Moisture Based Perspiration Level Estimation

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Abstract

Perspiration level monitoring enables numerous applications such as physical condition estimation, personal comfort monitoring, health/exercise monitoring, and inference of environmental conditions of the user. Prior works on perspiration (sweat) sensing require users to manually hold a device or attach adhesive sensors directly onto their skin, limiting user mobility and comfort. In this paper, we present a low-cost and novel wearable sensor system that is able to accurately estimate an individual's sweat level based on measuring moisture. The sensor is designed in a thread-like form factor, allowing it to be sewn into the seams of clothing, rather than having to act as a standalone sensor that the user must attach to their body. The system is comprised of multiple cotton-covered conductive threads that are braided into one sensor. When a person sweats, the resistance between the braided conductive threads changes as moisture becomes trapped in the cotton covering of the threads. The braided three-dimensional structure allows for robust estimation of perspiration level in the presence of external forces that may cause sensor distortion, such as motion. We characterize the relationship between the volume of sweat and measured resistance between the braided threads. Finally, we weave our sensors into the fabric of a shirt and conduct on-body experiments to study users' sweating level through various activities.

ACM Classification Keywords
I.2.9 [Robotics]: Sensor; H.5.m [Information interfaces and presentation (e.g., HCI)]: Miscellaneous; J.3 [Life and medical science]: Health; C.3 [Special-purpose and Application-based systems]: Real-time and embedded systems

Introduction
Perspiration, commonly known as sweating, is the primary mechanism for thermal regulation in human beings. Hence, the amount of sweat a person produces is a significant indicator of one's physiological conditions [9]. Sweat can be used to infer one's comfort level, health condition, emotion, and intensity of exercise [5, 9]. In many cases (e.g. babies), lacking the ability to produce sweat may lead to hypothermia, or even death [3]. Sensing sweat allows us to better detect and prevent sweat-related abnormalities and health conditions [4, 9].

Inspired by the importance of sweat sensing and the lack of robust and non-intrusive sensors available for detecting sweat, we propose a novel low-cost sensor system that can measure an individual's sweat level and is robust in the presence of body movements. The design is comprised of three conductive threads intertwined with cotton threads. The key idea behind the design is that the resistance between conductive threads varies based on the amount of sweat and moisture captured by the cotton threads. To ensure stable contact in presence of movement, the cotton covering is braided onto the conductive threads. The braided threads are then positioned in a triangular structure to capture moisture. A final cotton cover is braided over the triangle structure to stabilize the structure between threads.

System Overview
Our perspiration level estimation system consists of three parts: the sweat sensing module, the sensor calibration,

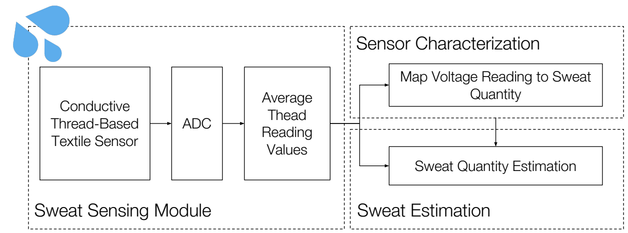

Figure 1: System diagram.

and the sweat quantity estimation. The sweat sensing module utilizes our conductive and cotton thread-based sweat sensor to convert the moisture level (the quantity of sweat absorbed by cotton threads in the sensor) to voltage. The output voltages obtained from the sensor are converted to a digital signal via an analog-to-digital converter (ADC) on the MCU (**Sensor Design** Section).To map the measured voltages output from our sensor to the quantity of the moisture between threads (e.g., in the unit of mg), we conduct sensor calibration. In this step, we apply known volumes of salt solution (simulating sweat) to the sensor and obtain a corresponding voltage from the sensor. After building up a mapping from solution quantity to voltage output, we conducted a fitting based on a simplified equation of solution resistance (**Sensor Calibration** Section).After performing sensor calibration, our system is able to estimate sweat quantities based on measured voltages from the sensor (**Sweat Estimation** Section). However, the quantity of sweat a person produces and perceives to produce is unique to the individual. As such, our system further estimates a user's perceived sweat level based on historical data observed from the individual.

