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Conformable, Wearable Embroidered Temperature Sensors for Real-Time Monitoring in Extreme Environments [†]

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Abstract: The critical need for accurate and non-invasive temperature monitoring is prevalent in extreme environments, such as scuba diving. Current temperature measurement technologies present limitations, prompting the development of innovative solutions. We propose the integration of embroidered wearable thermocouple sensors, demonstrating their versatility and reliability in real-time temperature monitoring. T-type thermocouples, embroidered onto fabric, offer flexibility in sensor placement, eliminating the need for skin attachment. The results indicate efficient temperature detection across different body areas, from 32.5 °C at extremities to 37.5 °C at the axial position. Testing in scuba diving conditions reveals potential applications, including overheating alerts and hypothermia prevention. This technology bridges the gap between temperature measurement and the challenges of underwater exploration, enhancing diver safety and data collection capabilities.

Keywords: wearable technologies; health monitoring; extreme environment; temperature; embroidered sensors

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1. Introduction

In the pursuit of exploring and understanding extreme environments, such as the depths of the ocean during scuba diving, the development of innovative temperature measurement technologies is crucial for ensuring diver comfort, safety, and performance. The accuracy and reliability of these temperature measurements influence critical aspects of diving, such as preventing hypothermia [1]. Determining dive durations, and aiding wildlife observation, as well as informing dive planning and environmental monitoring can also be dependent upon accurate temperature monitoring. However, current human body temperature measurement technologies offer a range of advantages and disadvantages, often lacking suitability for extreme environments. Traditional invasive methods and non-contact options like infrared, ear, or forehead thermometers have limitations that can compromise their effectiveness in extreme conditions.

To address these challenges, this work focuses on the integration of embroidered wearable thermocouple sensors as a groundbreaking innovation that provides a versatile and non-invasive solution for real-time temperature monitoring during scuba dives. These sensors, designed to withstand the harsh conditions of underwater exploration, offer quick response times and accurate readings, depending on the materials used. They present a promising avenue for enhancing the safety, comfort, and data collection capabilities of scuba divers in extreme environments. This paper outlines the construction and integration of embroidered thermocouple sensors and delves into the difference in body temperature for a scuba diver in various circumstances. By bridging the gap between temperature measurement technology and the challenges of underwater exploration, this research contributes to the advancement of knowledge and innovation in the field.

2. Methods

T-type thermocouples consisting of two different metal types, copper, and constantan [2], were embroidered (Brother Entrepreneur PR1050X) onto fabric swatches (Calico with polyester thread) or preconstructed items of clothing. In embroidery design, it is important to consider the requirements of the thermocouple, one of which is that the two-metals cross but only at one singular point creating the hot junction. At the cross point, a small voltage is generated by the contact of the two metals with the temperature of these two metals either increasing or decreasing the voltage in accordance with the Seebeck effect [3]. If the sensor is being embroidered onto clothing, the location of the cross must be at the point where the measurement is required. The cold junction is located away from the measurement position within the microcontroller electronics. The difference between the voltages at the junctions provides the temperature measurement. T-type thermocouples are the most accurate thermocouples operating within the range of human temperatures, providing an accuracy of ±1.1 °C [4]. It is not essential to apply a solder joint to the cross point; however, to ensure a good connection independent of the use case, the cross point of these sensors was soldered. The sensors were tested alongside the standard bought-in temperature sensors (T-type thermocouple and LM35 IC).

The measured temperatures were recorded via an Arduino microcontroller with the option to carry out board recording via an SD card, with post processing of the data, Bluetooth, and Wi-Fi transmission to a portable device. For the extreme environment of scuba diving, SD card data recording was carried out in conjunction with Bluetooth, which allows shore support to check the diver's temperature upon their regular surface intervals.

