Rapid prototyping of a temperature, humidity, and pressure monitor electronic layer for Pressure Ulcer wound patch

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Abstract. Pressure ulcer is a result of relieving pressure from skin or underlying tissues, causing localized injuries. In this study, a prototype of an electronic monitoring layer that can be placed on top of the wound patch is designed. The electronic layer is comprised of four force-sensitive pressure sensors, and an integrated temperature and humidity sensor to monitor the activities surrounding the wound site. In the simulated wound bed experiments, the results indicated that the utilization of the Bosch BME280 I2C module, when placed on top of a gauze pad, can deliver accurate and real-time monitoring of the temperature and humidity values. Furthermore, the force-sensitive resistors (FSR) installed can be utilized to detect external pressure beyond the set allowable force applied of 32 mmHg or 700g. Therefore, the electronic layer assembled from commercially available sensors can be used to monitor temperature and humidity while being able to detect externally applied pressure in real-time. However, improvements in the size and flexibility of the electronic layer are necessary to reduce the discomfort that patients suffering from pressure ulcers will experience.

1. Introduction
Pressure ulcers are caused by experiencing unrelieved pressure or stress over a certain period of time. Larger amounts of pressure applied to the skin may develop pressure ulcers in a shorter period, while smaller amounts of pressure in longer periods [1]. This external pressure experienced by the skin may cause the surrounding area to disrupt blood circulation and depriving the tissues of oxygen and nutrients [1]. Generally, prolonged external pressure greater than the arterial capillary filling pressure (>32 mm Hg) and the venous capillary outflow pressure (8 to 12 mm Hg) inhibits blood flow, resulting in hypoxia in the local tissue area [2]. The occurrence of pressure ulcers continues to pose an additional burden to the patient and the healthcare system [3]. However, the majority of these cases are avoidable. Mervis and Phillips (2018) pointed out that pressure redistribution through frequent repositioning (at least every two hours), a low angle of bed incline, and proper patient positioning can help reduce the incidence of pressure ulcers [4]. Aside from the aforementioned wound management techniques, several considerations such as glucose, oxygenation, pH, temperature, and humidity should be monitored to better care for the wound environment and accelerate recovery [5,6]. With the rapid advancement of technology in healthcare, there has been an emerging trend in the use of smart electronics-integrated wound dressings for real-time applications in the diagnosis, treatment, and monitoring of chronic wounds [7,8].

In this research, the measurement and evaluation of temperature, moisture, and pressure in the wound site are emphasized. Change in temperature is a determinant of wound healing. During the inflammation
phase, there is a consequent rise of 1.1-1.2 °C in the wound site due to the increase in blood flow [9]. However, a surge in temperature ranging from 4-5 °C is a potential indicator of on-site infection [9]. Note that the healthy skin temperatures range from 33-38 °C [10]. The right humidity environment on the other hand signals speedy epithelialization when a wound is covered with a dressing and is maintained moist [11]. A moist environment for the wound aids in increasing the proliferation of keratinocytes and fibroblasts while at the same time preventing the formation of scabbing [11]. Note that too much moisture may result in maceration, causing the skin to turn fragile, while an overly dry environment may cause desiccation of the skin [2]. Hence, it is important to maintain the right relative humidity range of 60%-75% as recommended to accelerate wound healing [12,13].

The multivariable effects due to lapses in the current pressure ulcer treatment and management are difficult to avoid if conventional medical practices are going to fully rely on this method. Factors affecting the wound bed such as temperature and humidity should also be observed to monitor for possible infections and to create an environment that promotes and accelerates wound healing. In a similar study conducted by N. Mehmood et al. (2015), a multi-layer flexible wireless monitoring system comprised of a temperature, moisture, and pressure sensor was successfully developed to cater for venous leg ulcer management and diagnosis [8]. For pressure ulcer application, the addition of a basic pressure mapping and alert system aims to aid health workers in better managing patients suffering from pressure ulcers. Furthermore, the utilization of commercially available sensors in a device makes it low-cost to develop. In this study, the reliability of the assembled wound monitoring layer prototype containing an integrated temperature and humidity sensor with a basic pressure mapping system was evaluated.