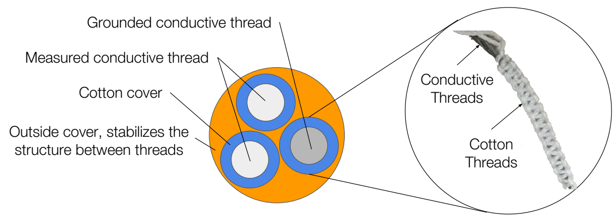

Figure 2: Sweat sensor cross section and close-up of a cotton-braided conductive thread.

Sensor Design

In this section, we detail the the design of our low-cost conductive thread-based sensor and how it will be used to achieve sweat level monitoring.

Conductive Threads Design

As mentioned earlier, the primary idea behind our sweat sensor is to measure the change in resistance between separated conductive threads as moisture trapped within the sensor changes. In order to capture moisture, we need to intertwine another material that can easily absorb liquid and reduce the resistance between conductive threads when wet. As such, we chose to interweave cotton between the conductive threads because it is very absorbent (able to absorb up to 27 times its weight in liquid [7]) and is also a common material embedded into clothing. In order to maintain a constant separation between conductive threads and stability, we braided the cotton threads into a cotton cover using square knots as shown in Figure 2. Another reason for braiding the cotton cover is to ensure an even cotton coating/absorption layer around each conductive thread. In order to measure the sweat, and to maintain constant separation between conductive threads, we braided a cotton cover on the surface of the conductive threads to absorb and hold the sweat in place. The resistance of cotton can be determined by the moisture content of the cotton by percentage of dry weight: $LogR = -9.3logM + B$. In this formulation, R is the resistance of the sample in mega-ohms, M is the moisture content of the cotton in percentage of dry weight, and B is a constant. Rearranging this equation, we arrive at $R = B'M^{-9.3}$, where $B = LogB'$. From this relationship, we see that a decrease in moisture of the cotton causes an increase in its resistance [6].

For the final sensor, we integrated three cotton-braided conductive threads together. One of the threads is grounded, while we take two measurements between the other two threads with respect to the grounded thread. The two voltage values taken are then averaged to obtain the final voltage reading. This structure enhances the quality of the sensor's measurements for three reasons: 1) Only a portion of the sensor may be in direct contact with the skin or sweat. As such, the position of the threads in the sensor may affect sensor outputs. By using multiple threads to take multiple measurements spatially and averaging our readings between more than one thread, we are able to reduce the sensitivity of the sensor to the position of the threads within the sensor. 2) Human motion may bend the threads, which may affect corresponding measurements. By averaging the voltage readings between multiple conductive threads and the grounded thread, our sensor is more robust to different bending conditions of the sensor. 3) Having three threads also allows us to pack the threads into a stable triangular structure, as shown in Figure 2.

Moisture Level to Voltage Conversion

To measure the moisture level trapped in the sensor, we measure the voltage difference between two conductive threads and a grounded thread. Consider the cotton between the conductive threads as a resistor, R_{sweat}, whose value varies based on the moisture content of the cotton, as described in the previous section. The cotton has infinite resistance when completely dry. For the non-grounded conductive threads, a resistor is connected between the thread and the reference voltage, Vcc. This reference resistor, R_{ref}, is known in advance (1M Ohm). When the cotton is completely dry, the output voltages (V_{out1} and V_{out2}), are measured to be equal to the reference voltage Vcc. When the sensor comes into contact with moisture, the circuit becomes a voltage divider, and the output voltages are computed as $Vout = Vcc * R_{sweat}/(R_{sweat} + R_{ref})$.

Sensor Calibration

In this section, we present the experiments we ran to obtain the mapping between the voltage output and quantity of sweat measured. Further human experiments to test the efficacy of the entire sensor system is presented in later sections.

