Development of Diagnostic Device for COPD: A MEMS Based Approach

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Summary
Chronic obstructive pulmonary disease (COPD) is one of most common diseases related to breathing. In this study, a new diagnostic method is developed to detect the COPD parameters by using a microelectromechanical system (MEMS) based acceleration sensor. It records the data of acceleration that occur the movements of the diaphragm in three axes during the respiratory. With the developed device in this work, the parameters such as Tidal volume capacity (TVC), forced vital capacity (FVC) and respiratory rate (RR) which are commonly associated with COPD are successfully measured and recorded on a secure digital memory (SD) card. 5 people are chosen as a subject (3 healthy, 2 copd) to perform simultaneous measurements with both medical spirometer and the developed system. The measurement results are compared. It is concluded that results are acceptable. Healthy people and the people having COPD are successfully determined by looking the measured FVC curves with the developed system. So the developed device is considered as an alternative method to spirometer and as well as portable device.

Key words:
Acceleration, COPD, diaphragm, data acquisition, signal processor.

1. Introduction

Nowadays, home-based diagnostic methods have become very popular. With the advancement of technology, new concepts have emerged for home-based diagnostic devices. These health record systems can help to make health care safer, cheaper and practical [1].

The architecture of the microcontroller based patient-controlled diagnostic system developed in this study is shown in Figure 1. A patient will be able to record her/his pulmonary parameters by herself/himself at home and retrieves the data to doctor via a memory unit (SD card) with the help of developed system. The doctor may have information about the patient's Tidal volume capacity (TVC) - forced vital capacities (FVC) parameters after examining the data recorded on the SD card. With this aspect, this study offers a practical solution for doctors.

COPD is also one of the most common pulmonary diseases. It is estimated to be the fourth leading cause of death worldwide by 2030 due to increasing in smoking rates and statistical changes in numerous countries [2]. The gold standard of diagnosis for COPD is pulmonary function test and it is performed by a medical device that is called “spirometer” [3].

Although COPD all belong to the obstruction of the respiratory airway, its nidi are different. Moreover, its diagnostic instruments are also differences. Spirometer is used for COPD. It measures the absolute values of the respiratory flow and volume. When testing COPD, the central nervous system is working.

The spirometer measures the parameters TVC and FVC as a function of time during respiration which is two important parameters to make a decision about COPD [4]. TVC and FVC determine the function of the narrow airways [5]. Spirometer is used to scan people who are at risk of pulmonary disease [6]. However, the spirometer devices are very costly and not suitable for using at home. It also needs several additional types’ equipment (latch, pipe, etc.).

Different methods have been developed for measuring COPD parameters from the diaphragm [7-8], but recently the most popular method is by use accelerometer [9-10]. The accelerometer based diagnostic devices are portable and highly practical. Using accelerometer to monitor the movement of the chest and abdomen has emerged as an alternative method recently [11].

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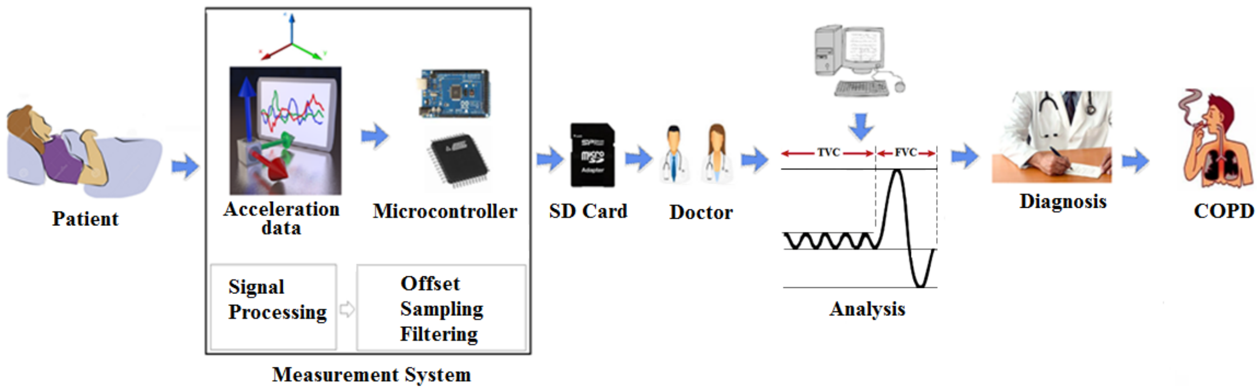


Fig. 1 The architecture of the diagnostic system.

