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Portable spirometer using pressure-volume method with Bluetooth integration to Android smartphone

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ABSTRACT

This paper presents a study on an embedded spirometer using the low-cost MPX5100DP pressure sensor and an Arduino Uno board to measure the air exhaled flow rate and calculate force vital capacity (FVC), forced expiratory volume in 1 s (FEV1), and the FEV1/FVC ratio of human lungs volume. The exhaled air flow rate was measured from differential pressure in the sections of a mouthpiece tube using the venturi effect equation. This constructed mouthpiece and the embedded spirometer resulted in a 96.27% FVC reading accuracy with a deviation of 0.09 L and 98.05% FEV1 accuracy with a deviation of 0.05 L compared to spirometry. This spirometer integrates an HC-05 Bluetooth module for spirometry data transceiving to a smartphone for display and recording in an Android application for further chronic obstructive pulmonary disease (COPD) diagnosis.

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1. INTRODUCTION

The functional performance of the respiratory organs can indicate human health. Spirometry can examine this performance, which assesses the integrated function of mechanical lungs, chest wall, and respiratory muscles by measuring the air volume exhaled from total lung capacity (TLC) to residual volume [1]–[3]. Spirometry is a global initiative for chronic obstructive lung disease (GOLD) standard for diagnosing and monitoring chronic obstructive pulmonary disease (COPD), asthma, and coronavirus disease 2019 (COVID-19) [4]–[9]. In addition, it is also used as a preliminary examination of COPD in smokers [10], [11]. However, its high cost is a barrier for people to self-monitor their lung health. There is a need for a low-cost spirometer to monitor their lung health by themselves. Furthermore, Meghji *et al.* [12] stated that COPDs are strongly associated with poverty in low-income and middle-income countries, especially in poor air quality environments [13].

Several studies have developed low-cost respiratory monitoring systems for home care applications using an embedded spirometer using a microcontroller to measure respiratory values. Laghrouche *et al.* [14] and Habibiabad *et al.* [15] focused on developing a micro-electro-mechanical systems (MEMS) sensor unit to measure the expiratory flow rate. The MEMS flow sensors have been widely used in biomedical applications to measure air flow, especially respiratory flow [16]–[18]. Meanwhile, a device has been developed to measure the other respiratory values, such as forced expiratory volume in 1 second (FEV1) and forced vital capacity (FVC) [19], and level of hydrogen sulfide, ammonia, acetone and alcohol in patients' exhaled breath [20]. Other studies have implemented the spirometer to detect asthma symptoms and COPDs providing effective treatment for the patients [21]–[23]. Other studies used a field programmable gate array (FPGA) for implementing a spirometry-on-chip device [24], [25].

Those spirometers used various sensor types, such as a MEMS anemometer in [14], [15], [24]–[26], and a pressure sensor in [19], [21]–[23], [27]. Furthermore, the widespread usage of smartphones as personal devices attracted several spirometer studies' attention. Instead of a microcontroller, a smartphone was used as a portable spirometer. These smartphone-based spirometers perform the respiratory data acquisition, processing, and displaying its data representation on its screen. Respiratory data was acquired by sensing exhalation or cough audio frequency signal via smartphone microphone/audio line-in using audio processing and machine learning in [28]–[35]. These spirometers offer rapid and simple screening tools. However, these respirators' accuracy was lower than those with dedicated sensors.

This study aims to develop an embedded spirometer using a microcontroller and a pressure sensor to measure exhaled air flow rate with high precision and accuracy, inspired by [19], [21]–[23], [27]. A mouthpiece for exhalation was designed, and the venturi effect equation from the differential air pressure of tube sections was applied to calculate air flow rate and lung volume, namely FEV1 and FVC. In contrast to other studies, the user can see his/her lung volume on his/her smartphone using an Android application, named Spirodroid. Data is communicated between the spirometer and the smartphone using a Bluetooth module. Based on FEV1, FVC, and FEV1/FVC ratio, Spirodroid can also diagnose users' obstruction or restriction of their lungs. The measurement data from multiple users can be recorded in the smartphone storage for further analysis. Users can then use this spirometer and the Spirodroid to diagnose their lungs obstruction or restriction diseases anytime.

