Journal of Engineering Science and Technology
Vol. 13, No. 5 (2018) 1205 - 1221

ESTIMATING THE VALUE OF THE VOLUME FROM ACCELERATION ON THE DIAPHRAGM MOVEMENTS DURING BREATHING

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Abstract

Information related to the movements of the diaphragm is very important and it is used in the detection of some respiratory diseases, which are common in all over the world, such as chronic obstructive pulmonary disease (COPD), asthma, and bronchitis. This article describes a practical method for estimating the value of the volume using the acceleration information on the diaphragm movements. The main goal of this paper is to develop a data collection system that measures acceleration values and to estimate the acceleration-volume relationship by examining the obtained data. Thus, two important parameters (TVC and FVC) in the diagnosis of COPD are measured in a more practical way. In the present case, these two parameters can be measured in a hospital environment by an expensive medical device called "spirometry". For this purpose, our device is placed on the abdomen region of the patient, diaphragm movements are examined and values of the volume are estimated from acceleration data (total 416 accelerometric data). Measurements are performed simultaneously by the spirometry and the developed device. Pearson coefficient ($p<0.01$) is calculated to determine the correlation between the measured data by using devices. Results show us that there is a positive correlation between measured values of the two devices (accelerometric and spirometric). It can be concluded that there is an acceptable correlation (91.4%) between accelerometric and spirometric results and the estimate error margin is quite low (0.08). In this respect, this study is considered to be an alternative method to spirometry tests, which is used in diagnosing COPD.

Keywords: Acceleration sensor, Spirometry, Inspiration-expiration, Diaphragm, statistical analysis.

Nomenclatures

d	Anteroposterior movement distance (Fig. 3)
g	Gravity acceleration
Hz	Hertz
I^2C	Inter-Integrated circuit
L	Liter
mg	Milligravity
mm	Millimeter
n	Data index
p	Pearson correlation coefficient
s	Estimated volume with developed system
sec	Second
x, *y*, *z*	Axes (Fig. 3)
µA	Microampere

Abbreviations

COPD	Chronic Obstructive Pulmonary Disease
CCS	Custom Computer Services
CT	Computed Tomography
FEV	Forced Expiratory Volume
FEV1	Forced Expiratory Volume (the end of the first second)
FIFO	First in, first out
FVC	Forced Volume Capacity
LCD	Liquid-Crystal Display
LSB	Least Significant Bit
MEMS	Microelectromechanical systems
MRI	Magnetic resonance Imaging
PFT	Pulmonary function tests
PIC	Peripheral Interface Controller
PWM	Pulse Wide Modulation
SD	Secure Digital
SPI	Serial Peripheral Interface
SPSS	Statistical Package for the Social Sciences
TVC	Tidal Volume Capacity
US	Ultrasonograph
USART	Universal Synchronous/Asynchronous Receiver/Transmitter
USB	Universal Serial Bus

1. Introduction

Data related to diaphragm movements during breathing is functional for many medical applications.

The movements of the diaphragm can be monitored as anatomically/functionally. Although overall radiological methods can be performed as anatomical, functional imaging is mostly done via different methods such as Fluoroscopy [1], Ultrasonography (US) [2], Computerized Tomography (CT) [3] or Magnetic Resonance Imaging (MRI) [4]. Some other methods with regard to monitoring of the diaphragm movements are explained in [5-8]. Likewise, some other measurement

methods have been developed for diagnostic of the different pulmonary diseases (like detection of normal and cancerous tissues) that are described in [9-10].

Information related to movements of the diaphragm is very important and is used in the detection of some respiratory diseases which are common all over the world, such as COPD, asthma, bronchitis etc.

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 numbers of countries [11]. The gold standard of diagnosis for COPD is pulmonary function test and it is performed by a medical device that is called "spirometry" [12].

The spirometry measures the volume of air drawn in (inspiration) or exhaled (expiration) as a function of time during respiration. It is the most important tool used to diagnose COPD [13]. Spirometry is used to scan people who are at risk of pulmonary disease [14]. The spirometry measures many important parameters to make a decision about COPD including Tidal Volume Capacity (TVC), Forced Expiratory Volume (FEV), Forced Expiratory Volume at the end of the first second (FEV1) and Forced Volume Capacity (FVC). However, the spirometry devices are very expensive and not suitable for using at home. It also needs several additional equipments (latch, pipe, etc.)

