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Heat flux systems for body core temperature assessment during exercise

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ABSTRACT

Heat flux systems are increasingly used to assess core body temperature. However, validation of multiple systems is scarce. Therefore, an experiment was performed in which three commercially available heat flux systems (3 M, Medisim and Core) were compared to rectal temperature (T_{re}). Five females and four males performed exercise in a climate chamber set at 18 °C/50% relative humidity until exhaustion. Exercise duration was 36.3 ± 5.6 min (mean ± standard deviation). T_{re} in rest was 37.2 ± 0.3 °C. Medisim's-values were lower than T_{re} (36.9 ± 0.4 °C, $p < 0.05$); 3 M (37.2 ± 0.1 °C) and Core's (37.4 ± 0.3 °C) did not differ from T_{re}. Maximal temperatures after exercise were 38.4 ± 0.2 °C (T_{re}), 38.0 ± 0.4 °C (3 M), 38.8 ± 0.3 °C (Medisim) and 38.6 ± 0.3 °C (Core); Medisim was significantly higher than T_{re} ($p < 0.05$). The temperature profiles of the heat flux systems during exercise differed to varying degree from the rectal profiles; the Medisim system showed a faster increase during exercise than T_{re} (0.48 ± 0.25 °C in 20 min, $p < 0.05$), the Core system tended to show a systematic over-estimation during the entire exercise period and the 3 M system showed large errors at the end of exercise, likely due to sweat entering the sensor. Therefore, the interpretation of heat flux sensor values as core body temperature estimates should be done with care; more research is required to elucidate the physiological significance of the generated temperature values.

1. Introduction

Accurate measurement of core body temperature (T_c) is a hot topic in health and exercise sciences. A single T_c does not exist; each measurement is the result of a local heat balance equation (Pušnik and Miklavec, 2009; Taylor et al., 2014). This variation complicates T_c measurements and its interpretation. Still, there is a need to track the body temperature in clinical, occupational and exercise settings, since high body temperatures compromise health, comfort and performance (Flouris et al., 2018; Periard et al., 2021).

In lab settings, the esophagus and rectum are the two most commonly used reference sites for T_c determination (Daanen, 2006; Yeoh et al., 2017). As the esophagus is in close proximity to the heart and major blood vessels (thoracic aorta and superior vena cavae) and has a low heat capacity, esophageal temperature (T_{es}) closely mimics the heart's blood temperature (Mekjavic and Rempel, 1990; Taylor et al., 2014). However, underestimation of T_c may occur due to cold saliva passing the sensor in the esophagus (Teunissen et al., 2011b). Further, during real-life activities, both esophageal and rectal thermometry are not practical as they are rated as uncomfortable by the users. Several non-invasive alternatives have major drawbacks as well regarding validity, reliability and usability (Craig et al., 2000; Daanen et al., 2000; Kistemaker et al., 2006; Latman et al., 2001; Moran and Mendal, 2002; Pušnik and Miklavec, 2009; Suleman et al., 2002; Teunissen and Daanen, 2011; Teunissen et al., 2011a). Therefore, there is a need for T_c methods that are valid, but also easy to use and comfortable.

Heat flux measurement is a technique to assess human body core temperature non-invasively. The basic idea is that a heat flux sensor with insulating layer covers a patch of skin and measures the heat flux from the warm tissue underneath to the environment. Some systems use a thermopile in the insulative layer or thermosensors on two sides of the heat flux disk to estimate the underlying deep tissue temperature. Other systems use additional heating in the insulative layer and wait until no more heat flux from the deep tissue to the skin is present. Such so-called zero heat flux (ZHF) systems aim to measure deep tissue temperature directly at the skin.

The first experiments using heat flux methods for T_c measurement were done at the sternum with large ZHF sensors showing promising

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results (Fox and Solman, 1971). The Terumo Coretemp® system employed a 25 mm ZHF disk at the sternum and the results were rather similar to esophageal temperature (mean difference 0.1 ± 0.3 °C) (Matsukawa et al., 1997). Later, Dräger developed a (non-zero) heat flux system that was positively evaluated for assessing the Physiological Strain Index (PSI) in warm operational environments (Gunga et al., 2008) and for evaluating circadian rhythms at ambient room temperature (Gunga et al., 2009). However, a recent paper observed that 54% of the values were more than 0.5 °C different from cardiopulmonary artery measurements at clinical settings, making it unsuited for clinical use (Sastre et al., 2019). This is in contrast with the observation that 98% of the values were within +0.5 °C of T_{es} perioperatively or in general intensive care units (Kimberger et al., 2009). Philips prototyped a ZHF system for clinical use, but never brought it to the market. This ZHF sensor tracked T_{es} rather well during mild therapeutic hypothermia after cardiac arrest (Zeiner et al., 2010) and during exercise in hot and stable ambient conditions (Teunissen et al., 2011b).

