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Development of conductive thread heating element on wireless heating e-textile belt for thermotherapy application

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ABSTRACT

Thermotherapy is the application of heat as a relief for pain and discomfort. That is because heat stimulates the sensory receptors in an isolated section of the body decreasing the transmission of pain signals to the brain. This study presents a heating e-textile belt to provide the needed temperatures for thermotherapy using conductive thread as heating elements. Bekinox 50/1 (BK 50/1) and conductive thread provided by Philippine Textile and Research Institute (PTRI) were tested on the threads' temperature response to the input voltage. A regression model having 30 samples each thread was computed and tested using T-test, both data samples obtained scores of *28.30499* for the BK 50/1 and *1.18830* for the PTRI conductive thread with a critical score of $t_{0.025,28} = 2.048$. BK 50/1 showed a linear relationship with the input voltage while the PTRI conductive thread showed none. The heating element made of BK 50/1 conductive thread was developed and has the capability of producing needed temperatures for thermotherapy. Implementing this heating element to the system, a series of 10 trials with different target temperatures was done. It produced accurate temperatures with a mean percent error of 0.1420%, 0.5051% maximum.

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Heating e-textile belt; thermotherapy; Bekinox 50/1; PTRI conductive thread

1. Introduction

Wearable technology has been paving the way in creating systems for monitoring physiological and environmental conditions. Textiles or fabrics with electronic devices integration such as sensors are what is considered electronic textiles (or e-textiles) [1]. E-textiles have different applications in health monitoring [2–10], particularly in the monitoring of different vital signs such as heart rate, pulse rate, and temperature; training in sports activity [11] and posture/activity recognition [12, 13]; and driver fatigue monitoring [14]. Also, some studies conducted using e-textile as an antenna [15–17]. Different kinds of clothing, such as shirts, and outer clothing were used as the placement of the various sensors. Data collection is controlled by wearable electronic components that transmit these data into a remote monitoring application software [18]. A wireless garment with embedded textile, sensor integrated vest, and comfortable wearable fabric are some examples of this technology [19].

The act of using heat for the relief of different ailments of the body is called thermotherapy. It is efficient in addressing pain. That is because heat, in itself, stimulates the sensory receptors in an isolated section of the body decreasing the transmission of pain signals to the brain, thus providing temporary relief from discomfort. It helps promote vasodilation in a specific area of the body. This dilation of the blood vessels increases the flow of oxygen and nutrients to the muscles and hastens the healing process of the damaged tissue. It also aids in the stretching of the soft tissues to make them more extensible getting rid of the stiffness and promotes relaxation caused by over usage and fatigue [20]. Common methods of application for thermotherapy include hot water bottles, hydrocollator tanks and packs, paraffin wax, electric heating pads, and heat wraps.

For proper application of thermotherapy, subjective classification of temperatures sensed on the skin, seen in Table 1, is taken into account. A safe but effective application is up to 44°C, depends on the comfort level of the patient, for 20 to 30 minutes. Prolonging or increasing temperature may cause burns [21].

Different conductive threads and textiles have been tested for their ability to produce heat. Using in-situ polymerization to bond a polymer to the textile to make it conductive, average uniform temperatures (°C) of 32.7, 67.7, and 167 throughout the textile were produced powered by voltages (V) of 6, 12, and 24, respectively, with parallel longish plates for contact to the power supply [22]. A polyester coated with copper reached a uniform temperature of 39 °C throughout the textile at 237.1 W of power using a similar parallel plate

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Table 1. Subjective classification of temperatures sensed on the skin.

Feeling	Temperature (°C)
Very Cold	0–13
Cold	13–18
Cool	18–27
Neutral	27–33
Warm	33–37
Hot	37–40
Very Hot	40–43

contact to the power supply [23]. Consumer-available Bekinox 50/1 (BK 50/1), manufactured by Bekaert, produced temperatures as high as 59.75°C with 149 mA of current (1.7 W) without employing a parallel plate configuration [24]. Conductive threads are also used for interconnects for various system components of the e-textile. Conductive thread paired with and plastic fibre incorporated into the weft and warp weave of the fabric was used to power sensor ICs mounted on the same fabric [25]. Zimsi-Econnect conductive textile is capable of both heating and interconnects with its flexible inner coil a conductive inner twist and a textile outer twist and USB1.1 data transfer [26].