There are several studies published in the literature to measure COPD parameters by using contacting or non-contacting techniques. Sherril et al. [15] developed a non-contacting measurement system to follow activity of the patient having COPD. Fox et al. [16] developed a new device namely "ActiWatch" to measure and transfer those data to computer using RF signals. Patel et al. [17] tried to classify the movements of patients by using wearable multiple accelerometer based sensors. Bates et al. [18] prepared an accelerometer based measurement system to measure nasal flow rate and breathing wave shape. He concluded that FVC values can be measured by using this system as a future study. The accelerometer based devices are portable and highly practical. Using accelerometer to monitor movement of the chest and abdomen has emerged as an alternative method recently. Torres et al. [19] tried to measure FVC values by using multiple sensor; the inspiratory pressure (IP) and the mechanomyographic signals of the left and righth emidiaphragms (MMGl and MMGr, respectively).

In this paper, a portable measurement instrument is developed in order to make a preliminary diagnosis of COPD by using an accelerometer sensor. With the developed device, the parameters such as volume flow signal, TVC and FVC are successfully measured and recorded on an eeprom. The purpose of this study is to estimate the volume values using the acceleration data by establishing the acceleration-volume relationship. The acceleration data measured by the developed device can be converted to the volume value (without a spirometry) with the help of developed device. Thus, patients will be able to perform measurements in a simpler and effortless manner without the use of an expensive and difficult-to-use spirometry. In this respect, this study is considered to be an alternative method to pulmonary function tests (PFT), which are cochlear diagnostic tests using a spirometry. Furthermore, by making an estimate from L to g, we prove how well the measuring system works and can be used in place of spirometry.

2. Material and Methods

Patient-controlled personal health record systems can help to make health care safer, cheaper and practical [20]. In particular, home-based diagnostic systems have become very popular, recently.

The architecture of the microcontroller based patient-controlled diagnostic system developed in this study has been shown in Fig. 1. With the help of this system, a patient can be able to record her/his pulmonary parameters by herself/himself at home and can retrieve the data to doctor via a memory unit (Secure Digital (SD) card, eeprom etc.). Then doctor may have information about the pulmonary after examining the data recorded on the memory unit. With this aspect, developed system offers a practical solution to doctors, beside the convenience it offers to patients.

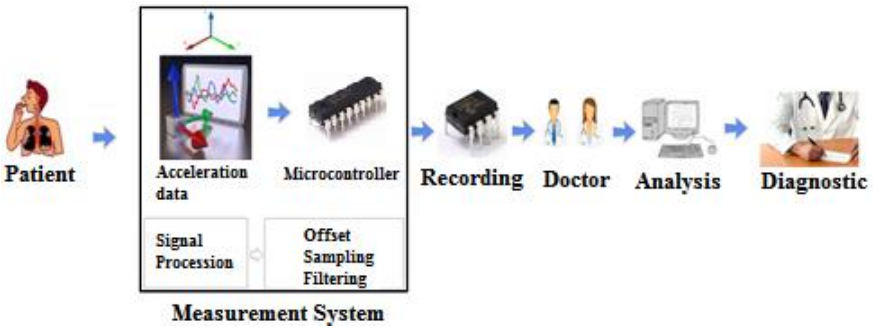


Fig. 1. The architecture of the diagnostic system.

Currently, data are measured by a Spirometry device of COPD in the Pulmonary Function Test at hospitals. Therefore, getting an appointment from a doctor takes month(s). Plus the Spirometry devices are quite expensive. Likewise, the spirometry devices are not suitable for using at the home for measuring COPD's parameters and the test has to be performed under supervision of a technician.

In this study, the accelerometer which has been very popular is used to measure accelerations occur because of diaphragm movements. Therefore, a data acquisition device is developed. Simultaneous measurements are performed with spirometry (Fukuda Sangyo brand spiroanalyz ST-75 model, Prg ver: 2.36B 16-Bit) and the device developed to estimate the volume value from acceleration value (data). The obtained data are analyzed statistically.

The measurement results were compared. It was concluded that results were acceptable. So the developed device was considered as an alternative method to spirometry and as well as portable device.

2.1. Acceleration sensor

Microelectromechanical systems (MEMS) and semiconductor technology [21] are combined on a single chip. So, MEMS accelerometers sense the acceleration on single or multiple axes on Cartesian coordinate system, and provide either digital or analog signal outputs [22]. Digital versions may have even multiple interrupt

modes. These features offer convenient and flexible solutions to users. MEMS based accelerometers are used for various purposes in military areas, as well as in health care industry [23-26].

