising 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 [Deb10].

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 [Deb09].

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

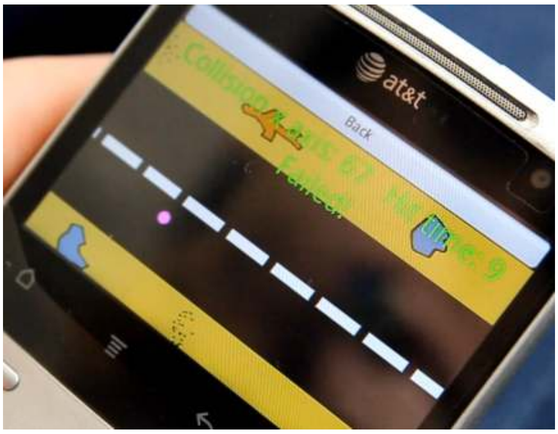

Figure 5.1: Game Exercises for COPD Patients

5.2 Key components in the game

In this designed exergaming, user controls the movement of a coloured 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 to 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 coloured 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 cannot 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 coloured 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 settable. 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.

Game difficulties can be increased through lowering the speed of the coloured ball which requires longer stable exhaling time in succeeding the game. Game difficulties can also get increased through requiring patients to use Pursed-Lip Breathing when inhale and use Diaphragmatic Breathing when exhale 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 exergamings have been played and success rate and send it to doctors side via internet. In this way, doctors can monitor patients in-home rehabilitation exercise through real data.

CHAPTER 6

EXPERIMENTS AND RESULTS

6.1 Sound-based Diagnostic System Experiments and Results

In order to find corresponding relations between sound strength and airflow volume, we sealed our sound generator with the mouthpiece of a digital portable spirometer. Thus, the entire air blow into our sound generator will go through the spirometer. We then set the distance from the sound generator to the phone microphone to be 45 to 47 inches, since microphone has a limit in detecting sound strength. This distance will always make the sound generated by our sound generator in the detectable range of the microphone.

We did 40 tests using HTC mobile phone status and our sound generator, which is sealed with a digital spirometer. Every 10 sets of test are in one certain range of sound strength which is generated by certain degree of blowing. We read the airflow volume in first second from the spirometer and read sound strength data from microphone using regression method to find a mathematical relationship between them. Below the Figure 6.1 shows that the volume of airflow (liter) per second and its corresponding sound strength is an exponential relationship:

$$y = 0.0456e^{8\times10^{-5}x} \tag{6.1}$$

y is the airflow volume (liter) per second and x is the sound strength detected by microphone.