As a result, modern conductive threads can produce heat that can be utilized in many different fields but BK 50/1 showed potential to provide temperatures for thermotherapy needing a relatively low power supply. The main objective of this work is to develop a wireless heating e-textile belt that utilizes conductive threads as heating elements for thermotherapy to help people with back pain, dysmenorrhea, and abdominal pain. Particularly, it aims to determine the amount of voltage needed for the heating textile made of two different conductive threads to produce temperatures for thermotherapy and to test for its accuracy to the set temperature and use T-test as a statistical tool.

2. Materials and Methods

The study starts by identifying the problem that will be trying to solve and formulating the objective in which to be the guiding factor on which the study will be based upon the validity of its results. In accomplishing this objective, the study is deemed successful. This objective is discussed in detail in the chapter before this. As a next step, it is, then, important to analyse previous works which are related to the study to know what has already been done and what the study can contribute to further the topic. Conceptualizing the system framework in which the research is to be implemented is the next step. Designing the system as well as the needed hardware schematics is where the tests are to be administered and data is to be gathered will be coming from. The study tests the conductive thread heating element to gather the data needed to achieve the objective of the study. Analysis of the gathered data using the statistical tool chosen will verify if the study has indeed able

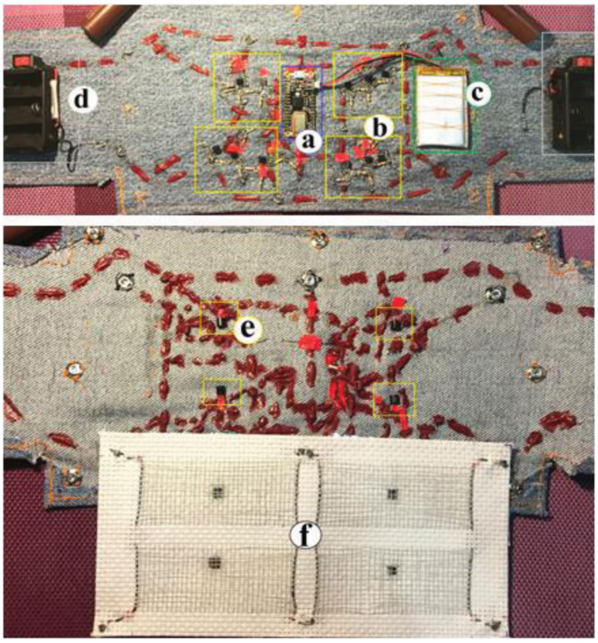

Figure 1. Wireless heating e-textile belt parts: (a) Adafruit Feather 32u4 Bluefruit LE, (b) Voltage Regulator Circuit, (c) LiPo Battery, (d) 18650 Batter Pack, (e) Temperature Sensor, (f) 4-quadrant Heating Textile.

to meet the objective set. Revisions are conducted to correct any unforeseen problems that may occur and if data gathered showed the system to have an unacceptable performance. The study shall, then, proceed in creating its conclusions and any recommendations for future studies.

2.1. Hardware design

The wireless heating e-textile belt used denim fabric as the base housing the microcontroller, voltage regulator circuitry, and batteries on one side, temperature sensor, and heating textile on the other. It consists of the Adafruit Bluefruit Feather with integrated Bluetooth Low Energy (BLE) module for wireless connectivity, connected via Pulse Width Modulation (PWM) ports to the transistor circuit to amplify the signals for powering the heating textile. The temperature sensors are connected to the analog ports of the Bluefruit and are situated near the heating textile. Denim fabric is used for the base of the e-textile where components are sewn using a 100% stainless steel conductive fabric. To insulate the interconnections from each other, clear nail polish and rubberized paint were used, this is shown in Figure 1. Figure 2 details the e-textile heating framework.