2. Materials and Methods

In this paper, a new portable and inexpensive diagnostic device is developed to make a decision about COPD. With the developed device, a lot of data about the patient such as TVC, FVC and RR can be empirically measured and recorded on an SD card and then be able to signal analyze. Simultaneous measurements are performed with spirometer (Fukuda Sangyo brand spiroanalyze ST-75 model, Prg ver: 2.36B 16-Bit).

The ethics committee of Ondokuz Mayis University faculty of medicine clinical research unit approved the developed device and the method of this study is numbered as 2015/123. For each subject of this study, Patient Informing Consent Form was filled out and the subjects were verbally informed about the study.

2.1 The study group

The study group consists of n: 5 patients (2 males (40%) and 3 females (60%)) with different characteristics ([mean] age, 33; height, 169.6cm; and weight, 75.6 kg). General characteristics of the study groups listed as given in Table 1. The study group was formed from healthy and COPD individuals (3 healthy, 2 copd) intentionally so that the developed device can precisely distinguish healthy and diseased individuals. There are no patients with overlap syndrome in the study group.

Table 1: General characteristic of the study group.

Patient No	Height (cm)	Weight (kg)	Sex (F/M)	BMI (kg/m^2)	Age (year)	COPD (Y/N)
H1	167	85	F	30.5	48	N
H2	159	44	M	17.4	23	N
H3	175	65	F	21.2	20	N
H4	187	108	M	30.9	34	Y
H5	160	76	F	29.7	50	Y

F: Female, M: Male, BMI: Body Mass Index, Y:yes, N: no.

Each person in the study group wears the acceleration sensor to abdominal region and uses a device program menu via Liquid-Crystal Display (LCD) screen. The acceleration data are measured with the sensors that connected to the abdominal region and are recorded on the SD card for further comparative signal analysis.

2.2 MEMS (microelectromechanical system) Based Acceleration Sensor

The accelerometer sensors measure the acceleration along the three axes (X, Y, and Z). It is possible to use the three axes measurement to determine the movement of the diaphragm during respiration. The accelerometer sensors might be used as a reliable tool in the diagnosis of certain pulmonary diseases such as COPD, dyspnea, sleep apnea, pulmonary hypertension, etc. [12-14].

MEMS semiconductor technology combines micromechanical structures and electrical circuits on a single silicon chip. With this technology, MEMS accelerometers can sense the acceleration on one, two or even three axes, with analog or digital outputs. Digital versions may even have multiple interrupt modes. These features offer to the user convenient and flexible solutions. Figure 2 shows the pin structure of the sensor. MEMS based accelerometers are used for various locations of military areas, as well as health care industry [15-17].

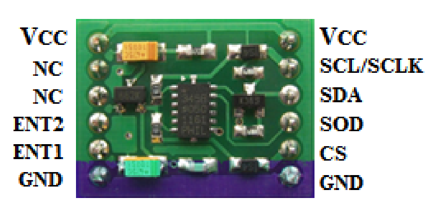


Fig. 2 The pin structure of the sensor

The ADXL345 is a one of MEMS based 3-axis accelerometer with digital output. It is manufactured by