This paper proceeds as follows. Section 2 derives the method for developing a portable spirometer to calculate lung volume and presents all used equations, the overall system block diagram, the Fritzing circuit diagram using Arduino, and the software flowchart. Section 3 provides the spirometer hardware and Android software implementation, analyses the system precision and accuracy, and provides a comparison of variously spirometers based on their sensor types. Section 4 summarizes the key findings of this study.

2. METHOD

Figure 1(a) illustrates the block diagram of the portable spirometer developed in this study. The spirometer measures lung volume and presents its value on the Spirodroid. It uses an ATMega328 on an Arduino Uno R3 board as the controller for data reading and transmission to the Spirodroid. The system can calculate the air exhaled in a few seconds by using the pressure value obtained from the MPX5100DP (absolute pressure sensor) and display the calculated FEV1 and FVC lungs volume on the Spirodroid under desired conditions. It can indicate the status of FEV1 and FVC measurement activity on the green and blue light emitting diode (LED). The calculated FVC and FEV1 values are transmitted to Spirodroid via a Bluetooth HC-05 module. This Spirodroid can also control the system to initiate the measurement and store FVC and FEV1 records for further user diagnosis. Figure 1(b) represents the system circuit diagram. The system uses a mouthpiece as a medium for user exhalation, as depicted in Figure 1(c). The mouthpiece has an A1 diameter of 2.2 cm, A2 of 1.7 cm, and length of h1 and h2, both 5 cm. The MPX5100DP sensor inlet is connected to P1 and P2 of the mouthpiece. When the user exhales through the mouthpiece, the MPX5100DP sensor reads its pressure value.

This study measures FVC and FEV1 (both in L) to calculate lung volume or capacity when the user exhales through the mouthpiece. The lung volume or capacity is normally affected by age, sex, height, and race [36]. The reference value of FVC is calculated from (1) and (2) for male and female persons, respectively, where A and H denote age (in year) and height (in cm). The reference value of FEV1 capacity is calculated from (3) and (4) for male and female persons, respectively. A healthy person has more than or equal to 80% of FVC and FEV1 reference values [3]. According to the FEV1/FVC ratio, a person normally exhales about 70% of FVC in a second. American Thoracic Society-Global Initiative for Chronic Obstructive Lung Disease-Chronic obstructive pulmonary disease (ATS GOLD COPD) was used to adjust disease obstruction and severity [37]. Based on the value of the FEV1/FVC ratio, they are classified as mild, moderate, severe, or very severe.

$$FVC_m = 0.93 \cdot (0.0576 \cdot H - 0.0269 \cdot A - 4.34) \quad (1)$$

$$FVC_f = 0.93 \cdot (0.0443 \cdot H - 0.026 \cdot A - 2.89) \quad (2)$$

$$FEV1_m = 0.93 \cdot (0.043 \cdot H - 0.029 \cdot A – 2.49) \quad (3)$$

$$FEV1_f = 0.93 \cdot (0.0395 \cdot H - 0.025 \cdot A – 2.6) \quad (4)$$

This study uses the venturi effect equation expressed in (5) and (6) to measure the airflow rate in the mouthpiece depicted in Figure 1(c). A smaller sectional area has a greater fluid velocity, and a larger sectional area has a smaller fluid velocity. P1 is smaller than P2 at a higher flow velocity, according to the venturi effect equation, and vice versa at a lower flow velocity if v1 is greater than v2. Q denotes the air exhaled flow rate in m^3/s. A1 and A2 denote the first and second sectional areas in m^2, i.e., 3.8×10^{-4} m^2 and 2.27×10^{-4} m^2. The v1 and v2 denote the first and second fluid velocities in m/s. P1 and P2 denote the first and second fluid pressure in N/m^2. ρ denotes the air density, which is 1.2 kg/m^3.