Calibration Settings

The goal of the sensor calibration is to find the relationship that maps sweat quantity to measured voltage. The calibration was done in a room with a consistent temperature and humidity to maintain a consistent sensing condition. A 10 cm sensor thread is fixed on a 3D-printed rack, and the entire rack is placed on a scale that can measure with 1 mg granularity. Prior research shows that the sodium concentration of human sweat can vary between 117 mEq per L to 172 mEq per L with an average of 137.8 mEq per L [2]. To simulate the conductivity and electrolytes found in human sweat, we used a one percent solution of sodium chloride to characterize the sensor [8].

For each trial, we first applied approximately 300 mg of the sodium chloride solution to completely saturate the sensor. Then, we waited for the sensor to completely dry out, recording the weight of the remaining the solution on the sensor and sensor voltage output over time. For each trial, we began recording solution mass/output voltage pairs once 150 mg of solution remained on the sensor. These measurements are then used to generate the fitting function that maps voltage to sweat quantity and will be further discussed in the next section.

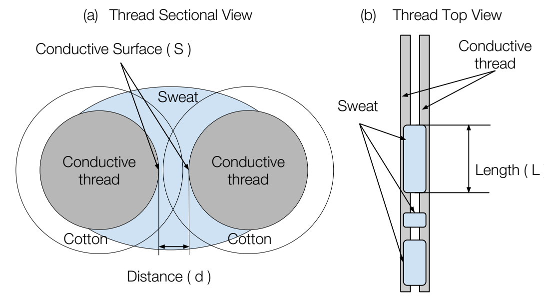

Figure 3: Sweat sensor simplified electrical conductivity model.

Sensor Reading Mapping

To be able to use the sensor, it is essential to understand the relationship between the target physical condition – the sweat quantity – and how the circuit of the sensor changes. The resistance between the conductive threads changes when different amounts of water are applied, leading to different voltage outputs measured from the voltage divider circuit.

We claim that the sensor fits the simplified electrical conductivity model as explained below. The resistance between the two conductive threads can be calculated as $R_x = R \cdot d/S$, where, R stands for the resistivity of cotton[1], d is the distance between the conductive threads, and S is the conductive thread surface area that is soaked by sweat. Figure 3 illustrates this simplified model with the sectional and top views between a pair of cotton-braided conductive threads. We consider the distance between threads, d, to be constant due to our stable braiding structure of the sensor. The surface area S is proportional to the length of the sensor that is soaked wet by liquid, L, as shown in the right-hand side of Figure 3. Therefore in presence of more sweat, the effective conductive surface between the two threads is larger, which reduces the effective resistance between the two threads. We utilize this relationship to fit a curve that maps voltage readings to the quantity of solution absorbed by the sensor.

Figure 4 shows the measurement of the resistance between the measured conductive thread and the ground thread. Data is collected for eight different sections of the sensor braid that is 10 cm long in a room where the humidity and temperature are controlled and constant. We observe that for solution quantities less than 80 mg, the resistance between the threads is consistently decreasing. However, the steepest part of the resistance vs. liquid quantity occur between 0 mg to 30 mg of solution left on the sensor. The voltage varies between 3.3 V (Vcc) to 0.77 V in this range. Different parts of the threads also show slightly different curves for solution quantities between 30 mg and 80 mg. We fit these readings to $p_1/(x + p_2)$.

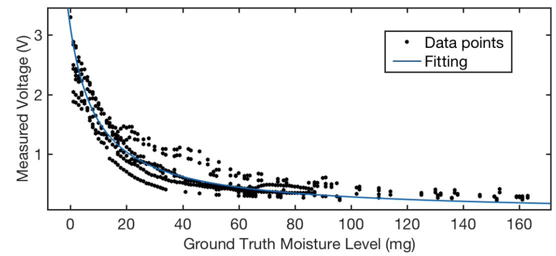

Figure 4: Sensor characterization: voltage vs. moisture quantity.

Sweat Estimation

Now that the sensor is characterized, we can obtain sweat level information through the sensor. The system estimates two types of sweat level information: the **measured moisture level** and the **perceived sweat level** of the user.