The ADXL345 is one of MEMS based 3-axis accelerometer with digital output. It is manufactured by Analog Devices Inc. in the U.S.

When the accelerometer operating principle is considered, it is seen that a seismic mass region is placed between the electrode pairs. When a motion is applied to accelerometer, the seismic mass moves towards the spring according to the amount of acceleration force. Subsequently, the change is sensed by the electrodes and an electric signal is transmitted representing the acceleration by means of electronic means. This structure belongs to a uniaxial accelerometer and is generally the same in other MEMS constructions. Figure 2 shows the structure of the sensor.

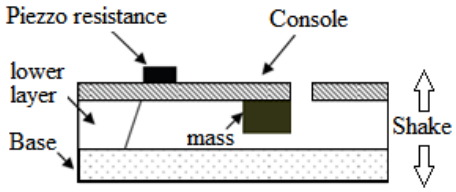


Fig. 2. The structure of an accelerometer [27].

It has a number of features such as; selectable ±2-g, ±4-g, ±8-g, or ±16-g measurement range; 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 I^2C 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 [23]. Hence, this combination of features makes the ADXL345 one of the most appropriate accelerometer for measuring of diaphragm movements in this study.

2.2. Diaphragm movements

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 [28]. So respiratory cycles are similar but they are actually different, because of different types of diaphragm movements. These differences are useful for medical studies [29-30].

Although the movements in the abdominal region are small during respiration, the respiratory cycles can be measured over the abdomen with an accelerometer [31-32].

It was understood from the literature [33-36] 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 sensor was placed on the patient's diaphragm so as to XZ-plane lies parallel to the ground and the X-axis was positioned perpendicular to the diaphragm. Hence, changes in the X-axis have shown diaphragm movement directly. Motion of the diaphragm was principally

axial, not dorsoventrally movement, so the sensor was placed on the diaphragm. Since the diaphragm was filled with air during the inspiration a movement occurred in the diaphragm (*d*=anteroposterior movement distance). Since the diaphragm movements were greater than the movements of the thorax (change in distance d) measurements were 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 X-axes, while there were no substantial movements detected in the Y and Z-axis (excluding people dependent parameters).The measured acceleration values were recorded on the eeprom and analyzed with computer. Placing the sensor on the patient's diaphragm and the coordinate system definitions are illustrated in Fig. 3.

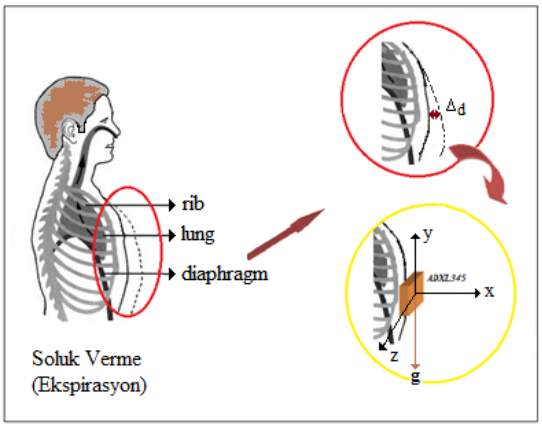


Fig. 3. Positioning the sensor on the patient [37].

Accelerations on the diaphragm during respiration were measured both by accelerometer and spirometry synchronous. The data were recorded on eeprom as 'g' in 3-axis (X-Y-Z). The total number of measured data was 416.

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.

2.3. Correlation analysis

Correlation analyses are used to determine the level of relationship between two variables. The Pearson correlation coefficient was calculated to investigate the relationship between the measured values of volume (L) from spirometry and the acceleration values (g) from the developed device, because experimental investigations suggest correlations (Pearson correlation coefficient)[38].

Correlation analysis was performed by Statistical Package for the Social Sciences software (SPSS V.2015).

2.4. Protocol and data acquisition

In this study, as a first step, a data acquisition card was designed. In the circuit, the sensor, which has ability to define position by using 3-axis Cartesian coordinate systems, was used to measure the accelerations that occur in diaphragm movements. The measured data from the sensor were either recorded on the eeprom or send to the computer via a universal serial bus (USB). These raw data, which were transferred to the computer, were grouped according to their axis (X-Y-Z) and plotted with the help of interface program. Figure 4 shows the structure of data acquisition card.