$$Q = A_1 \cdot v_1 = A_2 \cdot v_2 \tag{5}$$

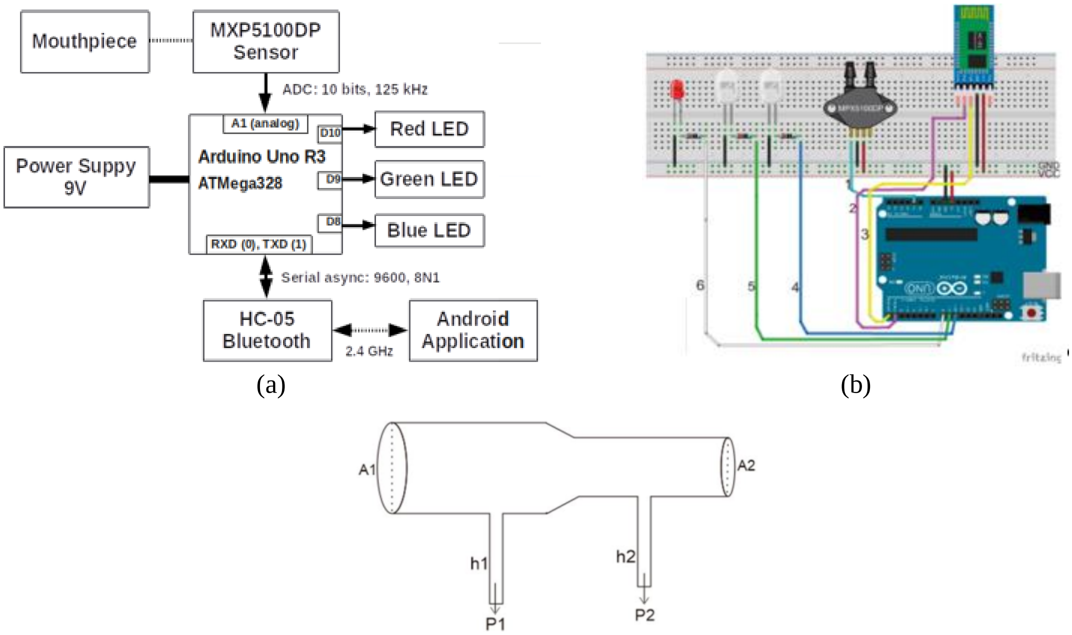
$$P_1 - P_2 = \Delta P = \frac{1}{2}\rho(v_2^2 - v_1^2) \tag{6}$$

The velocity v_1 in the first sectional of the tube is expressed in (7). By considering (5), flow rate Q (m^3/s) is expressed in (8). FEV1 represents the flow rate in a second, while FVC is the total volume V in t seconds as expressed in (9) where t denotes the time duration in seconds when Q is non-zero.

$$v_1 = \sqrt{\frac{2(P_1-P_2)/\rho}{\left(\frac{A_1}{A_2}\right)^2-1}} \tag{7}$$

$$Q = A_1 \cdot v_1 = A_1\sqrt{\frac{2(P_1-P_2)/\rho}{\left(\frac{A_1}{A_2}\right)^2-1}} \tag{8}$$

$$V = Q1(t1 - t0) + Q2(t2 - t1) + \cdots + Qn(tn - t(n-1)) \tag{9}$$



(c)

Figure 1. Portable spirometer system using Arduino Uno R3 with Bluetooth communication interface (a) block diagram, (b) circuit diagram, and (c) mouthpiece design

Arduino Uno R3 reads the exhaled air pressure from the user. The system uses the scheduling mechanism to sample and sum the exhaled value into FEV1 or FVC volumes periodically at 11 and 25 ms, respectively. The resulting volumes were sent to the Spirodroid via Bluetooth communication. The LEDs will light on to indicate the measurement status. When the user needs to measure the lung volume, the Spirodroid sends an ‘A’ character to the measuring system to initiate a measurement process; otherwise, the measuring system turns the green and blue LEDs off to indicate the ready status. The FVC and FEV1 volumes are then analyzed and displayed in the Spirodroid. The measuring system flowchart using Arduino is shown in Figure 2. Figure 2(a) represents the overall program, while Figure 2(b) represents the main loop routine.

The flowchart of FVC and FEV1 measurements is shown in Figure 3. FEV1 measurement from the exhaled air is conducted every 11 ms during the first second using (8). After obtaining FEV1, the measurement of the exhale value is followed by a time interval of 25 ms to get FVC volume. FVC measurement uses the previous FEV1 value and is added with the total first air exhaled after the first second using (9). When the sensor no longer detects the pressure value over 500 ms, the volume of FEV1 and FVC will be displayed. After completing FEV1 and FVC measurements, the green and blue LED will be off to indicate that the system is ready to receive the command from Spirodroid.