Analog Devices Inc. It has a number of features such as; selectable ±2-g, ±4-g, ±8-g, or ±16-g measurement range (selected the +-2g setup in this study); resolution of up to 13 bits; fixed 4-mg/ least significant bit (LSB) sensitivity; a tiny 3-mm × 5-mm × 1-mm package; ultralow power consumption (25μA to 130μA); standard 2-wire Inter-Integrated Circuit (I2C) and Serial Peripheral Interface (SPI) serial digital interfacing; and 32-level first in first out (FIFO) storage. A variety of built-in features, including motion-status detection and flexible interrupts, greatly simplifies the implementation of the algorithm for fall detection [18]. This sensor is also used to detect the COPD [19-20]. Hence, this combination of features makes the ADXL345 as a one of the most appropriate accelerometers to measuring of diaphragm movements in our study.

2.3. Data Acquisition and Software

Although the respiratory is known as an automatic function, it consists of inspiratory and expiratory events and is controlled by the help of different muscles [21]. So respiratory cycles are similar but they are actually different because of different types of diaphragm movements. These differences are useful for medical studies [22-23].

Although the movements in the abdominal region are small during respiration, the respiratory cycles can be measured over the abdomen with an accelerometer [24-25].

It was understood from the literature [26-29] that the ideal location for the accelerometer is the space between the 7th ribs, the region above the diaphragm (the solar plexus). Thus, in the designed system, the acceleration sensor is placed on a patient's diaphragm so as to XZ-plane lies parallel to the ground and the Z-axis is positioned perpendicular to the diaphragm. Hence, changes in the Z-axis show diaphragm movement directly. The motion of the diaphragm is principally axial not dorsoventrally movement, so the sensor is placed on the diaphragm. Since the diaphragm is filled with air during the inspiration a movement occurs in the diaphragm (Δd=anteroposterior movement distance). Since the diaphragm movements are greater than the movements of the thorax (change in distance d) measurements are taken from the diaphragm area. In order to obtain reliable results during the diaphragm movement, measurements were performed while the patients were in sitting position. Various respiratory efforts were performed by patients and 3-axis movement of the diaphragm was monitored.

Significant oscillations were observed along Z-axes, while there were no substantial movements detected in the X and Y-axis (excluding people dependent parameters). The acceleration values of each subject are measured by ADXL345 sensor. Placing the sensor on the patient's diaphragm and the coordinate system definitions are shown in Figure 3. The sensor is connected to the body (the abdomen region) with the help of a belt.

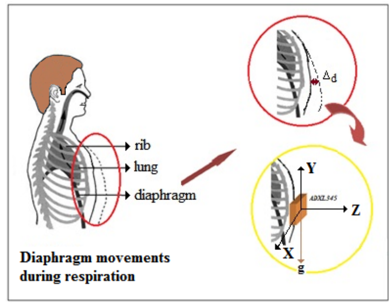


Fig. 3 The acceleration sensor to be placed on the diaphragm [30].

Accelerations on the diaphragm during respiration were measured both by accelerometer and spirometer synchronous. The data were recorded on SD as 'g' in 3-axis (X-Y-Z). The sensor is calibrated the acceleration unit as a flow or volume unit according to literature in [31].

The hardware for data measuring and recording system consists of a lot of parts. Figure 4 shows a block diagram of the designed and realized system.

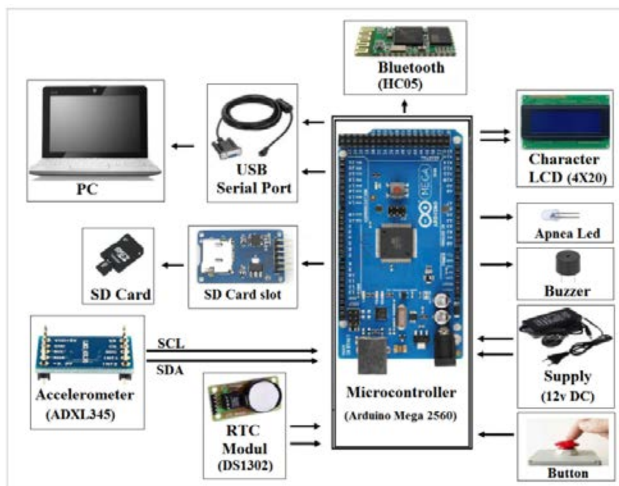


Fig. 4 The block diagram of designed and realized system

The system's sampling frequency is 20Hz. Each 32-bits of float received data are composed of x, y and z values. The data is recorded on SD card as 'g' in 3-axis (X-Y-Z).