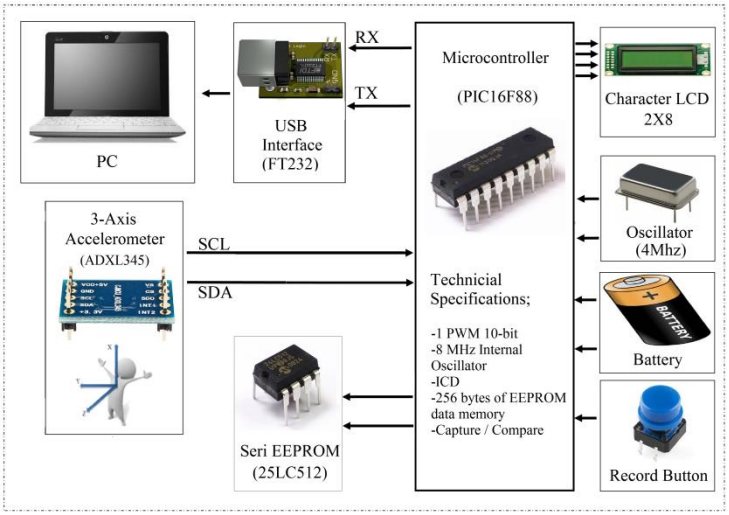


Fig. 4. The block diagram of data acquisition card.

The system's sampling frequency is 20 Hz. Each 32-bits of float received data are composed of x, y and z data. Thereby, the amount of data transferred is 20 x 3 x 32 = 1920 bits/s and it is suitable for a wireless transmission. As it is represented in Fig. 4, the system is open for improvements.

Microcontrollers are like the brain of the system they are used [39]. PIC16F88 microcontroller has been chosen to control the data acquisition card. The PIC16F88 features 8 MHz internal oscillator, 256 bytes of EEPROM data memory, a capture/compare/ Pulse Wide Modulation (PWM), an addressable universal synchronous/asynchronous receiver/transmitter (USART), a synchronous serial port that can be configured as either 3-wire Serial Peripheral Interface (SPI) or the 2-wire Inter-Integrated Circuit (I^2C) bus, 7 channels of 10-bit Analog-to-Digital (A/D) converter and 2 Comparators that make it ideal for advantage analog / integrated level applications in automotive, medical, appliances and consumer applications. Other components of the system are 2x8 character Liquid-Crystal Display (LCD) (used to see acceleration values in real time), accelerometer sensor(ADXL345), button (used to start a recording), crystal oscillator (4M Hz), eeprom memory component (24LC512, manufactured by The Microchip Technology Inc.) and data transfer circuit card(The USB interface, consists of ft232 circuit). The required power for the entire circuit has been obtained from a

circuit containing a 9V battery and LM7805 regulator. The accelerometer is extended via a cable (usb type of cable) during the tests.

As a second step, an interface program was developed by using Microsoft Visual C# 2010 (version 10.0.40219.1 SP1Rel) programming language as given in Fig. 5. The program developed transferred the acceleration values from the developed system to the computer. This program provided opportunities for saving the data measured as a text file or for plotting the graph of the previously recorded data. Custom computer services (CCS) software was used to program the PIC16F88 microcontroller.

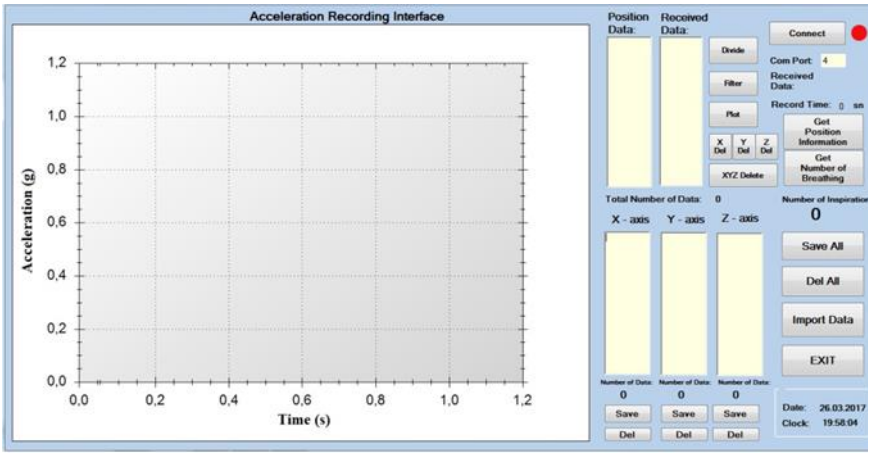


Fig. 5. Interface program (prepared by using C # programming language commands).