Figure 3 shows the schematic diagram of the proposed heating e-textile belt, the belt uses an Adafruit Feather 32u4 Bluefruit LE microcontroller. This microcontroller has a built-in Bluetooth Low Energy module for communication with the mobile application. Four LM35 temperature sensors connected to their

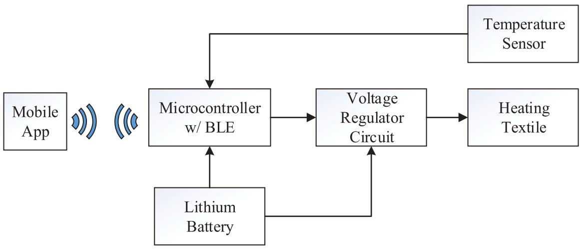

Figure 2. E-textile heating system framework.

respective analog pins of the microcontroller are used to sense the temperature of each quadrant with ±0.25°C typical temperature accuracy which is more than enough for temperature increments of 1°C needed for the device. For the voltage regulator circuit controlling the power to the conductive-thread heating quadrant, BS170 N-channel MOSFET, BC557, and BC547 pair BJT transistors are used. The pair transistors are configured to amplify the low-power Pulse Width Modulation (PWM) signals of the microcontroller and drive the MOSFET to control voltages of up to 12.6 V.

The Android mobile device used in the study to connect to the e-textile has a Qualcomm MSM8937 Snapdragon 430 chipset with 8 cores running at 1.4 GHz each, 3 GB of RAM, and an Android 7.1.1 Nougat operating system.

2.2. Conductive thread heating element

The conductive thread sewn into an 8.5 cm × 3.75 cm dimension is the base for testing its temperature response to voltage. Two conductive threads are tested for this. The first thread is the consumer-available BK 50/1 [5]. It has an 80/20 blend of polyester fibres and conductive material which is Bekinox chromium-nickel-molybdenum austenitic stainless steel fibres having a diameter of 6.5 µm. Philippine Textile and Research Institute (PTRI), a branch of the Philippine Department of Science and Technology (DOST), provided the study samples of conductive thread they are developing for the second conductive thread. It has the same 80/20 blend of polyester and conductive material. This however being pyrrole-treated pineapple yarns. Polypyrrole is the most commonly used conducting polymer. The thread is subjected to polymerization with the polypyrrole conducting polymer. Similar thread blend proportions being the basis of comparison.

To test for the two conductive textiles' ability to produce heat, a 30-sample data of voltage needed to heat the textile and the temperature read by the temperature sensor for each heating textile. The LM35 temperature sensor is used connected to the microcontroller for the temperatures to be read. Temperatures were measured after 10 minutes of being subjected to the input voltage starting from the ambient temperature. These data are analysed for its regression using the formula in Equation (1).

$$\hat{y} = \widehat{\beta_0} + \widehat{\beta_1}x \tag{1}$$

$\hat{y}$ is the estimated value of y with respect to x. y is pertaining to the temperature whereas x is the voltage. $\widehat{\beta_0}$ is estimated intercept and $\widehat{\beta_1}$ is the estimated slope of the regression model. The estimated slope is used to determine the t-score of the model. It is the basis for the