Currently commercially available systems include 3 M, Core and Medisim. 3 M developed a ZHF system for clinical use, the Spot-On, linked to the Bear Hugger warming system. This system was recently observed to underestimate rectal, bladder and esophageal temperature by about 0.3 °C (95% confidence interval from 0.1 °C to 0.4 °C), making it unsuited for fever detection (Hart et al., 2020). The Medisim system has been reported to provide reliable results in clinical settings with 94% of the measurements within ±0.5 °C of esophageal temperature (Evron et al., 2017). However, a more recent study observed 95% limits of agreement within −0.99 °C to +0.91 °C (Bräuer et al., 2022), a considerably larger range. The CORE (greenTEG AG, Rümlang, Switzerland) system, a wearable that was launched recently, has been shown to yield repeatable results, but quite different from T_{re} values (Verdel et al., 2021). In this study 50% of all paired measurements differed more than 0.3 °C. Good correspondence was show with tympanic temperature (Ajcevic et al., 2022), but tympanic temperature is not considered as a good reference since temperature readings are dependent on ear canal morphology (Daanen, 2006).

Since conflicting evidence exists regarding the validity of heat flux sensors for T_c assessment, a study was performed in which the commercially available 3 M SpotOn, Medisim Temple Touch and CORE system were compared to T_{re} during and after exercise at 18 °C ambient temperature. This relatively low ambient temperature sets a challenging situation for (zero) heat flux sensors.

2. Methods

2.1. Participants

Following approval of the experimental protocol from the Research Ethics Committee of the Vrije Universiteit Amsterdam (approval number VCWE-2021-157R1), 9 healthy and recreationally active participants (5 females and 4 males) with mean age 24.3 ± 1.2 years were included in the study. To participate in this study, all participants gave their written consent. Exclusion criteria were: (1) resting T_c of $\leq$38.0 °C; (2) history of cardiovascular, thermoregulatory, respiratory, neurological, or metabolic diseases; and (3) participants that took any medication affecting normal body temperature during time of participation, unless these medicines are regularly taken as long-term medication (e.g. contraceptives). A power analysis was performed using G*power version 3.1.9.6 prior to the study with α equal to 0.05 and β equal to 0.80, desired precision of 0.30 °C and standard deviation of 0.24 °C (derived from Teunissen et al. (2011b)) resulting in a minimum of 8 subjects.

2.2. Protocol

This study involved one visit to our laboratory at the Vrije Universiteit Amsterdam. The participants were requested not to consume alcohol 24 h prior to the test, abstain from coffee 6 h prior to the test and consume 500 ml water 0–2 h prior to the start of the experiment.

During this visit, participants completed an incremental cycling protocol to increase their body temperature (Monark Exercise AB, Vansbro, Sweden). The experiment was performed in an environmental chamber (b-Cat B.V., Tiel, The Netherlands) with air temperature set at 18 °C and relative humidity at 50%, similar to conditions in surgery rooms.

Upon arrival to the laboratory, participants redressed into their sports clothes (shorts, t-shirt, socks, shoes, and sports bra for females). In addition, as clothing acts as a barrier for heat and moisture transport between skin and environment, participants wore an extra layer of standardized clothing (sweatpants and jumper) over their sport clothes to enhance the increase in core body temperature. Hereafter, participants were equipped with the three heat flux sensors (3 M, Medisim, Core). The thermometers assessed body temperature simultaneously during three periods: rest, exercise and recovery every minute. Water intake was prohibited during all periods. Participants entered the climatic chamber when they were familiarized with all sensors and all sensors were stabilized, taking at least 10 min. The experimental session was initiated with 10 min rest in seated position. Then, participants started cycling at 1.0 W kg^{-1} body weight for the first 5 min, followed by incremental steps of 0.2 W kg^{-1} every 3 min until exhaustion. Participants recovered in seated position for 10 min after which the experiment was ended and participants left the climatic chamber. Participants 3–10 wore a polyester headband over the forehead sensors to ensure adherence of one of the heat flux sensors with the skin when participants started sweating.