2. Materials and Methods

2.1 Sensors

The sensors attached to the electronic layer (E-layer) was a 4pin I2C Bosch BME280 humidity, temperature, and barometric pressure sensor module 1.8-5.0V DC (Temperature Accuracy: ±1°C, Range: -40°C to 85°C; Relative Humidity Accuracy: ±3%, Range: 0-100%; module size: 13mm×10mm×1.9 mm), and four square force-sensitive resistor sensor (FSR) (FSR Model 406; Hysteresis: ±10%; working ADC return range (ESP32): 0-4095; active area: 40mm×40mm) [14-16]. In the Temperature test, a Xiaomi temperature and humidity monitor (Temperature Accuracy: ±0.1°C, Range: 9.9°C to 65°C; Relative Humidity Accuracy: ±0.1%, Range: 0-99.9%) was used as the reference temperature sensor.

2.2 Prototype design

The device consists of two main components. The first component in the E-layer includes an ESP32 NodeMCU development board Wi-Fi module, a 1200mAh Lithium-ion battery attached to a TP4056 micro-USB charging module, four FSRs, and a Bosch BME280 I2C module which was assembled at the bottom of the perf board to make contact with the wound contact layer (Figure 1). Despite the BME280 sensor’s capability to detect relative humidity (RH), temperature, and atmospheric pressure values, only the RH (%) and temperature (°C) values were extracted in this study.
Figure 1. Schematic Design of the Electronic Layer. (A) Top View and (B) Bottom View

Figure 2: Client Station Board (A) Schematic Design and (B) OLED Layout

The second component is the client station board (Figure 2A). It consists of the same ESP32 Wi-Fi module as the first component and a 1.3” I2C OLED display which displays the real-time temperature and humidity values obtained, an (X) mark indicator beside the temperature and humidity values whenever it goes lower or higher than 33-38 °C for temperature and 60%-75% for Humidity, and a basic quadrantal pressure mapping mechanism that blocks out the hollow rectangles when the FSC associated with it experiences applied pressure above 32 mm Hg (Figure 2B). Unlike the E-layer which can power itself with its inboard 1200mAh battery, the client station board only operates when connected to a micro USB cable and a charger that powers its onboard ESP32 module.

Figure 3: Programming Flowchart of Device
For the ESP32 Wi-Fi modules to communicate and operate synchronously, both components were coded through the Arduino IDE for Microsoft Visual Studios. The programming flowchart of the device is as shown in Figure 3.

2.3 Temperature Test
An electrothermal water heat pack, with a maximum capacity of generating 75°C to 80°C, was used to simulate the warming of peri-wound skin during healing. Then, a 4x4” gauze pad was placed on top of it to serve as the wound contact layer. Before placing the E-layer, the electrothermal heat pack was allowed to heat up for 5 minutes. The E-layer was then placed directly on top of the gauze pad. Beside it, the Xiaomi Temperature and Humidity Monitor, a commercially available temperature and humidity monitor, was placed directly on the simulated wound bed to evaluate the accuracy and reliability of the Bosch BME280 sensor when lined with a gauze pad (Figure 4). Every minute, for 10 minutes, the temperature reading is then recorded. Note that before the experiments were performed, room ambient temperature and humidity were first stabilized.

2.4 Humidity Test
As shown in Figure 5, a basic humidity test setup was prepared. Over the silicone mat, a 1cc syringe filled with water was fixed with adhesive. Over the needle of the syringe, a 4x4” gauze pad was placed on top of it and was likewise fixed with adhesive. The E-layer and a second setup comprised of only an I2C BME280 temperature and humidity module attached to an Arduino UNO board were then placed together over the gauze close to the tip of the syringe. The second BME280 module setup served as the reference humidity sensor to the sensor attached to the E-layer. Subsequently, the sensors were first allowed to stabilize on top of the gauze pad before conducting the experiment. Once they had stabilized, 0.05mL of water was released. The RH readings were then allowed to stabilize for two minutes before recording. The process was repeated until the elapsed time reached 20 minutes and a total volume of 0.5mL of water is released.
2.5 Pressure Test
In determining the ADC value that would approximate the pressure of 32 mm Hg. The researchers calculated the corresponding mass value using the equation for pressure,

\[ P = \frac{F}{A} \]