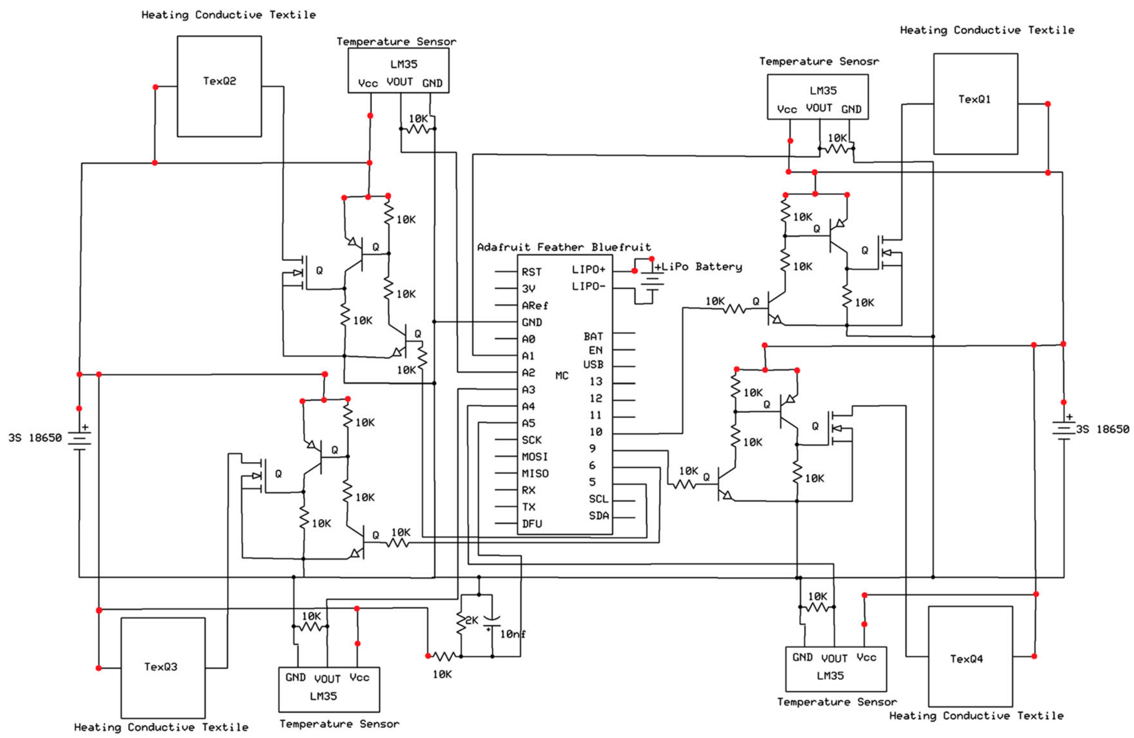

Figure 3. E-textile belt schematic diagram.

t-test to prove, with a 95% confidence interval, that voltage and temperature have a linear relationship to each other.

$$H_0{:}\beta_1 = 0 \tag{2}$$

$$H_1{:}\ \beta_1 \neq 0 \tag{3}$$

$$t = \frac{\widehat{\beta_1}}{se(\widehat{\beta_1})} \tag{4}$$

For the t-test of the regression, Equations (2)–(4) are needed. H_0 is the null hypothesis that the true slope of the regression model is zero. This means that voltage and temperature have no linear relationship.H_1 is the alternative hypothesis that the true slope is not equal to zero, meaning voltage and temperature have a linear relationship. To get the t-score of the regression model, the estimated slope is divided by its estimated standard error. The t-score is compared to the reference critical score from the t distribution table at a 95% confidence interval.

2.3. *Implementation of heating element*

The 8.5 cm × 3.75 cm heating textile in the previous section serves as a single quadrant of the whole heating textile of the belt for thermotherapy. Having four of them in the heating textile provides independent control of temperature, thus, ensuring temperature integrity for the whole heating textile. This 4-quadrant heating textile is independently controlled by a Proportional-Integral-Derivative (PID) controller programmed unto the microcontroller through the PWM ports. The low voltage PWM ports (3.3 V max) drive the voltage regulator circuit to provide ample voltage through a 18650 battery pack (12.6 V max) to each of the heating textile quadrants. PID control offers a feedback control for a more precise temperature to meet the target temperature.

The accuracy of temperature produced by the 4-quadrant heating textile is tested. The objective of this test is to check whether the heating textile can produce the target temperature set.