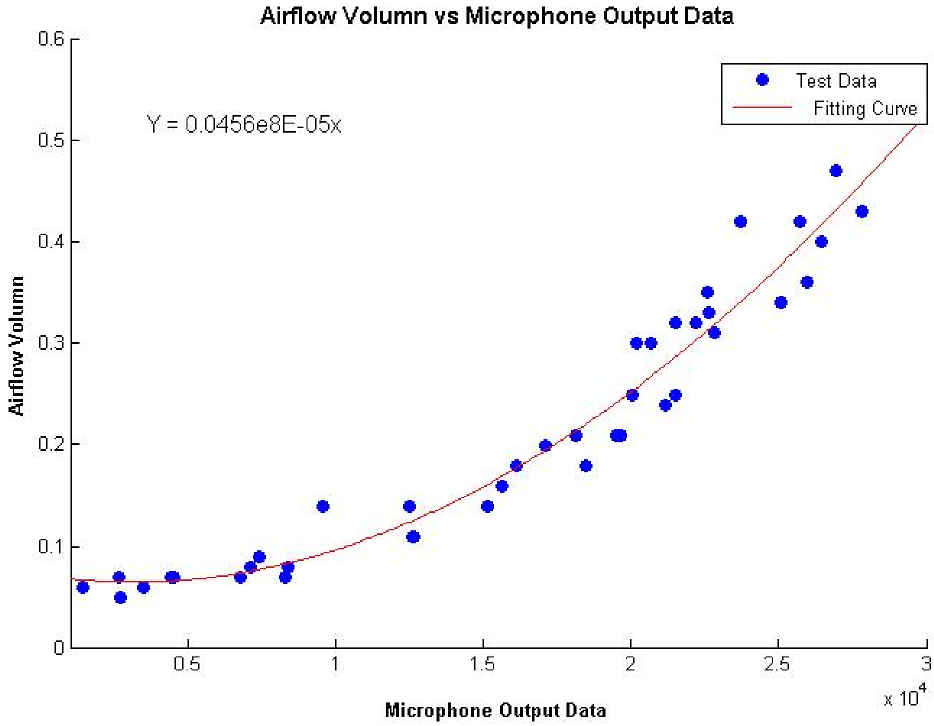

Figure 6.1: Sound Signal Strength versus Airflow Speed

We used this exponential relation to calculate FEV1 and FVC in mCOPD and did another 39 concurrently real breathing tests using mCOPD and using a digital Spirometer. Test results in Figure 6.2 show that the average deviation between the data tested by mCOPD and the data tested by the digital spirometer is about 10 mCOPD make diagnostic recommendation based on value FEV1 / FVC. Since FEV1 has the same deviation trend as FVC, the division makes the deviation between the final result FEV1 / FVC tested by mCOPD and simultaneously tested by the digital spirometer decrease to 0.85%.

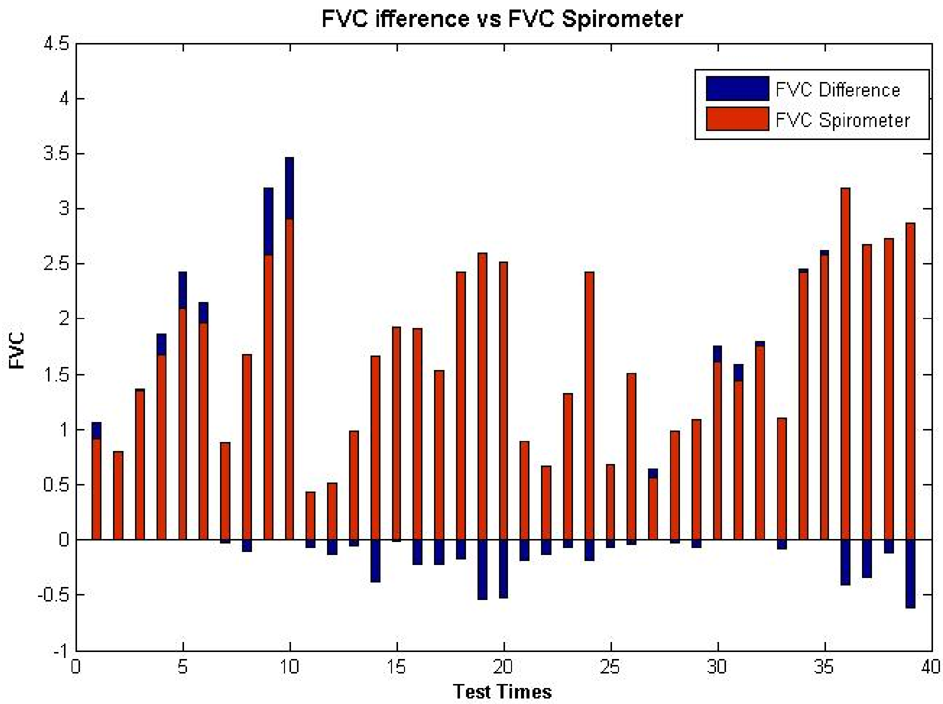

Figure 6.2: Difference between mCOPD Data and Actual Spirometer Data

6.2 Direct Airflow-based Diagnostic System Experiments and Results

In this section, we evaluate the effectiveness of the mCOPD direct airflow-based diagnostic system from 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.

6.2.1 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 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 to 15cm away from the air multiplier in order to catch the strongest airflow generating from it. The air multiplier as shown in Figure 6.3 is a bladeless fan producing speed-stable airflow with continuous airflow speed adjustment.

We did 12 training tests at the first place. Experiment setup is shown in Figure 6.4. The speed of wind in our training ranges from 2.1m/s to 4.4m/s with 0.2m/s per incremental. Experiment 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 6.5). Figure 6.6 shows all the frequency response curves of these 12 tests. We can see from Figure 6.6 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 6.6. Figure 6.7 shows the change in response intensity at a specific frequency point with the increase of airflow rate.

Figure 6.3: Dyson Air Multiplier used in our experiments [dys]

From Figure 6.7 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 6.7 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

Figure 6.4: Experiment Setup

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 system doing 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 t 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.