With,

\[ \text{Pressure } (P) = 32 \text{ mm Hg} = 4266.32 \text{ Pa} \]

\[ \text{Area of one square FSR } (A) = a^2 \]

\[ a^2 = (1.62 \text{ in})^2 = 2.56 \text{ in}^2 \]

\[ A = a^2 = 2.56 \text{ in}^2 = 0.00165161 \text{ m}^2 \]

Hence,

\[ \text{Force } (F) = (P) \times (A) \]

\[ F = 4266.32 \text{ Pa} \times 0.00165161 \text{ m}^2 \]

\[ F = 7.046 \text{ N} \] (2)

With these, we can calculate the mass using the force equation,

\[ F = \text{mass}(m) \times \text{acceleration due to gravity } (g) \]

To find the mass,

\[ m = \frac{F}{g} = \frac{7.046 \text{ N}}{9.8 \text{ m/s}^2} = 718.98 \text{ g} \] (3)

Considering this, the mass was then rounded off to 700g to detect weight nearing the arterial threshold. A glass bottle was then filled with water until it weighed up to 700g on the digital platform scale. The 700g bottle was then placed on top of each FSR to record the ADC return values displayed in the Arduino IDE’s serial monitor. The process was repeated 24 times. This method allowed the researchers to determine the lowest readout ADC value shown in the serial monitor which served as the metric threshold in signaling excessive pressure.

To determine the reliability of the set ADC value. Two glass bottles were filled with water until the weight read by the digital platform scale reads 699g and 701g, respectively. The bottles were then placed 24 times in each of the FSR (Figure 6). The recorded output of this experiment was to determine whether the sensors were able to differentiate external pressures above or below the set threshold.

![Figure 6: Pressure Test. (A) Below 700g and (B) Above 700g.](image-url)
2.6 Data processing of results
To evaluate the reliability of the device, three experimental runs were conducted for both the temperature and humidity tests. Both studies have gathered a yield of 11, including the initial measurement, reading from both the E-layer and reference sensor since the measurement interval for the temperature test is per minute in a total of 10 minutes, while it is 2 minutes in 20 minutes for the humidity test. The difference and percent difference per run is then calculated using these formulas,

\[
\text{Difference} = \frac{\text{Difference of Measured E-layer and Reference sensor values}}{2} \\
\text{Percent difference} = \frac{\text{Difference of Measured E-layer and Reference sensor values}}{\text{Sum of Measured E-layer and Reference sensor values}} \times 100
\]

3. Results and Discussion
3.1 Prototype of E-electronic layer
The prototype for the electronic layer and the client station display, as shown in Figure 1 and Figure 2 respectively, was successfully connected using flexible and lightweight low voltage wires. All four FSRs, which were connected to the ADC channels of the ESP32 module, were able to return an ADC value of 0-4095 when tested in the Serial monitor of the Arduino IDE. Furthermore, since the BME280 sensor module utilizes an I2C serial communications protocol, the connection to the SCL and SDA pins was sufficient to gather temperature and relative humidity data. Lastly, the installed Li-Po battery can be charged through the TP4056 and can give enough power supply for the device for 4 hours and 30 minutes, when fully charged.

Initial assessment of the E-layer running with and without batteries, when compared to the Xiaomi temperature and humidity monitor, both indicate that the temperature and humidity readings are well within the range of ±1°C and ±3%. Hence, the prototype E-layer design can deliver reliable results when a power supply is connected directly to the ESP32 module or is running on its built-in Li-Po batteries.

3.2 Temperature Test
Before conducting the experiment, the Xiaomi temperature and humidity monitor registers the room temperature from 25°C up to 25.7°C. The results showed that the temperature difference between the surface of the electrothermal heat pack and the temperature detected in direct contact with the gauze pad exhibited an average difference of 0.83, 0.99, and 0.74 °C respectively (Table. 1).

| Run | Average Difference (°C) | Average Percent Difference (%) |
|-----|-------------------------|--------------------------------|
| 1   | 0.83                    | 0.88                           |
| 2   | 0.99                    | 0.97                           |
| 3   | 0.74                    | 0.80                           |

Table 1. Average difference and percent difference of E-layer on gauze pad vs Xiaomi temperature and humidity monitor.

