Non-Invasive Measurement of Core Body Temperature in Marathon Runners

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Abstract

Long-term accurate measurements of core body temperature are essential to study human thermoregulation in ambulatory settings and during exercise, but they are traditionally carried out using highly-invasive techniques. To enable a continuous unobtrusive monitoring of core body temperature on ambulatory patients and exercising athletes, we have designed a wireless wearable system that measures the tympanic temperature inside the ear, as well as skin and environmental temperature, and that allows remote monitoring of the collected measurements. In this paper, we describe the design and implementation of the system and show that it can be used to identify the circadian rhythms of core body temperature, as well as to detect the variation in core body temperature due to prolonged physical exertion. We further describe the lessons learnt during a pilot deployment of our telemetric system on several athletes during the 5^{th} Lübeck Marathon, and discuss the impact of environmental parameters such as temperature and wind on the accuracy and meaningfulness of the measured values.

1. Introduction

Core Body Temperature (CBT) is a well-known indicator of the human body's effectiveness in maintaining its operating temperature within a constant range; and its precise and continuous measurement is a prerequisite for studies on human thermoregulation. Long-term measurements of CBT in ambulatory patients allow chronobiologists to derive an accurate profile of the circadian-system (the roughly 24-hours cycle in biological processes such as body temperature and hormone secretion), improving their understanding of the phase, amplitude, and stability of circadian rhythms [1]. In sports medicine, a precise knowledge of CBT during exercise can be used to optimize the athletic performance and to prevent common injuries such as hypothermia, hyperthermia, and heat stroke. Especially in case of prolonged exercise, an excessive heat production, in combination with factors such as climate, dehydration, (inappropriate) dressing, and high metabolic rate, may indeed result in a substantial decrement of physical performance and an increased risk of circulatory collapse with potentially fatal[1] consequences [4], [5].

Our aim is hence the development of a telemetric system that enables a continuous and unobtrusive monitoring of CBT on ambulatory patients and exercising athletes: this is not a straightforward task, since most techniques used to measure CBT are highly invasive or impair mobility (e.g., the use of rectal probes and ingestible pills to measure rectal and gastrointestinal temperature). Towards this goal, we have designed a wireless system that measures the CBT inside the ear by means of an infrared thermopile sensor pointing at the tympanic membrane and that allows to monitor the collected measurements remotely. Although

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1. In the context of Marathon runs, as well as in triathlon and Ironman races, deaths are not uncommon: six cases were reported in the Chicago Marathon in the last 14 years alone [2], and some of them were correlated to extremely high CBTs [3].

the measurement of tympanic temperature is a well-established method to estimate CBT [6], obtaining an accurate temperature measurement in the presence of exercising athletes is not an easy task. On the one hand, the mobility of the runners may affect the placement of the sensor inside the ear. On the other hand, varying environmental conditions (i.e., the influences of cloud cover, wind, rain, and direct sunlight on the device) may reduce the accuracy of sensor readings, and this especially applies to infrared thermopiles exposed to high thermal variations [7], [8]. Hence, in our study, we want to investigate the feasibility of a non-invasive wireless measurement of tympanic CBT in ambulatory settings and during exercise, and to examine the influence of physical movements and environmental conditions on the accuracy of the measurements.

In this work, after an overview of related literature (Sect. 2), we describe the design and implementation of the system (Sect. 3), and show the results of preliminary experiments suggesting that it can be used to identify the daily circadian rhythms of CBT, and to detect the variation in CBT due to prolonged physical activity (Sect. 4). We further report experiences learnt from the deployment of our system on several runners during the 5^{th} Lübeck Marathon, focusing on the impact of outdoor conditions on the accuracy and meaningfulness of the measured values (Sect. 5).

2. Related Work

Since the beginning of the 20th century, medical researchers have shown that CBT of Marathon runners can increase above 40 degrees by measuring the rectal temperature of the athletes immediately after the finish line [9], [10]. To get an understanding of the variations of body temperature *during* the race, researchers have undertaken studies in which Marathon runners were actively involved in the measurement process. For example, in [9], researchers have followed Marathon runners on moving vehicles matching their speed in order to connect the indwelling rectal probes to bulky measuring devices every nine minutes, and in order to hand-in skin thermistors that the runners would place in predefined body areas while running. Such awkward experimental setups were justified by the lack of reliable techniques to measure CBT in a non-invasive fashion. Measurements of rectal temperature (using rectal probes) and pulmonary artery temperature (using a catheter bathing in the artery blood) are indeed the standard ways to precisely measure CBT [11], and are not suitable outside clinical environments, as well as the measurement of oesophageal and nasopharynx temperatures using tiny thermistors [12]. The measurement of gastrointestinal CBT using ingestible pills [13], [14] is an attractive option allowing freedom of movement, but it is invasive, highly expensive (single-use), has limited lifetime (about 36 hours between ingestion and expulsion), and the measured temperature is strongly affected by the ingestion of cold liquids or food [15]. Furthermore, the communication range of an ingestible pill is very limited, and often causes non-negligible data loss [16]. As the measurements of oral (mouth) and axillary (armpit) temperature are not suitable to monitor exercising athletes, and as temporal artery temperature has been shown to be inaccurate in the context of exercising athletes and ambulatory adults [17], [18], we have resorted to the measurement of tympanic temperature, a well-established method to unobtrusively measure CBT in adults and infants [6].