The measured moisture level is the absolute quantity of sweat measured by the sensor, which is obtained by measuring a voltage value from the sensor and mapping the measured voltage to a quantity using the curve obtained in the previous section. However, it is difficult for people to know if they have produced a large or small amount of sweat just based on a quantity measured in mg. As such, we define a perceived sweat level scale to describe different perspiration conditions based on a user's belief of how much he perspiration he has produced.

On-body Experiments

We evaluated our sweat sensing system on human test-subjects. We sewed two sensors (10 cm each) to the back and one armpit of a shirt because the armpit and back are two body parts that tend to produce the most sweat. The experimental setup is shown in Figure 5. A communication board reads values from the sensor and sends the data to a sever via WiFi. The server calculates the moisture level in mg and estimates each user's perceived sweat level based on historical data. The user can check the measured sweat level as well as their estimated perceived sweat level on their mobile app.

In order to estimate the perceived sweat level of a user, we require labeled historical data from the user. To obtain the historical data needed to predict a user's perceived sweat scale, we had the user perform multiple exercises, mea-

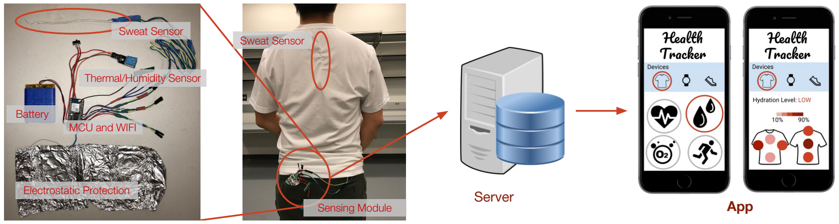

Figure 5: Sweat level estimation pipeline. The sensor obtains a moisture level reading and transmits the observed voltage to a server. The server calculates the moisture level in mg and estimates each user's perceived sweat level based on personal historical data. The user can check the measured sweat level as well as their estimated perceived sweat level on their mobile app.

sured his sweat quantity using our sensors, and asked the user to tell us his perceived sweat level. Details of the perceived sweat level scale we used are described in the following section. Using these sensor measurements labeled with the user's own perceived sweating level, we tested and evaluated the perceived sweat level prediction error.

System Parameters
To demonstrate the performance and robustness of our system, we had users perform four physical activities (sitting while moving arms, throwing ball to the wall, running in circle, and shuttle running), corresponding to four different levels of physical activity. The measured moisture quantities captured by the sensors on the back and armpit are shown in Figure 6, where the blue solid lines are the values obtained from the sensor sewn on at the armpit and the red dashed lines are the values obtained from the sensor sewn on the back.

Activity Comparison The four activities we selected represent four different activity levels. Moving arms while sitting is the least physically intense activity. As shown in Figure 6 (a), the sensor detects 0 mg of moisture even after 650 seconds. The second least physically intense activity is throwing a ball. As shown in Figure 6 (b), the back and armpit sensor begins to detect more than 0 mg of moisture after 500 seconds of activity. When the user begins doing the two most physically intense activities, we see from Figure 6 (c) and (d) that the measured moisture quantities show rela-

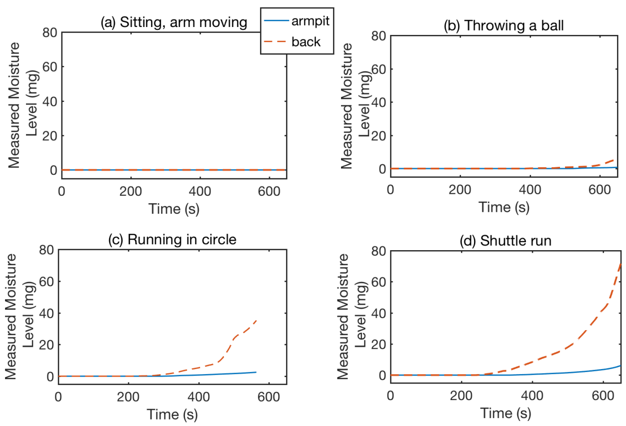

Figure 6: Sensor readings from sensors placed on armpits and back while user is conducting various activities.