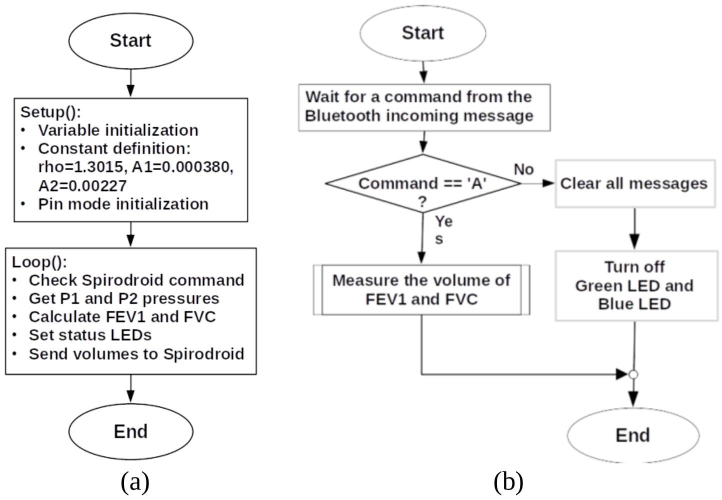


Figure 2. Flowchart of the system using Arduino programming (a) overall system and (b) *void loop()*

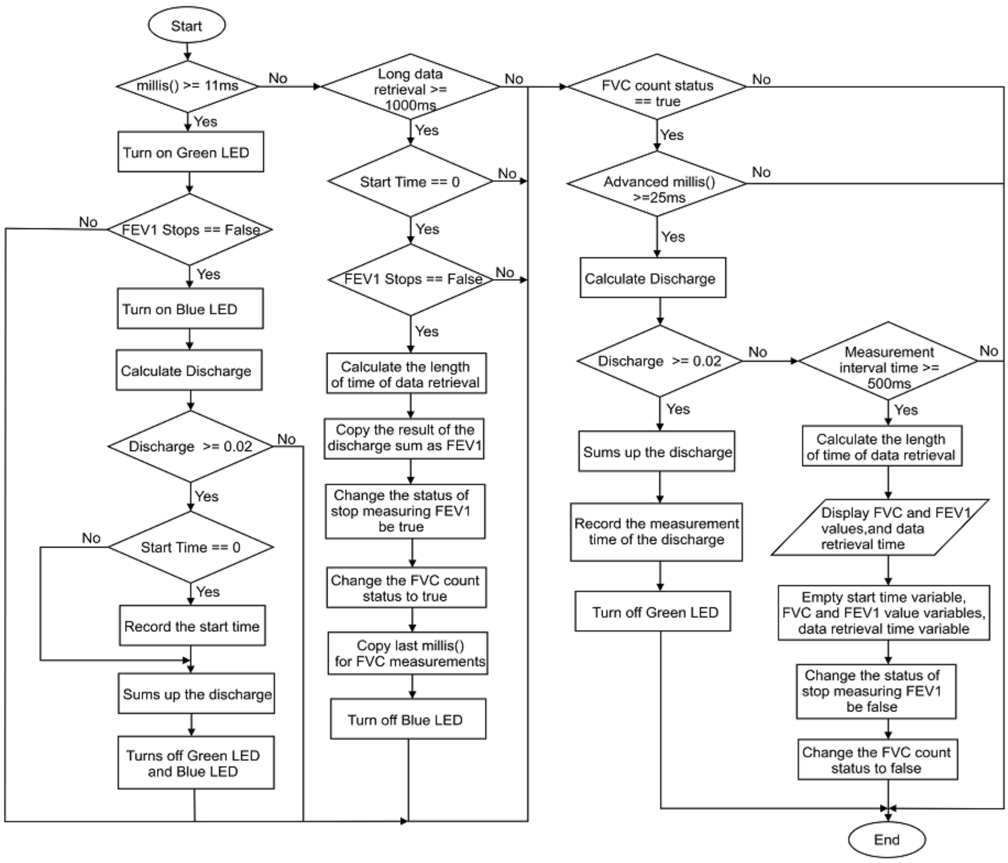


Figure 3. Flowchart of FVC and FEV1 measurements

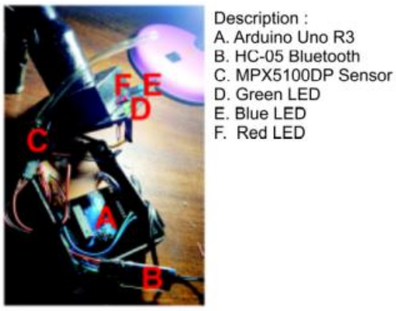
In this research, the system analysis was conducted to measure the precision and accuracy level of the lung measurement results. This precision level shows how close the test results are when repeated with the same sample using (10). The system is precise when the error value is small. *n* denotes the amount of measurement data, that is 15 times. *x* denotes the measured data, and mean is the average of the measured data. Accuracy testing was done by comparing this volume measurement system with a Spirometry tool on the same subject. The accuracy was calculated using (11), where *xs* denotes volume measured by the Spirodroid system while *xref* by the Spirometry.

$$Precision(\%) = 100 - \left(\frac{\sqrt{\sum_{i=1}^{n}(x_i - mean)^2}}{mean} \times 100 \right) \tag{10}$$

$$Accuracy(\%) = 100 - \left(\frac{|x_s - x_{ref}|}{x_{ref}} \times 100 \right) \tag{11}$$

3. RESULTS AND DISCUSSION

The lung measuring system works when the user exhales air through the mouthpiece to produce FVC and FEV1 volume values. Figure 4 shows the hardware implementation of the system: the component placement Figure 4(a) and the physical view Figure 4(b). The measuring software depicted in Figure 2 runs on this hardware. The measuring system was programmed using Arduino IDE software version 1.8.13.



(a)

(b)

Figure 4. Hardware implementation of the spirometer (a) the components placement and (b) the physical view

The Spirodroid application was programmed using the Android Studio 3.1. The Spirodroid was run on an Android smartphone with a minimal version of 8.1. Figure 5 shows the Spirodroid application interfaces: entry form Figure 5(a), 1st measurement Figure 5(b), 2nd measurement Figure 5(c), result information Figure 5(d), and the result analysis Figure 5(e). When the user fills the form on the volume measurement menu with the correct data, the