Thereby, the amounts of data transferred are 20 x 3 x 32 = 1920 bits/s and it is suitable for a wireless transmission. The device has the Bluetooth module and can also be sent recorded data via Bluetooth from SD to computer in addition to the USB.

The circuit of the system is composed of Arduino Mega (preferred because of the need for the number of

peripheral ports) microcontroller (licensed with Creative Commons Attribution Share-Alike 2.5), 4x20 character LCD display (for the program menu), accelerometer sensor, SD memory component, RTC (real time clock, produced by the Dallas company,) and a button (for menu selection). The required power for the entire circuit has been obtained from a circuit containing a 12V battery and LM7805 regulator. Arduino board is being programmed with the Arduino Software (IDE). The accelerometer is extended via a cable (usb type of cable) during the tests.
The interface program was developed by using Microsoft Visual C# 2010 (version 10.0.40219.1 SP1Rel) programming language. In addition, MATLAB program (version 7.12.0.635 (R2011a) 32-bit win32) used for data analysis and filtering. The developed interface program is shown in Figure 5.

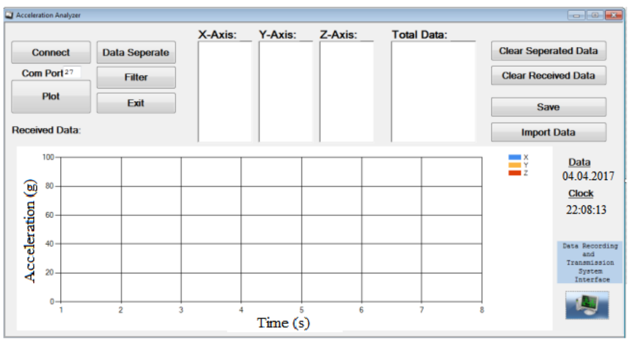


Fig. 5 The Interface program (prepared by using C # programming language commands)

The interface program transfers the acceleration values from the developed system to the computer. This program provides opportunities for saving the data measured as a text file or for plotting the graph of the previously recorded data. Diagnostic device and its equipment are shown in Figure 6.

Fig. 6 Developed diagnostic device and equipments

All data are transferred to the computer with the help of this interface. Filtering was needed for analyzing. Matlab is the most convenient and widely used program for filtering and analyzing. So, signal analyses were done in MATLAB (version 7.12.0.635 (R2011a) 32-bit win32).
DC components were thrown from the raw signal and 10 point average filter was used. The Matlab script code is shown below;

Algorithm 1: The Matlab script code

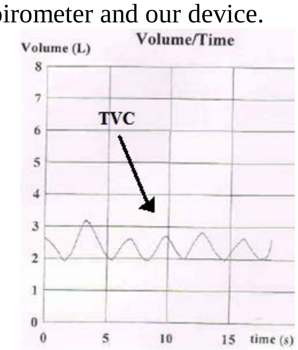
```
{
B = 1/10*ones(10,1);
out = filter(B,1,input);
windowWidth = 10;
kernel = ones(windowWidth,1) / windowWidth;
        out = filter(kernel, 1, myInputSignal);
}
```

3. Results

The COPD algorithm was started from the program menu for COPD measurements while the patients were in sitting position. The various respiratory efforts were performed by patients and 3-axis movements of the diaphragm were monitored. The RR, TVC and FVC parameters were measured.
Each subject in the study group wore the acceleration sensor to abdominal region and chooses COPD disease from the menu via LCD screen and the recording was performed. The TVC, RR and FVC are most commonly used parameters associated with COPD. These parameters were measured with both spirometer and the developed device simultaneously.