Figure 4 shows the developed android mobile application that is used to wirelessly set the temperature of the heating textile. After a wireless (Bluetooth) connection is established, the mobile application displays the Calibrate page, shown in Figure 4(a). On this page, the actual current temperature that the belt reads, the battery level, and Bluetooth connection status are displayed. The calibration process is needed to know if the actual temperature is greater than the minimum required temperature for thermotherapy of 33°C and sets it as the minimum temperature if so otherwise, the minimum temperature to be produced is set to 33°C. The e-textile is designed to heat up; hence, needing the current temperature as a base to heat up from if it is over minimum temperature. After the calibration,

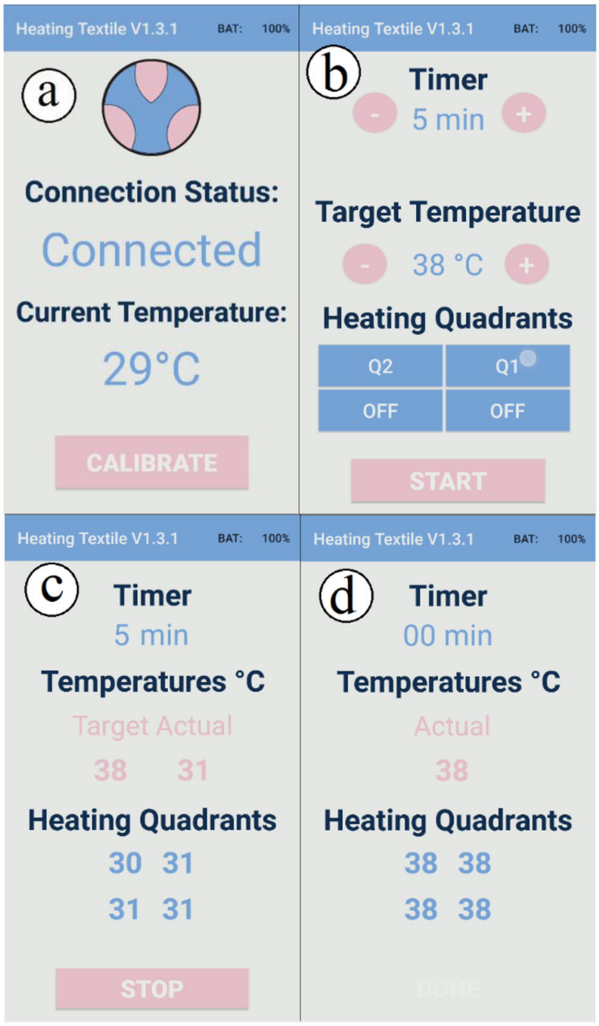

Figure 4. Android application user interface pages: (a) Calibrate Page, (b) Start Page, (c) HeatUp Page, and (d) Done Page.

the desired temperature is set to the minimum, and the timer is set to 5 minutes as a default. This can be changed into the desired temperature and timer of the user on the Start page in Figure 4(b).

On the Start page, the user can set the timer from 5 to 30 minutes with increments of 5 minutes in between. The temperature can be set from 33°C or the calibrated minimum temperature. The quadrants, 4 of which are set to heat up or not, can be set on this page as well. The heat-up process which control is taken over by the microcontroller is started when the Start button is pushed. This is when the HeatUp page, shown in Figure 4(c), is displayed and the HeatUp process starts.

HeatUp page monitors the actual temperature produced by the heating textile and the time left. The individual temperatures of the quadrants set to heat up are displayed. When the actual temperature meets the desired temperature, the timer starts and continues unless the timer expires or the stop button is press, or the application closes. The stop button sends the stop command, stopping the heating process. If the timer reaches the 0-minute mark, the stop command is automatically sent to the microcontroller. The Done page, displayed in Figure 4(d), is displayed after the stop command is sent.

The actual temperature is displayed on the Done page for the user to monitor it while cooling down. When the application closes, with the use of the back button on the Android mobile.