3. Results and Discussion

By embroidering these sensors firstly onto a patch of fabric (Calico), the location of the sensor can be easily changed to monitor differences in temperature across the area of interest or on different parts of a human without the need for taped skin attachment. The general accepted human skin temperature ranges between 36.5 °C and 37.5 °C [5] at the core and reduces when measured at the extremities such as the leg or arm, which are the areas that can first become susceptible to the impact of extreme cold conditions.

The sensors were first placed onto the lower leg (Figure 1a) and lower arm (Figure 1b) where the ambient temperature was measured at 19–22 °C and the measurement was taken over 10 min (600 s). For the lower leg and arm, the average skin temperature was measured at 32.5 °C, which is at least 4 °C lower than the accepted human skin temperature values [6]. When the sensors are removed from the skin, the temperature decreases and returns to the ambient temperature after approximately 60 s. When the sensor is placed onto the trunk of the individual, the average temperature rises to 36.9 °C and is consistent across the measurement time with a similar cooling rate to an ambient time of ~60 s (Figure 1c). In the axial position, the temperature should be the most accurate representation of a core/internal temperature measurement [7]. When the sensor is placed in this position, the average temperature is measured at 37.5 °C, which is at the upper end of the accepted range with the cooling rate consistent with other measurement positions (Figure 1d).

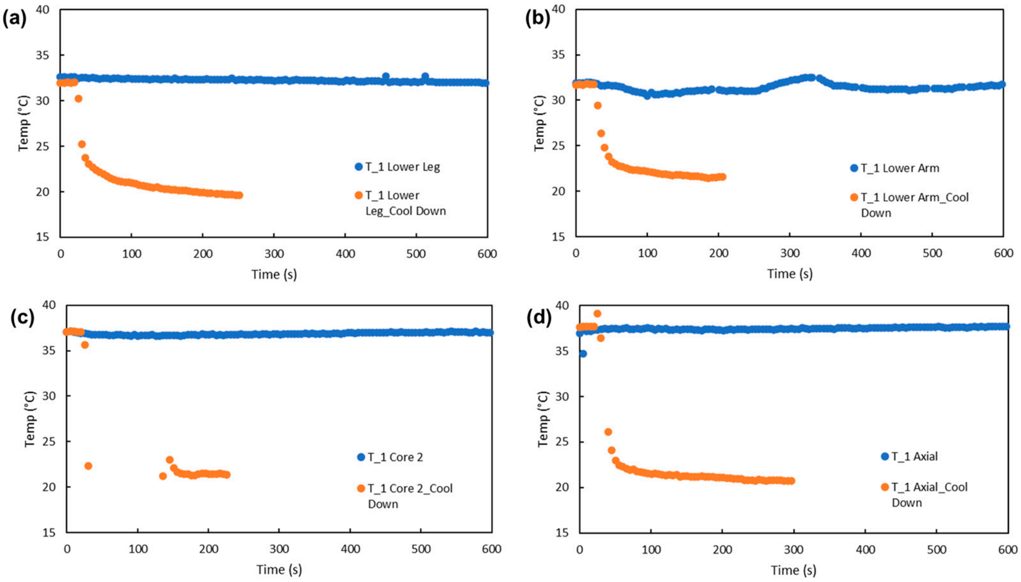

Figure 1. Temperature measurements. (**a**) Lower leg, (**b**) lower arm, (**c**) trunk; (**d**) axial.

The sensors have been proven to work as efficient human temperature sensors with the capabilities of detecting temperature variations across a human body. To test these in an extreme environment (scuba), the sensors were added to the axial position of a rash vest, which is a close-fitting item of clothing designed to protect a scuba divers' skin from coming into contact with any grit or dirt within the body of water and is therefore commonly worn. The close-fitting nature provided good, constant skin contact providing accurate data throughout a dive. On top of the rash vest, a dry suit was worn to provide an additional waterproofing seal for the electronics when being operated at depth. The data recorded by the sensors was recorded and transmitted in three different forms (SD card, Bluetooth and Wi-Fi); however, due to the transmission limitations caused by the water, the data could not be transmitted by Bluetooth or Wi-Fi so all the data were recorded on board for later analysis with Bluetooth enabled to check the divers' health when they came to the surface.