2.3. Measurements

2.3.1. Rectal and esophageal sensor

T_{es} and T_{re} were measured with a disposable thermal probe (Henleys Medical Supplies, Hertfordshire, United Kingdom) of 2 mm in diameter. The researcher inserted the probe in the esophagus through the participant's nostril at an insertion length according to the following formula: L (cm) = 0.479 * (sitting height) – 4.44 (Mekjavic and Rempel, 1990). Participants self-inserted the rectal probe 12 cm past the anal sphincter.

2.3.2. Heat flux sensors

This study evaluated three heat flux sensors. Before sensor placement, the skin was cleaned and disinfected with 70% ethanol. Firstly, 3 M's SpotOn sensor (3 M, Neuss, Germany) was placed above the left orbital ridge. Secondly, Medisim's Temple Touch Pro sensor unit (Medisim, Beit-Shemesh, Israel) was positioned at the participants' right temple. Lastly, the wearable device CORE (greenTEG AG, Zurich, Switzerland) was attached to a heart rate monitor strap and positioned at the torso about 20 cm below the armpit. All locations were in line with the recommendations of the manufacturers.

2.3.3. Skin temperatures

Local T_{sk} was measured at the neck, shoulder, hand and shin using iButtons (Thermochron, Sydney, Australia), which were attached to the skin with tape (Fixomull Stretch ADH, BSN Medical GmbH, Hamburg, Germany). T_{sk} was calculated as a weighted average of the four local skin temperatures (Ramanathan, 1964). Mean body temperature (T_b) was calculated using a weighing factor of 0.8 for T_{re} and 0.2 for T_{sk} (Hardy and Du Bois, 1938).

2.3.4. Other measures

Heart rate (HR) was measured to get an indication of the exercise intensity that the participants were performing, using a Polar device (Polar Electro, Finland) with a sample frequency of 1 Hz. For determination of the initial power output at the ergometer, the subject's mass was determined on a weighing scale (Sartorius, Göttingen, Germany) prior to exercise.

2.4. Data processing and statistics

All data was processed in MATLAB (version R2021b). Per 1 min, individual temperature parameters (T_{es}, T_{re}, T_{sk}, 3 M, Medisim and Core) were calculated. Differences in temperature values were evaluated within subjects using factorial analysis of variance from the general linear models in Statistica (TIBCO_Software_Inc, 2020) with participants as random factor, and rest/exercise and system (T_{es}, T_{re}, T_{sk}, 3 M, Medisim and Core) as independent factors. Post-hoc analysis was performed using the Fisher LSD test.

3. Results

The participants' characteristics and intensity parameters are presented in Table 1. Exercise duration averaged 36.3 ± 5.3 min.

T_{es} was considerably affected by the cold saliva passing the sensor in the esophagus and was therefore not included in the analysis.

A typical example (participant 1) of the evolution of T_{re} and the temperature patterns recorded by the 3 heat flux sensors over time is shown in Fig. 1. After 32 min, the exercise was stopped. The 3 M system stopped working after about 31 min, probably due to sweat leaking into the system.

Table 2 shows the rest and maximum temperature values after exercise as well as T_{sk}, mean body temperature (T_b) and HR values. Missing data were observed for 3 M for participants 2 and 7 (sweat in sensor during exercise phase) and Core for participant 8 (no connection with app). Over the first 20 min of exercise, all heat flux systems showed a significant difference with T_{re} ($p < 0.05$).

Fig. 2 shows the average temperature values of the heat flux systems compared to T_{re} for the first 29 min of exercise, in which all participants were active. Also, the plots of rectal temperature against the difference between heat flux system values and rectal temperature are shown. The 3 M system data are shown until minute 21 of exercise since at that moment systems of multiple participants dropped out due to sweat in the sensor. The Medisim system overestimated T_c during the second part of exercise. The Core systems showed an unexpected increase after about 23 min of exercise followed by levelling off.