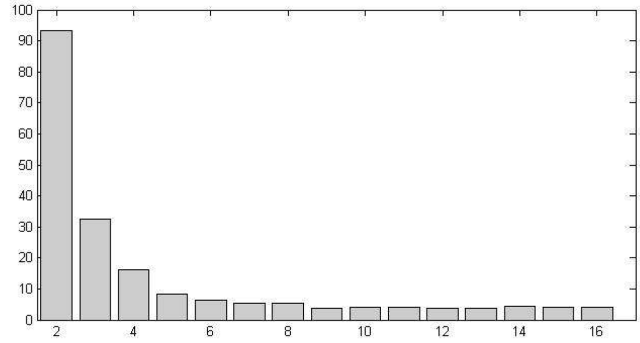

Figure 6.5: Frequency Response of Microphone to Airflow with Speed 2.1m/s

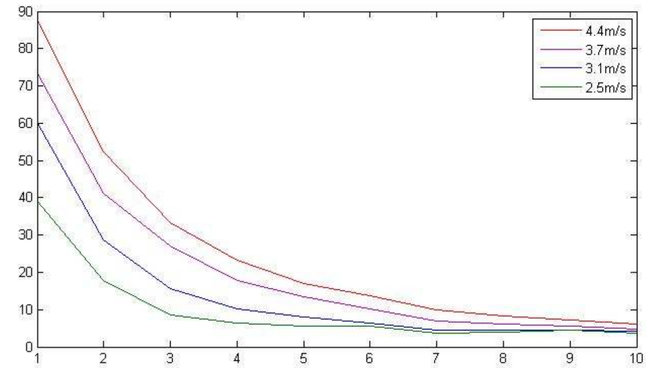

Figure 6.6: Frequency Response Curves on different airflow speed

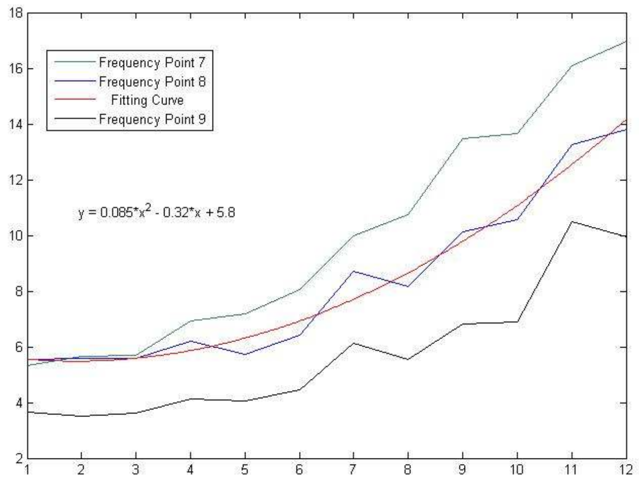

Figure 6.7: Change in Frequency Response Intensity with the increase of airflow speed

6.2.2 mCOPD Performance on FEV1, FVC Calculation

After we verified our microphone model, we transferred our mathematical model into our mobile phone application mCOPD. 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 6.8 shows the use procedure of mCOPD. 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 testers 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 efforts. 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.

Test results (Figure 6.9) 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 6.10); the average deviation of the data FEV1/FVC when compared to the clinical spirometer is 3.9% for common measures of lung function (Figure 6.11).

Figure 6.8: One Subject with traditional spirometer and mCOPD

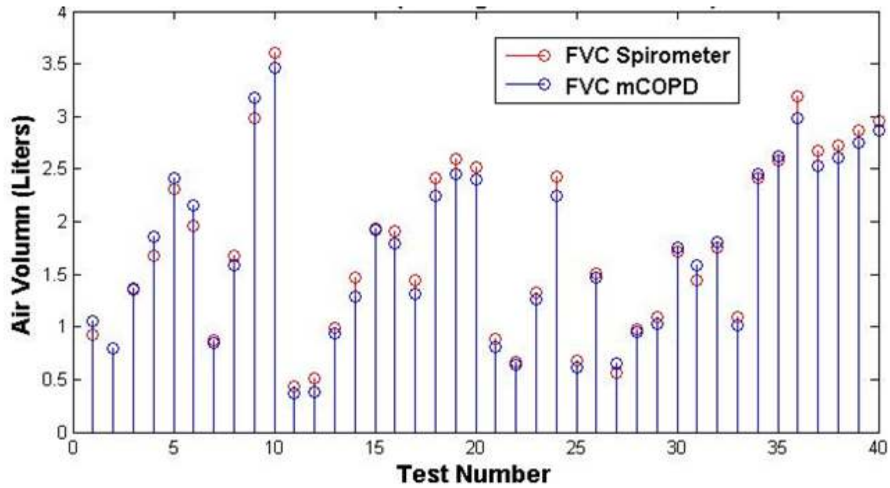

Figure 6.9: FVC Difference between mCOPD Data and Actual Spirometer Data (average deviation is 6.5%)