Spirodroid will open the data retrieval window and try to connect with the measuring system. The result page displays user data, ideal FVC, ideal FEV1, FEV1/FVC ratio, measurement value, and data analysis after the second measurement. The data retrieval results can be saved as PDF files in the Spirodroid folder on the user's internal smartphone memory.

The HC-05 Bluetooth module testing measured its maximum data transmission range in line-of-sight conditions. During the testing, the module can send 100 data at a distance of up to 20 meters. However, the data transmission speed started to decrease when measuring at a distance of 15 meters. From this view, the data transmission was effective when the distance between the measuring system and the Android device was up to 10 meters without obstacles as found also in [38]. This result shows that HC-05 module is more suitable for this portable spirometer, instead of using a local liquid crystal display (LCD) or universal serial bus (USB) connection as in [20], [22]. It can provide energy-efficient short-range wireless data transmission with good throughput between mobile phones and many biomedical devices [39], [40], such as in a portable vital sign monitoring system [41], low-cost portable electrocardiogram (ECG) monitoring systems [38], [42]–[44], and an electroencephalogram (EEG)-controlled system for disabled and elderly people [45]. Furthermore, management and treatment of COPD patients can be integrated with clinical information systems in hospitals using an IoT-based system [46], [47].

The NXP MPX5100DP sensor testing was done using a manual pump to test the sensor functionality. The maximum pressure value that the sensor can read is 99.61 kPa. The maximum pressure value obtained in the test shows that the sensor worked well under the characteristics of the MPX5100DP sensor that has a maximum pressure value of 100 kPa as in [21], [22]. There are, however, other MEMS piezoelectric absolute pressure sensors that can also be used for Spirometers, such as the STMicro LPS22HH, LPS22HB, and the Bosch BMP388, with the LPS22HH showing the best performance [23].