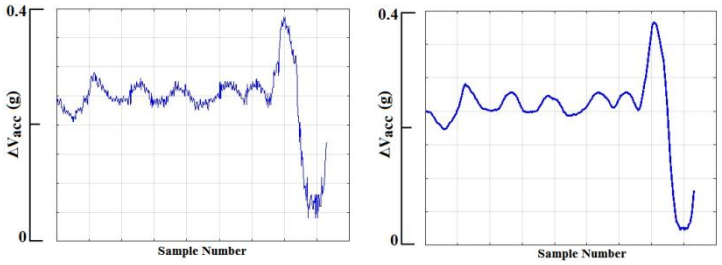
All data were transferred to the computer with the help of this interface. Filtering was needed for analyzing. Matlab is the most convenient and widely used program for filtering and analyzing [40]. So, analyses were done in MATLAB (version 7.12.0.635 (R2011a) 32-bit win32).

DC components were thrown from the raw signal and 10 point average filter was used.

The Matlab script code is shown below;

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

The raw and filtered (using Matlab) measurement results are as given in Fig. 6.



(a) (b)

Fig. 6. The measurement result of the developed device (a) raw and (b) filtered.

3. Results and Discussion

Firstly, in order to show the performance of developed system, the patients' acceleration (g) patterns that occur in diaphragm movements (respiratory) were measured after data acquisition and results are presented graphically as in Fig. 7.

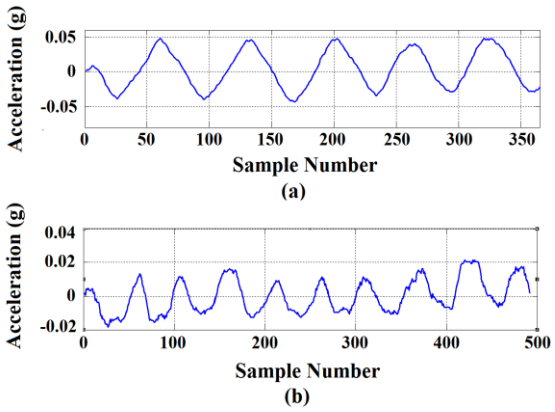


Fig. 7. The measured patterns after data acquisition from patient -1 (slow inhalation) (a) and from patient-2 (fast inhalation) (b).

There are several parameters about pulmonary. Some of these parameters are shown in Fig. 8.

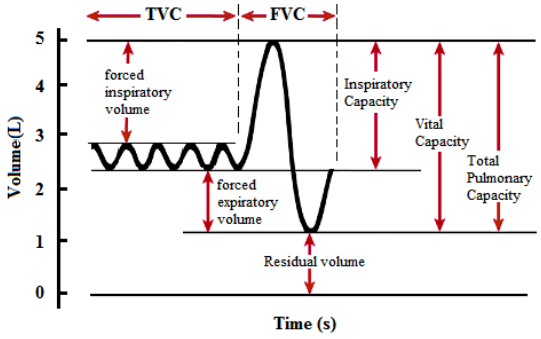


Fig. 8. Pulmonary volumes and capacities [41].

Pulmonary parameters (TVC and FVC) were measured by using both devices simultaneously. Figure 9 shows TVC (0 s-16 s) and FVC (16 s-24 s) measurement results from spirometry.

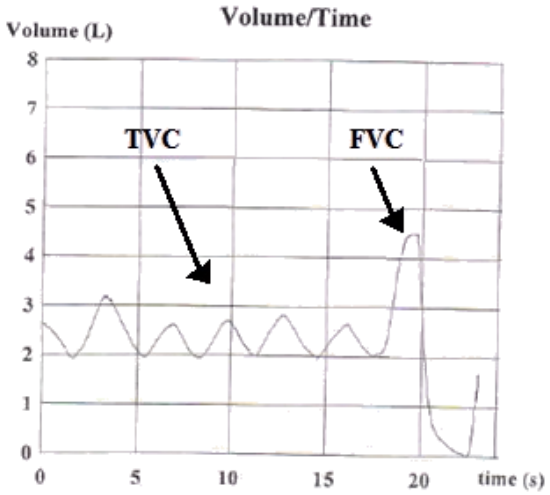


Fig. 9. Pulmonary parameters measured by spirometry.