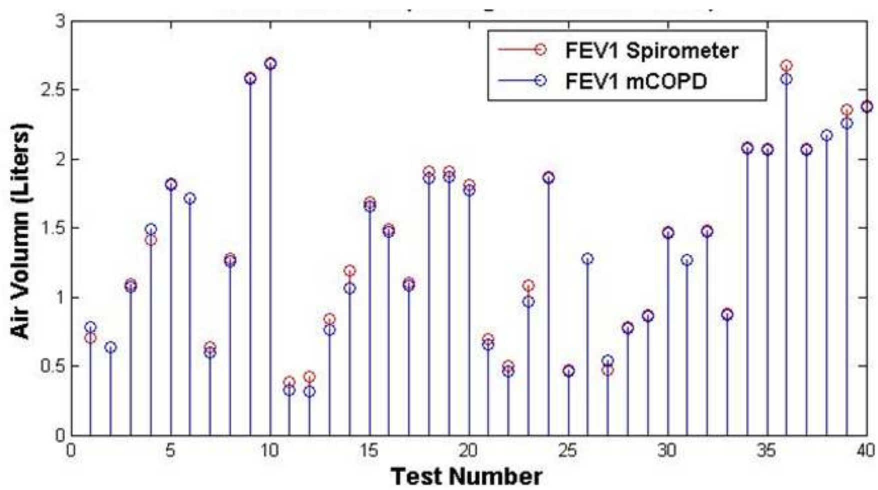

Figure 6.10: FEV1 Difference between mCOPD Data and Actual Spirometer Data (average deviation is 3.6%)

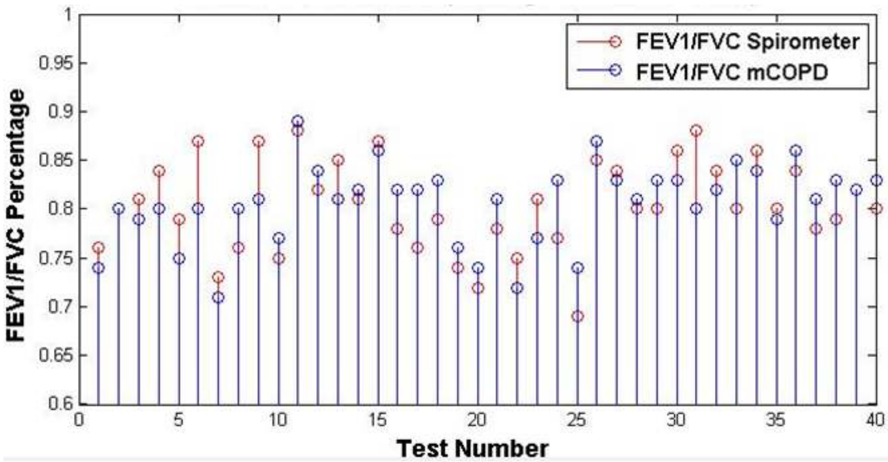

Figure 6.11: FEV1/FVC Difference between mCOPD Data and Actual Spirometer Data (average deviation is 3.9%)

6.2.3 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 6.12). mCOPD will also provide different treatment recommendations for different stages. For example, after a breathing test, mCOPD detects that the tester may possibly be at one stage 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.

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 6.12: Stages of COPD [Dis12]

CHAPTER 7

FUTURE WORK

7.1 Better Sound Generator

Sound generator plays a very critical role in breathing test using mCOPD sound-based diagnostic system. Currently we cut a scale from a harmonica and use it as the prototype of our sound generator. This prototype has two drawbacks: first, it is small. User needs to draw their lips together and blow like with whistling. This way has blocked on the amount of air user can exhale at the first second. Thus, has an effect on the accuracy of our detecting value FEV1. Second, the sound generator makes sharp and noisy sounds when blowing during the test. We want to alter the shape of sound generator just like the mouthpiece of a spirometer and put some kind of reed in the middle which generates gentle sound when vibrating. In the direct airflow system, this problem does not exist. However, considering the unique advantage of sound-based diagnostic system, more research should be done on both approaches.