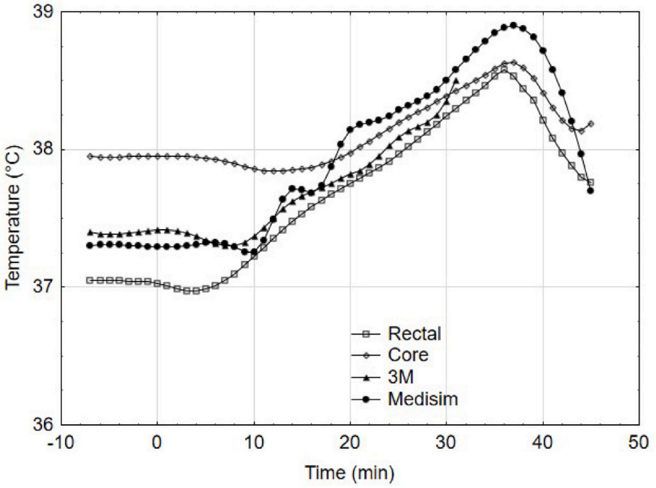

Fig. 1. Typical example of rectal temperature values over time with values for the Core, 3 M and Medisim system (participant 1). The exercise phase lasted from 0 to 32 min.

4. Discussion

The aim of the present study was to compare the values of the commercially available 3 M SpotOn, Medisim Temple Touch and CORE system with T_{re} during and after exercise at 18 °C ambient temperature.

All sensor systems showed deviating patterns from T_{re} and suffered from different confounding issues; the data of two out of nine participants had to be removed for the 3 M and Medisim system and one participant for the Core system. The Medisim system yielded significantly lower values than T_{re} in rest, and higher values during exercise. The temperature increase over the first 20 min was almost 0.5 °C higher for the Medisim system than T_{re}. This is higher than values in previous studies comparing (zero) heat flux devices to T_{re} during exercise in warmer than the current conditions (0.12 ± 0.24 °C in 35 °C (Teunissen et al., 2011b); −0.08 ± 0.35 °C in 25 °C (Gunga et al., 2008)). The average and maximum values of 3 M and Core during rest and exercise did not differ significantly from T_{re}, although visually displaying a different pattern.

Note that the forehead heat flux sensor data were likely influenced by sweat. The 3 M sensor acted like a sponge absorbing sweat and failed to record during the last exercise phase for most participants. Sweat may also have led to overestimation of the core temperature in the Medisim system. We observed an increase in temperature values after sweating onset. Further, to ensure skin-sensor contact, participants 3–9 wore a polyester headband covering the forehead heat flux sensors. This extra layer of insulation may have influenced temperature measurements, but was necessary to keep the sensor on the sweating skin. Unfortunately, sweat entering the sensor likely caused missing data. Reduced sticking of the sensor to the skin during sweating was observed in a clinical study with the 3 M system (Hart et al., 2020).

The Medisim system seemed to function properly in all participants but we observed a rise in temperature that exceeded the temperature rise in T_{re}. It can be argued that the increase in T_{re} is slower during exercise than T_{es}, which is indicative of central blood temperature (Mekjavic and Rempel, 1990), and that Medisim rather reflects T_{es} than T_{re}. Indeed, Evron et al. observed no significant evidence of increasing or decreasing systematic bias (mean difference) or variability (spread) between the Medisim temperature and esophageal reference measurements with increasing temperature in 25 investigated patients (Evron et al., 2017). This is in line with previous studies comparing ZHF sensors at the head to T_{es} (Teunissen et al., 2011b).

The closed Core system was not influenced by sweat and its evolution

Table 1
Participants' anthropometric characteristics (mean ± SD), sex, and intensity parameters. M = male; F = female; P = power output; HR max = maximal heart rate.