To the best of our knowledge, this is the first body sensor network designed to measure CBT inside the ear that has been also tested in ambulatory environments and on exercising athletes in realistic racing settings. In the context of the MarathonNet project [19], Pfisterer et al. have proposed to use wireless sensor networks to measure biometric information on runners, but focused on connectivity issues. In the context of the ESPRIT project, Lo et al. have proposed the use of an ear-worn sensor to improve athletic performance, but focused on activity recognition and did not target precise temperature measurements on athletes [20]. Sanches et al. [21] have patented a Bluetooth headset to measure the temperature inside the ear and show his usability in a long-term data collection, but did neither use a contact-less technology, nor did they target a frequent telemetric assessment, nor did they test their system in ambulatory settings or on exercising athletes.

3. System Design and Architecture

Each runner wears an unobtrusive body sensor that measures CBT at the tympanic membrane, skin temperature at the outer ear, ambient temperature in the proximity of the ear, and that transmits the collected measurements wirelessly (Fig. 1). Support bikers following the Marathon runners on the track are equipped with wireless sink nodes that collect the measured data. With the help of a mobile phone collecting the current GPS position and acting as a gateway, the measurements are forwarded to a remote database, so that trainers and caregivers can monitor

Figure 1. Wireless body sensor measuring CBT at the tympanic membrane.

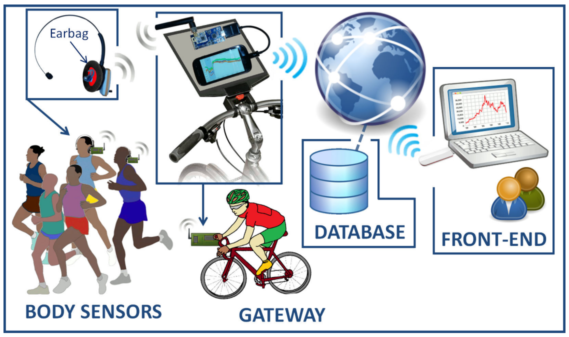
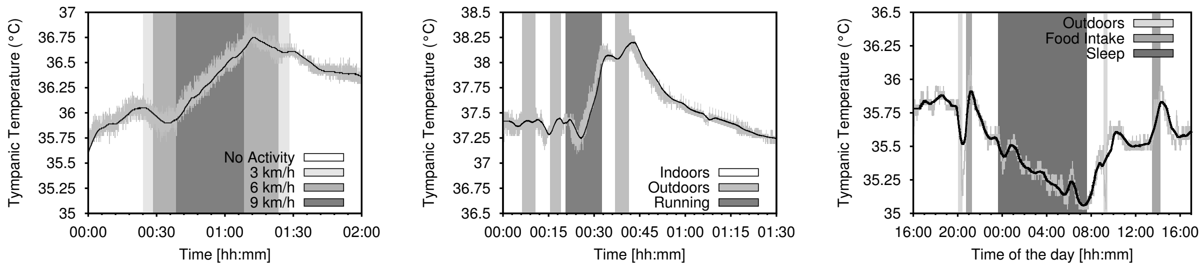


Figure 2. Overview of the system architecture.

the physiological parameters of the athletes during the race and can immediately be alerted as soon as the risk for a circulatory collapse becomes too high. In principle, runners could carry the mobile phone themselves inside a pocket. However, in our setup, we use the mobile phone also to record changes in the environmental conditions, such as presence of direct sunlight, wind, or shadow, and the bikers have the task of signalling all these information by interacting with the mobile phone placed on the handlebar of their bikes. Fig. 2 summarizes the architecture of the system.