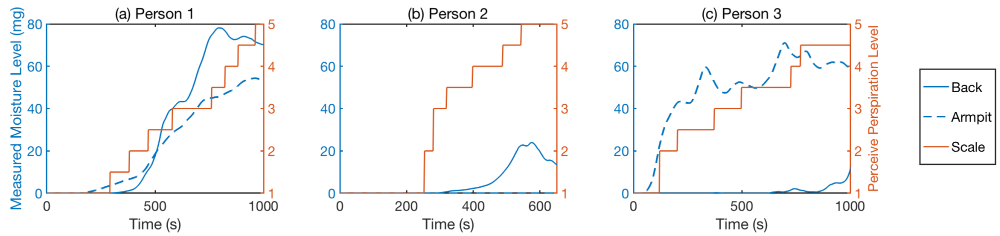

Figure 7: Sweat measurements from three participants while exercising. The x-axis is the time in which a person is exercising. The solid blue lines are the measured moisture quantity of the sensor on the back of the user. The dashed blue lines are the measured moisture levels for the sensor on the armpit. The red line is the user-reported perceived sweat level based on the scale summarized in Table 1.

tively similar curves, despite the activities requiring different levels of physical activity. This indicates that the intensity of the exercise is not correlated to the sweating rate. Rather, the duration of exercise has a bigger impact on sweating rate, according to a personal trainer that was consulted.

Body Part Comparison In this section, we explore the amount of sweat a person produces on the back and armpit, the two locations that produce the most sweat. We see that for the same participant, each activity produces more sweat on the back than on the armpits. For the least physically intense activity of arm moving while sitting, both body parts did not show any quantity of sweat, as shown in Figure 6 (a). When the user begins to throw a ball, the back sensor detects more moisture than that on the armpit. For the rest of the activities, the sensor on the back also records more sweat than the sensor on the armpits, as shown in Figure 6 (c) and (d). When a user is running or exercising, the armpit periodically opens up allowing for the air around the user to quickly evaporate any sweat in the area, which is why the armpits could be detecting less moisture.

Perceived Sweat Scale

Each person perceives their own sweat level differently from others. To detect each person's perceived sweat level, we had users run in a circle inside a room with a stable temperature. Afterwards, we asked each participant how wet they believed their shirt was on a scale from 1 to 5. The five different perceived sweat levels are summarized in Table 1. based on multiple trials conducted for each participant. The rest of the section analyzes the perceived sweat profile of the three participants.

Scale	1	2	3	4	5
Extent	dry	start to sweat	light sweat	heavy sweat	soaking wet

Table 1: Perceived sweat scale

Figure 7 displays the measured moisture quantity, perceived sweat scale recorded of the three users who were running over time. Figure 7 shows examples of three participants marking perceived sweat scale (as listed in Table 1) and the corresponding sensor measurements. We observe that the sensor readings corresponding to a perceived sweat level of 'start to sweat' and the 'heavy sweat' is the most sensitive. This perceived sensing range corresponds to a measured moisture of below 60 mg in general.

Discussion

So far, experiments conducted with the conductive thread-based sweat sensor has shown promising results at early stage. However, limitations of the study and room for improvements could include the following. Firstly, sensing consistency against motion and the variance of environment might be reinforced. Another issue could be the salt trapped in the sensor after a long time use, potentially affecting the sensing result. It means that a periodic cleaning will be necessary. Lastly, it is possible to reduce the PCB size and power consumption with coin battery and BLE technology.

Conclusion

We have presented a novel conductive thread-based sweat sensor that can be seamlessly incorporated into the seams of ordinary clothing. Then we calibrate the sensor and utilize the sensor and calibration map to measure people's perspiration profile. Finally, we demonstrate the sensor performance with real world on-body experiments through different activities.

Acknowledgement

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