Participant	Age (yrs)	Sex	Body mass (kg)	Body surface area (m^2)	P_{start} (W)	P_{end} (W)	Exercise duration (min)	HR_{max} (bpm)
1	24	M	97	1.65	97	180	35	185
2	25	M	70	1.77	70	228	47	193
3	25	M	68	1.81	68	184	32	191
4	23	M	72	1.71	72	205	41	197
5	25	F	61	1.88	61	236	41	171
6	24	F	60	1.89	60	212	35	202
7	26	F	67	1.89	67	224	35	190
8	25	F	53	1.73	53	180	32	192
9	22	F	63	1.60	63	133	29	187
Average	24.3		67.9	1.8	67.9	198	36.3	190
SD	1.2		12.4	0.1	12.4	32	5.6	8.7

Table 2
Mean values (±SD) for esophageal temperature (T_{es}), rectal temperature (T_{re}), 3 M, Medisim and Core system, mean skin temperature (T_{sk}) and mean body temperature (T_b) in °C and heart rate (HR) in beats/min for the rest period and the maximum values during exercise. Δ with T_{re} shows the mean difference (±SD) over the first 20 min of exercise of T_{re} with the 3 M, Medisim and Core systems.

	T_{es}	T_{re}	3 M	Medisim	Core	T_{sk}	T_b	HR
N	5	9	7	7	8	9	9	9
Rest	36.8 ± 0.2	37.2 ± 0.3	37.2 ± 0.1	36.9 ± 0.4[a]	37.4 ± 0.3	31.8 ± 0.7	36.1 ± 0.3	91 ± 13
Exercise	38.1 ± 0.4	38.4 ± 0.2	38.0 ± 0.4	38.8 ± 0.3[a]	38.6 ± 0.3	33.8 ± 1.0	37.4 ± 0.3	190 ± 8
Δ with T_{re}			0.27 ± 0.34	0.48 ± 0.25$	−0.01 ± 0.35			

$ Δ-values significantly different from 0 ($p < 0.05$).

[a] Heat flux system values significantly different from T_{re} ($p < 0.05$).