The PID in the microcontroller makes sure that the temperature produced is as accurate as possible to the set temperature. A series of 10 trials through different target temperatures, conforming to the subjective classification of temperatures sensed on the skin in Table 1, are gathered [2]. Temperatures are measured at the 3rd minute during a 5-minute session. These temperatures (T_a) is compared to the set temperatures (T_s). A 5% Percent Error is set as the minimum percent error. The percent error is defined in Equation (5).

$$\text{Error (\%)} = \left|\frac{T_s - T_a}{T_s}\right| \times 100\% \tag{5}$$

$$H_0: \mu_D = 0 \tag{6}$$

$$H_1: \mu_D \neq 0 \tag{7}$$

$$t = \frac{\bar{d}}{s/\sqrt{n}} \tag{8}$$

To ensure statistically-sound sample data, a t-test is needed. The null hypothesis (H_0) is that the mean of the differences of the temperatures is zero, meaning the temperature readings is reliably the same as the temperature set.H_1 is the alternative hypothesis that the mean of the difference of the temperatures is not zero, This means the temperature readings are not reliably the same as the temperature set. To compute the t-score, the mean of the differences is divided by the standard deviation over the square root of the sample size. The t-score is compared to the reference critical score from the t distribution table at a 95% confidence interval.

3. Results and discussion

3.1. Produced temperatures of conductive threads

A total of 60-sample data are presented in Table 2 having 30 samples each for the conductive thread. Each sample was gathered after subjecting the textile to a constant voltage for 10 minutes, then the temperature and voltage are logged, through an LM35 temperature sensor connected to the microcontroller and a digital multimeter. Every before sample collection, the textile is important to be at the ambient temperature of roughly 29 to 30°C.

Plotting Table 2 in Figure 5, the trend of the two heating textiles can be better shown.

Although the trend can be seen, it is imperative to show this trend quantitatively. The computed equations for the regression lines of the BK 50/1 and PTRI conductive textile are shown in Equations (9) and (10), respectively.

$$\hat{y} = 29.37085 + 2.15541x \tag{9}$$

$$\hat{y} = 29.99034 + 0.02365x \tag{10}$$

The estimated intercept ($\widehat{\beta_0}$) and slope ($\widehat{\beta_1}$) of the regression model from the sample data of BK 50/1 are 29.37085 and 2.15541, respectively. Computing for the estimated standard error of the slope, se($\widehat{\beta_1}$), the value of 0.076149 is obtained. With these data, the t-score (t) for the estimated slope of the sample data of BK 50/1 thread is computed to be *28.30499*. Since the reference value of t with a *95% confidence interval* is $t_{0.025,28} = 2.048$, our computed t-score is well above

Table 2. Voltage versus Temperature response of conductive threads.

Bekinox 50/1		PTRI Conductive thread	
Voltage (V)	Temperature (°C)	Voltage (V)	Temperature (°C)
0.0016	30	0.452	30
0.0019	30	0.535	30
0.0024	30	0.826	30
0.82	32	1.23	30
0.812	31	2.2	30
0.84	32	2.94	30
1.622	34	2.88	30
1.593	33	4.73	30
1.653	34	5.08	30
3.18	35	5.13	30
3.19	35	4.09	30
3.21	35	4.81	30
4.05	37	4.85	30
3.99	37	5.29	30
4.07	37	6.21	30
4.73	38	7.3	31
4.85	38	7.2	31
4.8	38	5.93	30
5.66	41	8.29	31
5.52	41	7.23	30
5.65	42	7.33	30
6.3	45	8.37	30
6.4	45	8.54	30
7.2	45	8.44	31
7.25	46	9.53	30
7.7	46	9.28	30
8.09	48	9.35	30
8.19	48	10.69	30
7.5	45	10.83	30
7.26	45	11.87	30

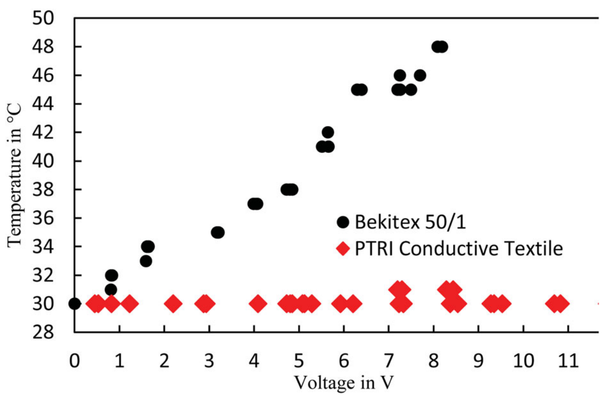

Figure 5. Voltage vs Temperature response of BK 50/1 and PTRI conductive textile.