Hardware. The body sensor nodes worn by the runners are based on the Atmel ATmega128RFA1 chip that embeds a low-power 8-bit MCU with 16 KB SRAM and an IEEE 802.15.4-compliant 2.4 GHz radio transceiver. In order to measure the CBT at the tympanic membrane, we use a Melexis MLX90614-DCA infrared thermopile with medical accuracy, and connect it to the MCU through the system management bus (SMBus). The version of the infrared thermopile that we employ partially compensates for internal temperature gradients inside the packaging, which would otherwise affect the measurements noticeably. In addition to CBT, the body sensor nodes worn by the runners also measure the skin temperature on the outer ear and the ambient air temperature in proximity of the ear by means of two precision NFC thermistors. In order to fully exploit the input range of the ADC and to maximize its resolution, we have built a conditioning circuit that adapts the analog signal from the thermistors and makes sure that the measured temperature is independent from the voltage supply and reduces the self-heating effect due to the current flowing through the thermistor. After calibration of the NFC thermistors, we have obtained an accuracy of 0.02°C over the temperature range of 16-42°C [1]. The sensor nodes are powered using a 150 mAh Li-Polymer rechargeable battery and packaged into a 41x25 cm wide OKW Minitec enclosure attached to a resizeable headset as shown in Fig. 1. In order to reduce the measurement noise of CBT, we use a Bose StayHear anatomic silicone ear tip holding the thermopile inside the ear canal: this also helps in avoiding a misplacement of the sensor due to the user's mobility or other mechanical solicitations. To protect the inner ear from external airflow and wind (and hence limit temperature gradients inside the thermopile packaging), we have added an *earbag* to the resizeable headset shielding the outer ear. The sink nodes collecting the measurements from the runners are off-the-shelf Maxfor MTM-5000MSP motes based on an MSP430 MCU and a CC2420 radio, and include a 5 dBi external SMA antenna. Google Nexus S smartphones connected to the sink nodes via USB act as gateways and forward the collected data to a remote database using the GSM network. Sink nodes and smartphones are enclosed into a Proporta BeachBuoy rainproof bike mount that is placed on the handlebar of the support bikers.

Software. All sensor nodes run the Contiki operating system [22]. The body sensor nodes sample temperature at a configurable rate (2 seconds in our experiments) and group ten readings in packets of 92 bytes that are buffered locally and wirelessly sent to the sink nodes as soon as they are in-range. The packets contain also information about the battery voltage, as well as a reference time so that the exact time at which the temperature is sampled can be reconstructed using the NTP-synchronized mobile phone as a time reference. We use acknowledgements to monitor connectivity between the wearable sensors and the sink nodes and keep track of the number of retransmissions. The mobile phone runs a custom Android application that retrieves the data from the USB serial interface and forwards it, together with the current GPS position, to a remote server through the GSM network every 25 seconds. Caregivers can monitor athletes anytime during the race through a Java application that displays the CBT and current location of each runner.



(a) Indoor exercise (b) Outdoor exercise (c) 24 hours experiment

Figure 3. Evolution of CBT during indoor (a) and outdoor (b) exercise, and along the course of a day (c).

4. Evaluation in Ambulatory Settings

Before deploying our system in a race event, we carried out a series of experiments in ambulatory settings to verify its reliability. In particular, we conducted tests on exercising subjects in indoor and outdoor settings and monitored the evolution of CBT on subjects wearing our system in their daily life. Firstly, we measured the evolution of CBT on a 27-years old female running on a Sprintex slat-belt treadmill. The experiment was carried out at the Sportdiagnostik Lab of the medical University of Lübeck, hence in an indoor environment at a constant ambient temperature, and followed a well-defined protocol. In order to wait for the temperature measurements to stabilize, the subject waited at least 20 minutes after wearing the sensor, as suggested by previous work [23]. After a warm-up phase in which the subject ran at 3 and 6 km/h for 5 and 10 minutes respectively, the subject kept a constant pace of 9 km/h for 30 minutes before slowing down at 6 and 3 km/h for 15 and 5 minutes respectively, and terminating the experiment after a 7610 meters run. Fig. 3(a) shows the evolution of tympanic CBT throughout the experiment[2]. After an initial decrease (that we conjecture is related to the increased airflow caused by the motion of the runner), CBT increased by approximately 1°C during the run, before slowly declining to its original value once the subject terminated the experiment.