The patient's accelerations (g) that occurs in diaphragm movements (respiratory) and volume (liters) were measured by using both devices and results are presented graphically as in Fig. 10. (note that the volume values in the graph are sampled at the frequency of 20 Hz of the original spirometry values).

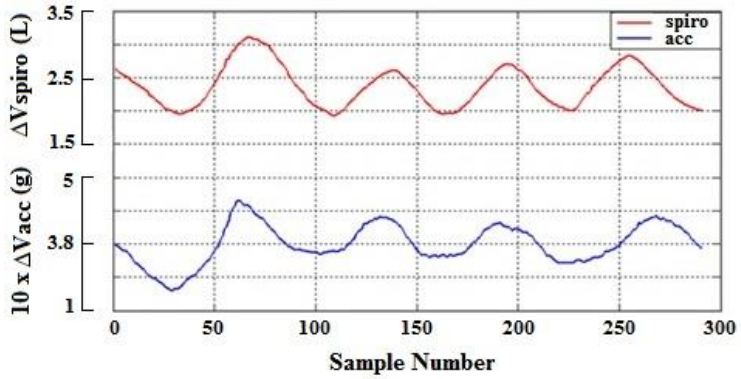


Fig. 10. The measuring patterns from patient-3.

There is a close similarity between the measurement results, graphically. This is important because the doctors often assess patient outcomes graphically when making a diagnosis. The interface program is developed exactly for this purpose.

For estimation 137 data were selected randomly from the dataset (416 data) and they were investigated to question whether there was relation between the volume (v) measured by medical spirometry and the acceleration value (g) measured by the developed system. Comparisons of some sample data (from 137 the data to be

estimated) were given in Table 1. These data were measured as tidal volume during the normal volume of air displaced between normal inhalation and exhalation where extra effort was not used.

Table 1. Comparison of data.

Sample Number	Accelerometeric(g)	Spirometric (L)
1	0.38	2.63
2	0.39	2.62
3	0.37	2.56
4	0.39	2.52
5	0.36	2.45
6	0.35	2.44
7	0.34	2.42
8	0.37	2.4
9	0.35	2.38
10	0.34	2.36
11	0.35	2.32
12	0.34	2.29
13	0.35	2.23
14	0.34	2.16
15	0.33	2.12
16	0.32	2.09
17	0.33	2.05
18	0.31	2.03
19	0.33	2.02
20	0.32	2
21	0.34	2.02
22	0.36	2.05
23	0.4	2.08
24	0.45	3.01
25	0.43	3.06
26	0.44	3.08
27	0.46	3.12

Pearson correlation coefficient (p) has been calculated by using SPSS statistical software package, as $p<0.01$. In addition, since $p < 0.01$ the correlation between measured values is significant. Correlation results are shown in Table 2.

Table 2. Correlation results.

		Spirometric
Accelerometric	Pearson Correlation (p)	0.914(**)
	Sig. (2-tailed)	.000
	n	137

***** Correlation is significant at the 0.01 level (2-tailed).***

In addition to this correlation investigation, measured acceleration and volume values are plotted with respect to each other as given in Fig 11. In Fig. 11, x-axis shows the measured acceleration values and y-axis shows the Spirometry measurement volumes for the same corresponding sample. It is seen from the graph that when the volume is in between 2 liters to 4 liters, there is good correlation between acceleration values and Spirometry values. It means that, it is needed to use the more accurate and the more sensitive accelerometer to get good correlation for lower Spirometry volume as well as high volumes.

As a result of the analysis, an eq. defining the relation between the data is found as given Eq. (1).

$$s = (gx6.4)_{[n]} + 0.14 \quad (1)$$

where g is the acceleration measured from developed device, s is the estimated volume with developed system and n is the data index.

Although the coefficient and constant are generally available by deriving from the Eq. (1), it can vary from patient to patient.