7.2 Diagnostic Recommendations and Treatments for Different Stages

Diagnostic recommendation function should be added into mCOPD in future. mCOPD can give diagnosis at the end of every breathing test based on test results (FEV1, FVC, FEV1/FVC) and guidelines from the Global Initiative for Chronic

Obstructive and Lung Disease (GOLD) for COPD Diagnosis and Management. It is also necessary to add different treatment recommendations for different stages. For example, after a breathing test, MCOPD detect that the tester may possibly be at 1 stage 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.

7.3 Remote Data Transfer and Video Calling

In the further development, all statistic results (test and exercise records) will be automatically sent to personal doctors via phone on a regular basis. Thus, doctors could monitor their patients disease progress and home rehabilitation exercise through checking the data and making a video call if they feel necessary. Patients can also video call their doctors through mCOPD if they have some concerns about COPD or if they need to talk to their doctors face to face. This function reduces the need to go to clinics in person and doctors can make diagnosis and monitor their patients on real data.

7.4 Portability on different devices

We want to make mCOPD have portability on different smartphone devices. We got the mapping equation of airflow volume per second and sound strength through testing on HTC Status. Since microphones of devices are different, same strength of sound in real world may have different detected values on different smart phones. We need to add a training process into mCOPD in future. mCOPD will require users do certain sets of sample breathing tests on their first use and generate a device specific mapping equation based on these sets of training.

CHAPTER 8

CONCLUSION

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.

References

[AQW01] K. Anderson, Y. Qiu, A. R. Whittaker, and M. Lucas. "Breath sounds, asthma, and the mobile phone." *Lancet*, **358**(9290):1343–4, 2001. Anderson, K Qiu, Y Whittaker, A R Lucas, M England Lancet. 2001 Oct 20;358(9290):1343-4.

[Ass07] American Lung Association. "COPD Fact Sheet." 2007.

[AWH86] N. R. Anthonisen, E. C. Wright, and J. E. Hodgkin. "Prognosis in chronic obstructive pulmonary disease." *Am Rev Respir Dis*, **133**(1):14–20, 1986. Anthonisen, N R Wright, E C Hodgkin, J E N01-HR-72901/HR/NHLBI NIH HHS/ N01-HR-72902/HR/NHLBI NIH HHS/ N01-HR-72903/HR/NHLBI NIH HHS/ etc. Am Rev Respir Dis. 1986 Jan;133(1):14-20.

[BCL12] A. Bumatay, R. Chan, K. Lauher, A. M. Kwan, T. Stoltz, J. P. Delplanque, N. J. Kenyon, and C. E. Davis. "Coupled Mobile Phone Platform With Peak Flow Meter Enables Real-Time Lung Function Assessment." *Ieee Sensors Journal*, **12**(3):685–691, 2012. 890ZG Times Cited:0 Cited References Count:25.

[Che08] W Chen, H. "The relationship between airflow and harmonica reed vibration." 2008.

[CM04] B. R. Celli and W. MacNee. "Standards for the diagnosis and treatment of patients with COPD: a summary of the ATS/ERS position paper." *Eur Respir J*, **23**(6):932–46, 2004. Celli, B R MacNee, W ATS/ERS Task Force Denmark Eur Respir J. 2004 Jun;23(6):932-46.

[Com] Johns Hopkins University Computational Sensory-Motor Systems Lab. "MEMS Microphone.".

[Deb09] RN Deborah Leader. "How To Perform Diaphragmatic Breathing With Pursed Lips." 2009.

[Deb10] RN Deborah Leader. "How Do I Perform Pursed Lip Breathing?" *About.com Guide*, 2010.

[Dis12] Global Initiative for Chronic Obstructive Lung Disease. "GOLD Guidelines COPD Diagnosis and Management: At-A-Glance Desk Reference." 2012.

[dys] dyson. "dyson air multiplier.".

[Eli09] Wilf Leblanc Elias Nemer. "Single-Microphone Wind Noise Reduction by Adaptive Postfiltering." *IEEE Workshop on Applications of Signal Processing to Audio and Acoustics*, 2009.

[Equ13] BTL Medical Equipment. "BTL-08 Spiro Pro.", 2013.

[Eri11] Sean Liu Margaret Rosenfeld Shwetak N. Patel Eric C. Larson, Tien-Jui Lee. "Accurate and Privacy Preserving Cough Sensing using a Low-Cost Microphone." *UbiComp*, 2011.