Figure 5. Spirodroid interfaces (a) entry form, (b) 1st measurement, (c) 2nd measurement, (d) result, and (e) analysis

The precision testing of the proposed system was carried out on two subjects, namely a 22-year-old man with a height of 170 cm and a 14-year-old man with a height of 164 cm. Both tests measured their FVC and FEV1 for 15 times experiments. Figure 6(a) shows FVC and FEV1 for the first subject with 4.02 L of FVC mean volume, 96.27% of FVC precision, 3,526 L of FEV1 mean volume, and 98.05% of FEV1 precision, while Figure 6(b) for the second subject with 95.16% of FVC precision and 97.42% of FEV1 precision. The measured FVC and FEV1 data and their precision calculation from the first and second subjects are shown in Table 1 and Table 2. The average FVC precision from both measurements was 95.72%, while the average FEV1 precision was 97.735%.

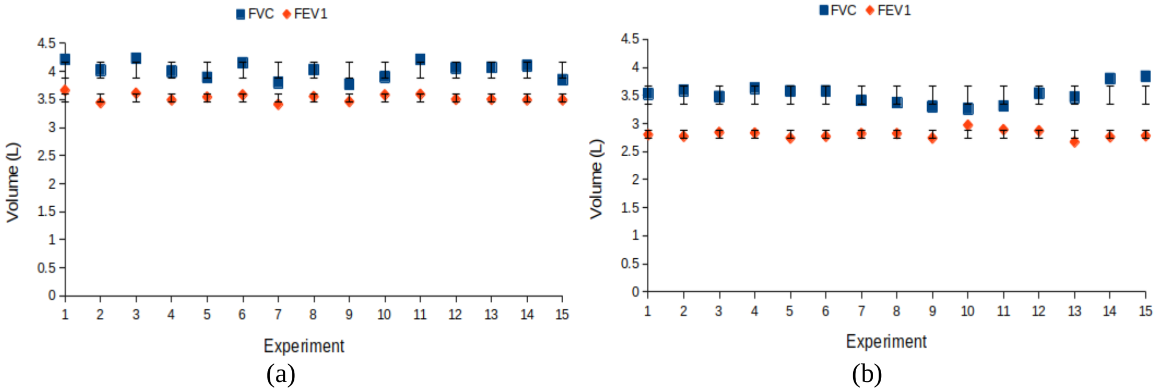


Figure 6. Precision FVC and FEV1 testing of the system for 15 times (a) the first subject and (b) the second subject

Table 1. FVC and FEV1 measurement data for testing precision calculation on the first subject

Experiment	FVC (L)	FVC-Mean	(FVC-Mean)^2	FEV1 (L)	FEV1-Mean	(FEV1-Mean)^2
1	4.21	0.19	0.0361	3.66	0.13	0.0169
2	4.02	0	0	3.44	-0.09	0.0081
3	4.23	0.21	0.0441	3.61	0.08	0.0064
4	4	-0.02	0.0004	3.49	-0.04	0.0016
5	3.89	-0.13	0.0169	3.54	0.01	0.0001
6	4.15	0.13	0.0169	3.58	0.05	0.0025
7	3.8	-0.22	0.0484	3.41	-0.12	0.0144
8	4.03	0.01	0.0001	3.55	0.02	0.0004
9	3.77	-0.25	0.0625	3.46	-0.07	0.0049
10	3.9	-0.12	0.0144	3.58	0.05	0.0025
11	4.21	0.19	0.0361	3.59	0.06	0.0036
12	4.06	0.04	0.0016	3.5	-0.03	0.0009
13	4.07	0.05	0.0025	3.5	-0.03	0.0009
14	4.1	0.08	0.0064	3.49	-0.04	0.0016
15	3.85	-0.17	0.0289	3.49	-0.04	0.0016
Total	60.29	-0.01	0.3153	52.89	-0.06	0.0664

Table 2. FVC and FEV1 measurement data for testing precision calculation on the second subject