Secondly, we carried out outdoor tests to verify the impact of the environment on the accuracy of the measurements. We instructed a 26-years old male to wear our system while running outdoors during a hot summer afternoon ($\approx$30°C air temperature). Fig. 3(b) shows the evolution of CBT during the run and highlights the instants in which the subject was indoors or outdoors. After an initial decrease (that we believe is caused by the airflow cooling down the body), CBT quickly increases above 38°C after only 10 minutes of running, showing how prolonged exercise in extremely hot conditions may indeed be dangerous for the body's thermoregulation [3], [4]. After a short indoor break after the run, we instructed the subject to sit outdoors and face the sun for approximately 5 minutes. Fig. 3(b) shows that the impact of sunshine results in a visible rise ($\approx$0.2°C) in CBT.

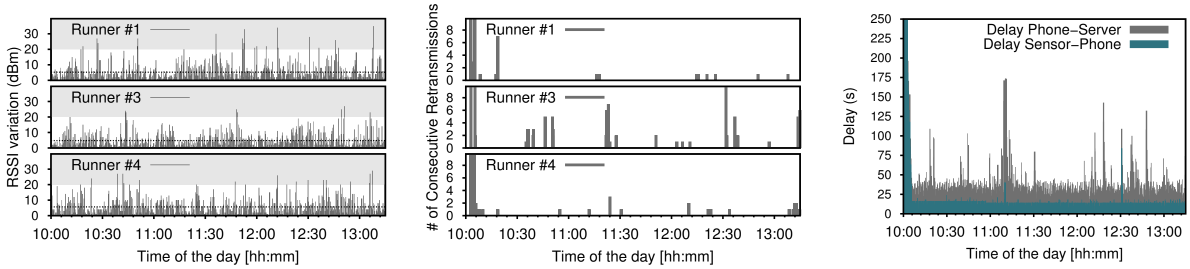
Finally, we ran a long-term experiment during January 2013, in which the same subject from the previous experiment was wearing the sensor in his daily life. Fig. 3(c) shows the evolution of CBT over the course of the day: one can identify a clear decrease of CBT during the night and a rise over the day, as a results of the circadian rhythms. From the plot, one can also observe that short-term fluctuations of CBT can be correlated to changes in environmental temperature (moving outdoors during the winter at a temperature close to 0°C), and to food intake (temperature increases by roughly 0.4°C after eating a complete meal). This shows that our system can be useful to monitor thermoregulation during exercise, but that it can be also useful for chronobiologists that need to derive an accurate profile of the circadian-system activity from long-term temperature measurements [1].

5. Field Deployment at a Marathon Race

We have deployed our system on 5 athletes (2 males, 3 females) during the 5^{th} Lübeck Marathon that took place in Lübeck, Germany, on October 2012[3].

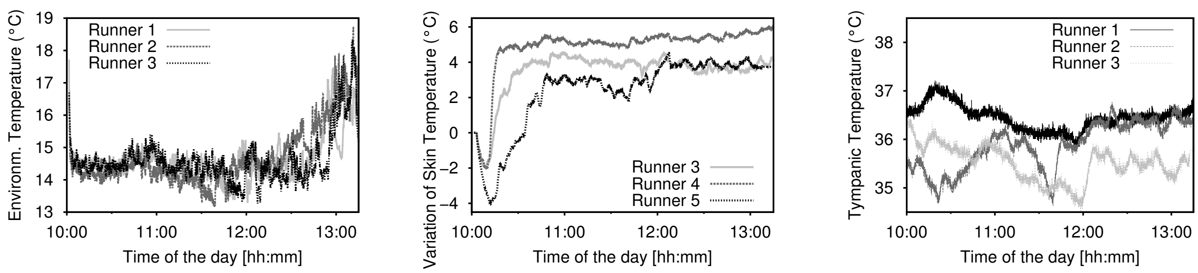
2. Please note that tympanic CBT is typically below 37°C and strongly depends on individual differences and surrounding temperature. Previous medical studies have shown that it is about 1°C lower than rectal temperature, in the range 35.5-36.5°C [23].

3. Ethical application number 12-174 approved by the Ethic Commission of the University of Lübeck on October 04, 2012.



(a) RSSI Variations (b) Amount of Retransmissions (c) End-to-End Delay

Figure 4. RSSI variation between two consecutive packets received from the body sensor nodes worn by the runners (a), amount of packets retransmitted throughout the race (b), and end-to-end delay between the ear-worn body sensor nodes and the remote database (c). The Marathon started at 10:00 AM.



(a) Environmental temperature (b) Skin temperature (c) Core body temperature

Figure 5. Evolution of environmental (a), skin (b), and core body temperature (c) w.r.t. the start of the race.