Three different diving conditions were decided on for the sensor testing. Condition one was in a standard swimming pool where the temperature was kept constant at 24 °C and a maximum depth of 1.8 m. The temperature of the diver was measured over a period of 20 min (Figure 2a) with the skin temperature starting at 35.5 °C and increasing by 2.5 °C to 38 °C, signifying the start of an overheating event, indicating that intervention might be required as the trend is still increasing. The second condition was in another swimming pool (marine pool) with a greater overall depth (4 m) and a cooler overall temperature of 18 °C. During this dive, the temperature was again recorded over 20 min in the axial position (Figure 2b). The temperature varied by 0.5 °C over this period but otherwise remained constant over the dive period, indicating that the diver was not experiencing any adverse health effects in these conditions. The third condition was the most extreme with the individual diving in an open water lake where there was no control over the ambient weather conditions or the temperature of the water. The overall depth of the lake was measured at 8 m and at the time of the dive, the water temperature was 15 °C. With the temperature sensor in the axial position, the diver's temperature was measured over the course of 20 min. Due to the overall colder conditions, the diver's temperature started at below 32 °C and continued to decline over the measurement period, plateauing around 30.5 °C (Figure 2c). At this temperature, the diver might start to experience hypothermia, with intervention being required to bring the diver to the surface and to start to raise their body temperature [8,9].

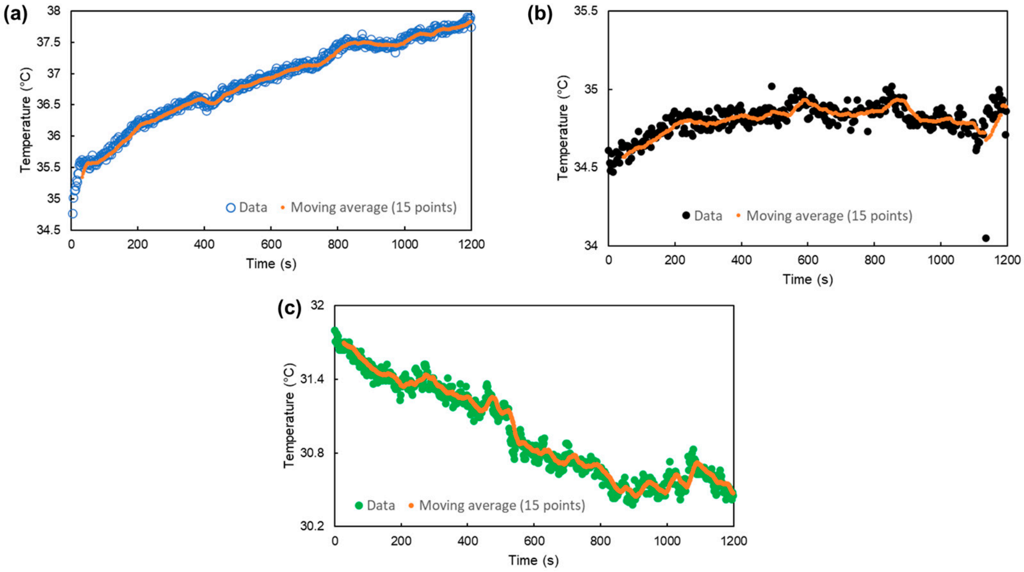

Figure 2. (**a**) Temperature profile of a diver in a heated (24 °C) indoor pool with a maximum depth of 1.8 m, (**b**) temperature controlled (18 °C) marine pool with a maximum depth 4 m and (**c**) an open water lake (Ellerton Lake), which has an uncontrolled water temperature governed by natural heating (15 °C at dive time) and a maximum depth of 8 m.

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