Experiment	FVC (L)	FVC-Mean	(FVC-Mean)^2	FEV1 (L)	FEV1-Mean	(FEV1-Mean)^2
1	3.53	0.02	0.0004	2.8	0	0
2	3.59	0.08	0.0064	2.77	-0.03	0.0009
3	3.48	-0.03	0.0009	2.84	0.04	0.0016
4	3.63	0.12	0.0144	2.83	0.03	0.0009
5	3.58	0.07	0.0049	2.74	-0.06	0.0036
6	3.58	0.07	0.0049	2.77	-0.03	0.0009
7	3.41	-0.1	0.0100	2.82	0.02	0.0004
8	3.37	-0.14	0.0196	2.82	0.02	0.0004
9	3.3	-0.21	0.0441	2.74	-0.06	0.0036
10	3.26	-0.25	0.0625	2.97	0.17	0.0289
11	3.31	-0.2	0.0400	2.89	0.09	0.0081
12	3.54	0.03	0.0009	2.87	0.07	0.0049
13	3.47	-0.04	0.0016	2.67	-0.13	0.0169
14	3.8	0.29	0.0841	2.76	-0.04	0.0016
15	3.84	0.33	0.1089	2.78	-0.02	0.0004
Total	52.69	0.04	0.4036	42.07	0.07	0.0731

The accuracy testing of the proposed system was carried out by comparing this developed system with a Spirometry tool on the same subject. The test subject exhaled twice to the measuring system, and the results were compared with the Spirometry. The accuracy of the system is summarized in Table 3. The FVC accuracy of the system on the first try was 97.71%, with a 2.29% deviation (0.09 L). The FEV1 accuracy of the system in the second try was 98.56% with 1.44% deviation (0.05 L), while the FVC accuracy was 96.50% with 3.50% deviation (0.13 L), while the FEV1 accuracy was 95.58% with 4.42% deviation (0.13 L). The average FVC accuracy from both measurements was 97.11%, while the average FEV1 accuracy was 97.07%.

The performance of this proposed system is as good as [19], [21], [22] Table 4, which uses an absolute pressure sensor to measure the lung volume using pressure-volume method with a wireless communication advantage. However, Grunfeld [23] suggests potentially using a lower-price sensor, LPS22HH or LPS22HB, to reduce the spirometer cost. It has a synchronous serial interface which most microprocessor boards support. Also, this proposed system only measures and presents PVC, PEV1, and the FEV1/FVC ratio on users' smartphones because they are the mandatory spirometry values for diagnosing COPD [37]. However, it can be extended to allow other values for further lung disease detection, as in [48]. Furthermore, machine learning algorithms can be used to enhance the accuracy of spirometer readings and COPD diagnosis classification [49]–[54].

Table 3. Accuracy of the proposed system

Age	Height (cm)	Sex	Spirometry			Spirodroid		
			FVC (L)	FEV1 (L)	FEV1/FVC (%)	FVC (L)	FEV1 (L)	FEV1/FVC (%)
22	170	Male	3.93	3.48	88.55	4.02	3.53	87.81
21	170	Male	3.72	3.07	82.70	3.85	2.94	76.36

Table 4. Various absolute pressure sensors implemented in spirometers

No	Sensor Types	Used in	Pressure range (kPa)[a]	Interface	Unit Price[b]	Performance[c]
1	STMicro LPS22HH	[23]	26 to 126	I2C, SPI	\$3.79	S_{TE}: 30.90 (best)
2	STMicro LPS22HB	[23]	26 to 126	I2C, SPI	\$4.21	S_{TE}: 58.29
3	Bosch BMP388 (absolute), replaced by BMP390	[23]	30 to 125	I2C, SPI	\$5.36	S_{TE}: 32.42
4	NXP MPXV5050	[19]	0 to 50	Analog	\$25.28	Functional
5	NXP MPX5100	The proposed system, [21], [22]	15 to 115	Analog	\$36.36	Accuracy: 97.11% (FVC), 97.07% (FEV1) Error: 0.5 to 4.21% [21] Standard deviation: 0.610 (FVC), 0.510 (FEV1) [22]

Note: [a] is the pressure ranges are given from the sensor datasheet, [b] is unit prices are obtained from Digikey, [c] is STE expresses a total error score.

4. CONCLUSION

The constructed Venturi tube and the embedded spirometer in this proposed system have good precision and accuracy of FVC and FEV1 readings in diagnosing COPD. It can perform measuring FVC and FEV1 with an average FVC precision of 95.72%, an average precision of FEV1 of 97.74%, an average accuracy of FVC of 97.11%, and an average accuracy of FEV1 of 97.07%. The accuracy of this system is as good as other systems, which use an absolute pressure sensor to measure lung volume. Still, it has the advantage of wireless communication using Bluetooth.

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