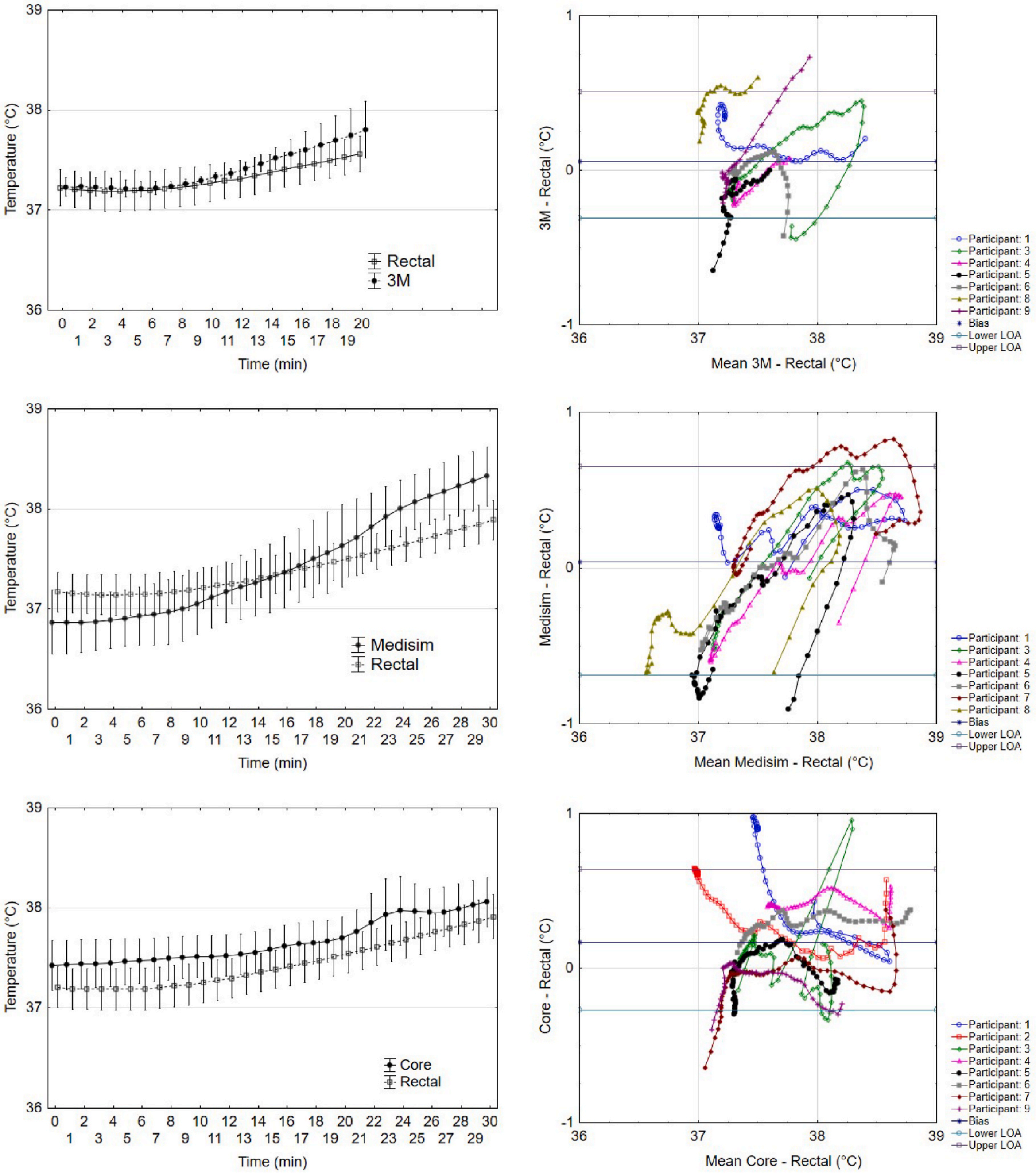

Fig. 2. Left panel: Rectal temperature plotted with values of the 3 M system (top, N = 7), Medisim system (middle, N = 7) and Core system (bottom, N = 8), averaged over the participants. Vertical bars indicate 95% confidence intervals. Right panel: Bland-Altman plots of mean values of rectal temperature/heat flux system values against difference between heat flux system values and rectal temperature for each participant. The points are connected for clarity. Bias and lower and upper limits of agreement (LOA) are included in each plot.

was closely related to T_{re}, though overestimating it during the entire experimental session. The average overestimation of T_{re} of about 0.2 °C (Fig. 2) was similar to the constant overestimation (0.23 ± 0.35 °C) in a previous study (Verdel et al., 2021). Due to a sudden increase of over 1 °C for about 4 min in a single subject, a temporary increase in average values and confidence interval can be observed in Fig. 2 during minutes 21 to 25. These outliers are not removed because there was no valid reason to eliminate the data. A correction of the offset makes the results comparable to T_{re}.

Despite the mentioned caveats, which require to interpret the T_c estimates with care, the heat flux systems seem able to outperform practical alternatives like infrared measurement in ear (Craig et al., 2002; Daanen, 2006; Muir et al., 2001; Pusnik and Drnovsek, 2005; Teunissen et al., 2011a) and on the head (Kistemaker et al., 2006; Suleman et al., 2002; Teunissen and Daanen, 2011). The same applies in comparison to real-time estimations based on physiological measurements by wearables (Falcone et al., 2021). The 95% CI of 3 M approached the generally considered acceptable limit of 0.5 °C, indicating its potential for practical application.

Practical application during work or exercise in the heat seems currently only appropriate for the Core system, being the only sweat-resistant device. This also holds for other sweat inducing conditions like high fever. In this study, the time that profuse sweating occurred was not registered. For future research it is recommended to record the moment that participants start to sweat, so that this moment can be linked to deviations in the core temperature recordings. This enables an analysis to estimate the impact of sweat rate on temperature deviations. For the time being, the 3 M and Medisim system may be useful for non-sweat (clinical) settings, like therapeutic hypothermia or surgery.

As the Core system closely tracked the T_{re} pattern, it should be taken into account that the peak temperatures and quick fluctuations visible in T_{es} might be missed (Teunissen et al., 2012). Conversely, 3 M and Medisim might track T_{es} better than T_{re}, in view of their higher rate of increase during exercise. Future comparison with T_{es} in warmer conditions could clarify this issue. In addition, future research could evaluate whether the outliers in the current Core measurements were incidental or yield a structural technical issue. We also recommend to includes measurements of the systems over several days in future studies, so that the day-to-day variation can be included in the analysis.

Author statement

Hein Daanen: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing - review & editing. Veerle Kohlen: Data curation; Formal analysis; Investigation; Methodology; Project administration; Software; Validation; Visualization; Writing - original draft. Lennart Teunissen: Writing - review & editing.

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Declaration of competing interest

There are no competing interests.

Data availability

Data will be made available on request.

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