Based on the results gathered from the experiment, the average difference and percent difference in temperature between the Xiaomi sensor and the BME280 sensor installed in the E-layer were within the range of ±1°C. Although there were instances wherein the temperature readings between the two sensors varied by more than ±1°C, this was already anticipated since the gauze pad served as a barrier that, to a
certain degree, acts as a thermal insulator which contributes to the decrease in heat transfer between the E-layer and the simulated wound bed. Nevertheless, the BME280 sensor remains dependable in detecting wound bed temperature when in contact with a gauze pad as it posed a general average of less than ±1°C.

3.3 Humidity Test
Before each experimental run, similar to the temperature test, the RH value of the room was measured using the Xiaomi temperature and humidity monitor. In all three of the experimental runs, the RH value of the room measured between the range of 53% and 53.5%. The RH reading from the BME280 sensor from the E-layer, like the temperature test, was compared to the second integrated temperature and humidity BME280 sensor assembled in a separate Arduino UNO board. The results showed that the average percent difference of relative humidity was 0.89%, 0.79%, and 1.08% respectively (Table 2).

It was shown that the differences and percent differences of each experimental run did not exceed ±3%. However, improvements in the experimental setup such as improving the control sensor into a higher accuracy sensor would aid in evaluating the sensor installed in the E-layer. Nonetheless, the humidity detecting sensor installed in the E-layer is dependable as it detected the change in humidity experienced by the wound contact layer, and it was consistent with the reference BME280 sensor that is attached to an Arduino UNO board.

| Run | Average Difference (°C) | Average Percent Difference (%) |
|-----|-------------------------|-------------------------------|
| 1   | 0.91                    | 0.89                          |
| 2   | 0.82                    | 0.79                          |
| 3   | 1.07                    | 1.08                          |

3.4 Pressure Test
In setting the ADC threshold value, wherein a 700g water bottle was used to simulate the allowable maximum applied pressure. The serial monitor outputted the maximum value of 3797, which was recorded from the 15th run on the 4th FSR. Conversely, the lowest ADC value of 3208 was recorded from the 23rd run on the first FSR subjected to the test. Therefore, the ADC return value of 3208 was used as the benchmark to determine whether the externally applied pressure has exceeded the allowable pressure that the skin or the wound site may be subjected to.

After calibration, the results of the 701g weight showed that for all 24 runs in each FSR, the client station board was alerted. However, for the 699g weight, the results were erratic. Out of the 24 runs in each FSRs, only the 1st FSR alerted the LCD monitor over 50% (14/24) of the time. Meanwhile, the 2nd, 3rd, and 4th FSRs only alerted 11/24, 12/24, and 9/24 times, respectively. The results indicate that all applied forces above >700g detected by the E-layer were properly detected by the sensor as it sends an alarm to the client station board. However, applied forces nearing <700g may also send an alarm to the client station board. This occurrence was expected due to the nature of the FSRs which has a compromised accuracy of readings that may lead to non-linearity and hysteresis in results [14]. Nonetheless, FSRs provide users a suitable component that is flexible, lightweight, and ultra-thin with a high tolerance to chemicals, moisture, and temperature [14].
4. Conclusion
Management of patients who have developed pressure ulcers during recovery remains one of the biggest challenges posed onto the healthcare system. This study presents a monitoring system that aims to aid the healthcare system to better supervise patients suffering from pressure ulcers by sensing the environment of the wound in real-time and by detecting whether the wound site is being subjected to excessive pressure. Based on the experimental results collected, the BME280 sensor can detect the temperature and humidity values within the acceptable range. Moreover, the square FSRs used in the assembly of the E-layer were able to alarm the system when it detects externally applied pressure beyond the set allowable pressure of 700g (lowest ADC return value: 3208). In conclusion, the assembled E-layer when placed on top of a gauze pad can deliver accurate temperature and humidity readings in real-time. Furthermore, the device is also capable of sending an alert to the client station display whenever the temperature, humidity, and pressure values go beyond their set threshold. In spite of this, a redesign aiming to improve the size, packaging, and materials is needed to reduce discomfort and allow flexibility of the device prior to it undergoing human testing.

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