Reliability of communications. The telemetric acquisition of sensor data was flawless, and all the data was delivered to the caregivers within a very short delay. On average, temperature measurements were delivered to the mobile phone within 14 seconds, whereas the average delay between the reception of the data on the mobile phone and the storage on the server was 19 seconds, for an average end-to-end delay from the ear-worn body sensor nodes to the remote database of 33 seconds (Fig. 4(c)). Because of the large number of athletes, the support bikers were unable to stay in proximity of the starting line, which caused the data to be buffered locally and increased the delay significantly. The connectivity between support bikers and runners was optimal throughout the race, and, on average, only between 0.3% and 2.7% of the packets had to be retransmitted, as one can see in Fig. 4(b). The average received signal strength (RSSI) varied for each runner from a maximum of -64 dBm to a minimum of -80 dBm, and RSSI variations between consecutive readings were reasonably small. Fig. 4(a) shows the first derivative of the RSSI of the packets received from the body sensor nodes worn by the runners: only 1.49% of the times the RSSI variation between two consecutive packets was above 20 dBm (shaded area), in contrast to the results in [24].

Evolution of temperature during the run. The packaging of the body sensor nodes turned out to be robust to mechanical shocks and was well-accepted by all Marathon runners. During the race, the measured skin temperature resembled the expected trend, with a sharp decrease at the start of the race followed by a continuous increase as a result of physical exertion (Fig. 5(b)). The CBT measured during the race turned out to be relatively low (ranging between 34.5 and 37°C) because of the low outdoor temperature (see Fig. 5(a)) and the cold winds blowing on the track. Fig. 5(c) shows the evolution of CBT on three runners during the race: there is no visible increase in CBT during exercise as in the measurements shown in Fig. 3 due to environmental impact.

Environmental impact on CBT measurements. The low outdoor temperature and the cold wind blowing against the runners may have had a dual impact on the CBT measurements. On the one hand, they may have caused a physiologic drop of tympanic CBT due to the cold blood flow from the face to the inner ear. Medical researchers have indeed studied the response of tympanic CBT to environmental temperature variations by artificially applying a cold stimulus on the face [25], [26] or by keeping subjects into cold or hot thermal chambers [23], and experienced CBT variations higher than 0.5°C. On the other hand, despite the use of *earbags* to shield the inner ear, external airflow and wind may have generated temperature gradients inside the thermopile packaging. To better understand whether the CBT fluctuations were due to a physiological change in tympanic temperature, to a sensor inaccuracy, or to both, we have observed the CBT fluctuations at two specific points of the Marathon track and related them to the environmental temperature. In the first half of the Marathon, the runners were facing the cold wind coming from the coast. At half Marathon, the runners turned back and returned along the same path to the finish line without facing wind anymore. As soon as they passed the turning point, the environmental temperature suddenly rose, whereas CBT started to gradually increase in the following minutes, as can be seen in Fig. 6 (top). We conjecture that this increase in CBT is physiological, as it is gradual, and as it is likely that the absence of direct wind on the runners limited the body cooling and hence increased the CBT. We have also analysed the CBT of the runners while entering the 780 metre-long "Herren Tunnel" underneath the river Trave. Fig. 6 (bottom) shows that the fluctuations of CBT and environmental temperature while entering and exiting the tunnel are strongly correlated, possibly because of the airflow cooling down the runners' body.

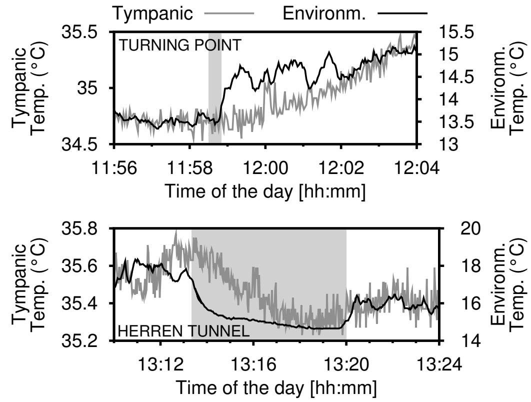


Figure 6. Evolution of the CBT and environmental temperature at the half Marathon turning point (top) and inside the Herren Tunnel (bottom).

6. Conclusions

We have developed an unobtrusive system to measure the CBT of Marathon runners using wireless body sensors. We have carried out preliminary tests in ambulatory environments and deployed our system on several athletes during the 5^{th} Lübeck Marathon, showing that a telemetric acquisition of body temperature on freely-moving subjects through an in-ear body sensor is feasible. We are now planning to build a customized silicon prosthesis to make the packaging more ergonomic and to better shield the thermopile sensor from environmental changes, as well as to carry out controlled studies as in [23] to quantify to which extent the environment affects sensor accuracy and physiological changes in tympanic CBT.

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