3.1 Tidal Volume Capacity

TVC is defined as the volume of gas displaced from the lungs during normal breathing. TVC is a lung volume that can be measured simply by the spirometer. If maximum expiration is performed slowly, it is called as TVC and if maximum expiration is performed forcefully it is called as FVC. Figure 7 shows TVC (0sec - 18sec) measurement results from spirometer and our device.



(a)

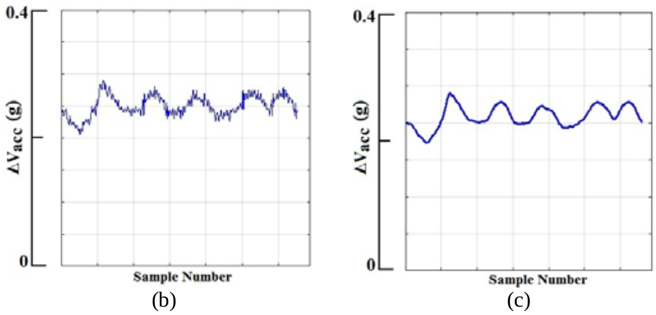


Fig. 7 One comparison case; an example of the measurement result of spirometer (a) and our device (b) raw and (c) filtered recorded on the same control subject.

The signals were sampled at the frequency of 20Hz in order to compare. The graphical curves are very similar to each other (it is important because the doctors usually assess patient outcomes graphically when making a diagnosis.).

3.2 Respiratory Rate

RR value of the other patient was measured and the signal was analyzed in Matlab. The peaks showed the status of inspiration, the dip points indicated the expiration. The dots at the peak of the signal represented the number of RR. In Figure 8, the number of points shown with red dots at the peak of the signal represents the number of RR of each sample.

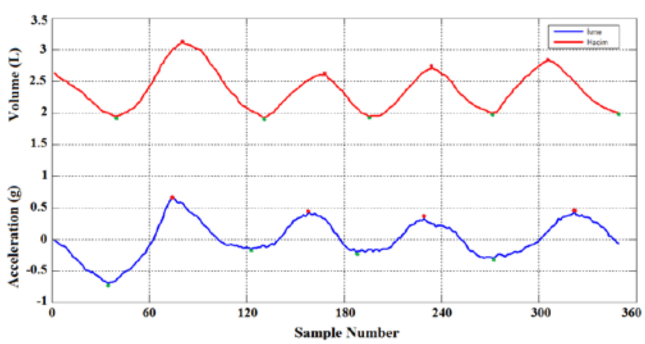


Fig. 8 Finding inspiration-expiration number from volume and acceleration.

3.3. Forced Vital Capacity

Under normal condition, FVC is equal to TVC, but in the case of airway obstruction FVC is smaller than TVC. Figure 9 shows normal and obstructive flow-volume curve.

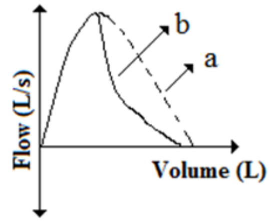


Fig. 9 Normal flow-volume curve case (a), obstructive flow-volume curve case (b)

The measurements for all participants have been carried out with both spirometer and developed device simultaneously, and the results are shown in Figure 10.