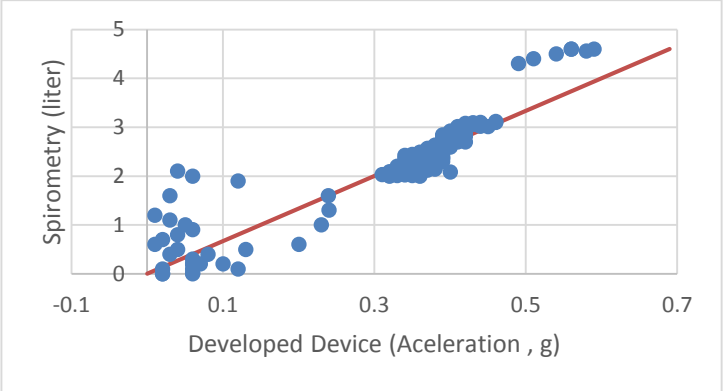


Fig. 11. The correlations between both measurements according to patient-3 measurement results.

The results showed that, the relationship between spirometric and accelerometric values were found as 91.4%. Thus, it is seen that very high and positive relationship is found between two devices measurements. In addition, it has also been found to be $p < 0.01$ and the relationship between measured values are quite significant.

For investigating the performance of eq. (1), 15 different data are chosen from the dataset randomly which are not given in Table 3 and are applied are applied in eq. (1). Resulting estimated values according to measured value are tabulated as given in Table 3.

As shown in Table 3, it can be said that average estimate error margin between the developed device and spirometry measurement results is quite low (0.08) and negligible. In this respect, this study is considered to be an alternative method to spirometry tests, which is used in diagnosing of COPD.

The relationship between the measured values and the estimated values is given graphically in Fig. 12.

Table 3. Prediction results of system.

Number	Accelerometric (g)	Spirometric (L)	Estimated (L)	Difference
1	0.38	2.54	2.572	0.032
2	0.37	2.4	2.508	0.108
3	0.31	2.03	2.124	0.094
4	0.34	2.29	2.316	0.026
5	0.4	2.68	2.7	0.02
6	0.42	2.83	2.82	0.002
7	0.46	3.1	3.084	0.016
8	0.39	2.64	2.636	0.004
9	0.45	3.01	3.02	0.01
10	0.32	2.09	2.188	0.098
11	0.36	2.41	2.444	0.034
12	0.41	2.7	2.764	0.064
13	0.33	2.2	2.252	0.052
14	0.44	3.1	2.956	0.144
15	0.23	1	1.612	0.612

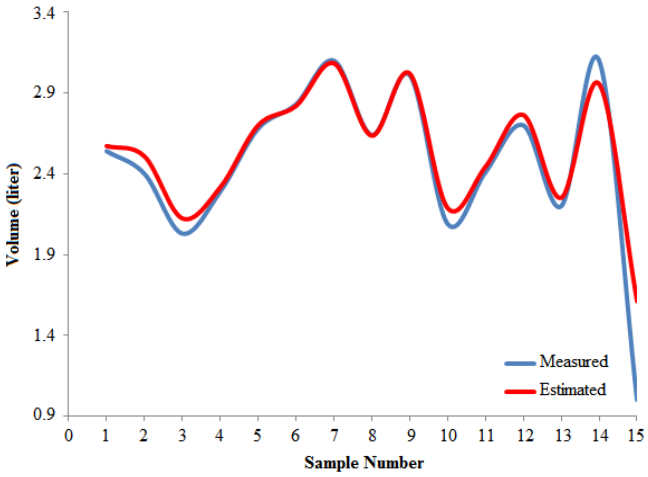


Fig. 12. The relationship between the measured values and the estimated values.

4. Conclusions

In this paper, a system is designed to measure accelerations occurring on the diaphragm. Simultaneous measurements are performed by medical spirometry and the developed device. Then, it is tried to estimation of the volume values is realized from measured acceleration values with the help of the developed device. The results are very close to each other (91.4%). Further, Pearson correlation coefficient has been calculated by using SPSS statistical software package. A positive correlation between

the results is determined. Hence, an equation is defined which gives the volume of air entering the body while breathing from "g" values. It is showed that calculated volume by eq. (1) is very close to the value measured by medical spirometry. In contrast to spirometry the developed system does not have any pipe or nose clip. New measurement system has only accelerometer as a sensor.

Acknowledgement

This study is supported by the Coordinatorship of Karabük University's Scientific Research Projects (KBÜ-BAP-15/1-DR-001), Karabük, Turkey.

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