[Eri12] Gaetano Boriello Sonya Heltshe Margaret Rosenfeld Shwetak N. Patel Eric C. Larson, Mayank Goel. "SpiroSmart: Using a Microphone to Measure Lung Function on a Mobile Phone." 2012.

[Fer97] et al. Ferrer M, Alonso J. "Chronic obstructive pulmotary disease and health related quality of life." *Ann Intern Med*, **127**:1072–1079, 1997.

[fif] fifthplay. "COPD telemonitoring." http://www.fifthplay.com/node/177.

[Fri] Wendy C. Fries. "Exercise, Lose Weight With 'Exergaming'." *WebMD Feature*.

[GMR10] W. T. Goldsmith, A. M. Mahmoud, J. S. Reynolds, W. G. McKinney, A. A. Afshari, A. A. Abaza, and D. G. Frazer. "A system for recording high fidelity cough sound and airflow characteristics." *Ann Biomed Eng*, **38**(2):469–77, 2010. Goldsmith, W T Mahmoud, A M Reynolds, J S McKinney, W G Afshari, A A Abaza, A A Frazer, D G Ann Biomed Eng. 2010 Feb;38(2):469-77. doi: 10.1007/s10439-009-9830-y. Epub 2009 Oct 30.

[Han] SPIRIVA HandiHaler. "Breathing Exercises.".

[HF04] A. Homs-Corbera and J. Fiz. "Time-frequency detection and analysis of wheezes during forced exhalation." *IEEE Transaction*, **51**(1), 2004.

[HHC09] Hiromichi Maki Hidekuni Ogawa Ishio Ninomiya Kouji Sada Hiroki Tawa, Yoshiharu Yonezawa, Shingo Hamada, and W. Morton Caldwell. "A Wireless Breathing-Training Support System for Kinesitherapy." *31st Annual International Conference of the IEEE EMBS*, 2009.

[Jer09] Andrew Bremer Andrew Dias Jeremy Glynn, Jeremy Scheaefer. "Low-Cost Spirometer." 2009.

[Jir08] Miroslav Husaik Jiri Kroutil. "Detection of Breathing." *ASDAM 2008, The Seventh International Conference on Advanced Semiconductor 167 Devices and Microsystems*, 2008.

[K S97] Shumon Alam K S Rabbani, Suravi Islam. "A Novel Gas Flow Sensor Based on Sound Generated by Turbulence." *IEEE Instrumentation and Measurement Technology Conference*, pp. 19–21, 1997.

[Med13] Promed Medical. "Micro Diary - Patient Spirometry Monitoring at Home.", 2013.

[ML96] C. J. Murray and A. D. Lopez. "Evidence-based health policy–lessons from the Global Burden of Disease Study." *Science*, **274**(5288):740–3, 1996. Murray, C J Lopez, A D New York, N.Y. Science. 1996 Nov 1;274(5288):740-3.

[Mob] Mobipulse. "Mobipulse." http://www.mobipulse.com/.

[Nie98] Michael S. Niederman. "Introduction: Mechanisms and Management of COPD: We Can Do Better - It's Time for a Re-evaluation." *Chest*, **113**, 1998.

[NMO98] "NHLBI morbidity and mortality chartbook." 1998.

[Ole10] Dinko Oletic. "Wireless sensor networks in monitoring of asthma." 2010.

[RD05] Jeremy Webster Richard Raspet and Kevin Dillion. "Framework for wind noise studies." *Acoustical Society of America*, **43**(28):9, 2005.

[S 03] S. von Hunerbein T. Wu S. Bradley, J. Backman. "The mechanisms creating wind noise in microphones." *Acoustic Engineering Society Convention*, 2003.

[Sal13] INC. Sallberg Medical. "KoKo Trek-USB Spirometer (USB Interface Version).", 2013.

[Sid11] Nonso Anyigbo Ashutosh Sabharwal Siddharth Gupta, Peter Chang. "mobileSpiro: Portable Open-Interface Spirometry for Android." *Wireless Health*, 2011.

[THO] THORMED. "SpiroTube Mobile Edition." http://www.thormed.com/index.php.

[Viv08] N.C.S Ramachandran Vivek Agarwal. "Design and development of a low-cost spirometer with an embedded web server." *Int. J. Biomedical Engineering and Technology*, 2008.