Table 3. Temperature accuracy table for 5-minute sessions.

Target (°C)	Average Produced (°C)	Difference (°C)	Error (%)
33	33.1667	0.1667	0.5051
34	34	0	0
35	35.1667	0.1667	0.4763
37	37	0	0
38	3.1667	0.1667	0.4387
39	39	0	0
40	40	0	0
42	42	0	0
43	43	0	0
44	44	0	0
Mean		0.0500	0.1420
. Standard Deviation		0.0805	
T-Score		1.9640	

the critical region. This means that the null hypothesis is rejected and the alternative hypothesis holds true. The voltage input for BK 50/1 conductive thread has a linear relationship to the temperature reading.

For the regression model of the PTRI Conductive thread in Equation (10), $\widehat{\beta_0} = 29.99304$ and $\widehat{\beta_1} = 0.02465$ with $se(\widehat{\beta_1}) = 0.01990$. Computing for the t-score of the $\widehat{\beta_1}$, the value of *1.18830* is obtained. Again, with the same reference value of $t_{0.025,28} = 2.048$, the computed t-score is below the critical region, rejecting the alternative hypothesis and holding the null hypothesis true. This means that the voltage input for the PTRI Conductive Thread has no linear relationship to the temperature reading.

3.2. Accuracy of the implemented heating element

Table 3 shows the results of the testing of the implemented heating element to the e-textile. A 10-trial test for accuracy through different set temperatures is gathered every minute of a 5-minute thermotherapy session. The LM35 temperature sensor is used. The average temperature of the 4-quadrant heating textile made from BK50/1 is recorded. It reveals the temperatures produced by the textile are at par with the desired temperatures set. With the BK50/1-based heating element, the maximum mean temperature differential is only ±0.1667°C. The mean percent error of the 10-sample data is computed to be 0.1420%. Its t-score is 1.9640. The reference value of t with a confidence interval of 95% is $t_{0.025,9} = 2.262$. Comparing it to the t-score to the critical, it can be seen that the heating textile made from BK 50/1 is below the reference value; therefore, rejecting the alternative hypothesis and holding the null hypothesis true. This means, using the BK 50/1 as the heating element, the set desired temperature and the temperature measured are reliably the same.

4. Conclusion and future works

A wireless heating e-textile belt was presented that used conductive thread as a heating element for thermotherapy to help people with back pain, dysmenorrhea, and abdominal pain. Two different conductive threads were tested for temperature response to the input voltage, Bekinox 50/1 (BK 50/1) and Philippine Textile and Research Institute (PTRI) conductive thread. A 30-sample data was gathered for each conductive thread and the results were tested for regression. Conducting a T-test to the regression models of both data samples obtained scores of *28.30499* for the BK 50/1 and *1.18830* for the PTRI conductive thread with a critical score of $t_{0.025,28} = 2.048$. BK 50/1 showed a linear relationship with the input voltage while the PTRI conductive thread showed non. The heating element made of BK 50/1 conductive thread was successfully developed and has the capability of producing needed temperatures for thermotherapy. Implementing this heating element to the system, a series of 10 trials with different target temperatures was done. It produced accurate temperatures with a mean percent error of 0.1420%, 0.5051% maximum. A two-tailed paired-sample t-test yielded a score of 1.9640 which is below the critical score of $t_{0.025,9} = 2.262$. This means, using the BK 50/1 as the heating element, the set desired temperature and the temperature measured are reliably the same.

Testing for the effectiveness of the thermotherapy of the belt on patients is recommended. Other conductive threads especially Filipino-made ones are recommended to be tested for the heating capability. Extension of the application of the heating element is also recommended.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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