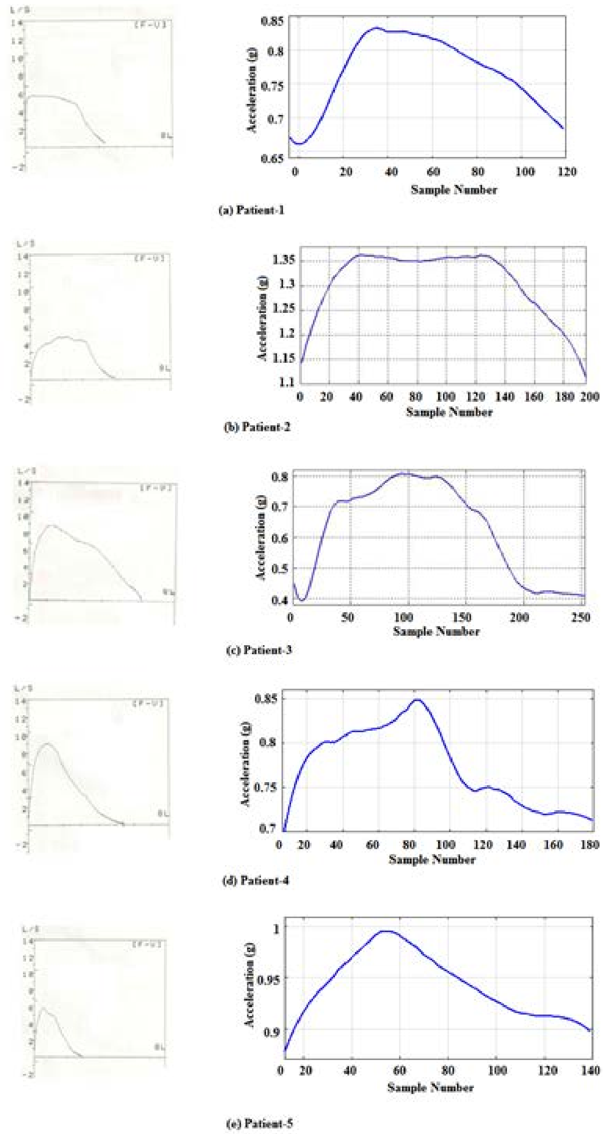


Fig. 10 All Patients' FVC curves measured by spirometer (left) and developed device (right- filtered).

Accordingly, patient 4 and 5 are diagnosed with COPD by FVC curves. Likewise, the patient 1, 2 and 3 are healthy according to FVC curves. The breathing of patients with COPD is also slow, so this case can be easily understood both graphs.
When figure 10 is examined carefully, it is understood that flow-volume curves the same conclusion can be reached with both spirometer measurements the acceleration curves of patients. The normal patients and the obstructive patients are curves which are different from each other and it is easy to distinguish the obstructive patients' curves. Therefore, developed measurement device is a convenient method for doctors to diagnose.
The difference between the normal patients and obstructive patients can be understood easily by looking at the acceleration curves of patients to diagnose the COPD. The developed device is more cheap, economical and low cost, comfortable, and convenient than existing systems for not only the patients but also the doctors. The patients can easily use these devices at their home environment.

4. Conclusions

This paper presents an alternative approach for spirometer measurement using accelerometer attached to the patient's abdomen. Based on the data acquired from the sensor, we were able to estimate measurements suitable for COPD diagnosis.
A new diagnostic device for and COPD is presented in this paper. The methods of monitoring and recording of the diaphragm movement by using mems based semi-conductor acceleration sensor seem to provide a versatile, useful and, at least theoretically, acceptable solution than most other methods for recording of the diaphragm movement.
Developed device is expected to be an important place in spirometer technology with the ability to measure the parameters of COPD.
It was seen that; results were very similar. So the developed device is considered as an alternative method to spirometer as well as portable property. This study is considered as an alternative method to available on pulmonary function test devices.

5. Discussion

A new diagnostic method has been developed for COPD in this study. The flow signal, TVC, FVC and RR parameters were measured. The measurement results were very similar to the results of spirometer. So the device developed under this study can be considered as an alternative measurement instrument of spirometer.
It is shown that the developed method using accelerometer sensor might be a reliable method to diagnose of some obstructive disease. In addition, it is shown that the developed method is easy to use, reliable and can also be easily used at home.

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Author Contributions

The authors declare that they have all participated in the design, execution, and analysis of the paper, and that they have approved the final version.

Conflicts of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper and the material described is not under publication or consideration for publication elsewhere.

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