

Monitoring core temperature of firefighters to validate a wearable non-invasive core thermometer in different types of protective clothing: Concurrent in-vivo validation

C.C. Roossien^{a,*}, R. Heus^b, M.F. Reneman^a, G.J. Verkerke^{a,c}

^a University of Groningen, University Medical Center Groningen, Department of Rehabilitation Medicine, Hanzeplein 1, 9713 GZ, Groningen, the Netherlands

^b Institute for Safety (IFV), Zilverstraat 91, 2718 RP, Zoetermeer, the Netherlands

^c University of Twente, Department of Biomechanical Engineering, Drienerlolaan 5, 7522 NB, Enschede, the Netherlands

ARTICLE INFO

Keywords:

Ambient conditions

Core temperature

Heat stress

Physical activity

ABSTRACT

This study aims (1) to test the validity of a new non-invasive core thermometer, Cosinuss[°], in rest and (2) during firefighting simulation tasks, against invasive temperature pill and inner-ear temperature and (3) to compare the change in core temperature of firefighters when working in two types of protective clothing (traditional turnout gear versus new concept). 11 active firefighters performed twice a selection of tasks during their periodic preventive medical examination and a fire-extinguishing task. Without correction no correlation between the Cosinuss[°] and thermometer pill ($ICC \leq 0.09$, $p \geq 0.154$, $LoA \geq 1.37$) and a moderate correlation between Cosinuss[°] and inner-ear infrared ($ICC = 0.40$, $p = 0.044$, $LoA \pm 1.20$) was observed. With individual correction both correlations were excellent ($ICC \geq 0.84$, $p = 0.000$, $LoA \leq 0.30$). However, during and after working all correlations were poor and non-significant ($ICC \leq 0.38$, $p \geq 0.091$, $LoA \geq 1.71$). During firefighting tasks, the Cosinuss[°] is invalid for measuring the core temperature. No differences in heat development in the two types of protective clothing was proven.

1. Introduction

During their job firefighters are exposed to a high thermal load due to heavy physical activity, external heat exposure from fires and the wear of highly insulated protective clothing. High thermal load can cause heat stress (McQuerry et al., 2018) (Costello et al., 2015) (Yazdi and Sheikhzadeh, 2014) (Nunneley, 1989) (Levels et al., 2014), resulting in heat exhaustion, dehydration, mental confusion, physical fatigue and loss of consciousness which affects productivity and risk perception (Chang et al., 2017) (Cvirm et al., 2019) (Epstein and Moran, 2006) (McInnes et al., 2017) (Barr et al., 2010). To monitor and prevent heat stress among firefighters, a reliable and continuous thermometer which is able to measure the real-time core temperature of firefighters is desirable. (Mazgoaker et al., 2017) (Savage et al., 2014) (Steck et al., 2011) (Uth et al., 2016).

Invasive core temperature (T_c) measurements may not be practical in a working situation (Levander and Grodzinsky, 2017) (Lim et al., 2008) (Saurabh et al., 2014) (Taylor et al., 2014). The invasive temperature sensor pill is minimally invasive, but at the moment it is only available

for remote T_c monitoring for a specific period of time and it is difficult to standardize the location of the sensor in the gastrointestinal tract (Mazgoaker et al., 2017). Additionally, the pill must be swallowed at least 4–6 h prior to the measurement (HQInc., 2018a,b) which is difficult in occupations such as firefighting because it is unknown when duty will call. Moreover, temperature sensor pills are impractical due to the high cost and inability for them to be reused (Mazgoaker et al., 2017). In addition, food and liquid intake can influence the accuracy of the temperature sensor pill and higher body weights and/or abdominal proportions obstruct reading of the sensor. Other methods and research concerning non-obstructive measurement or prediction of T_c , e.g., via skin temperature or multiple parameters are not yet reliable or available for workers (Langridge et al., 2012) (Gonzalez-Alonso et al., 1999) (Lim et al., 2008) (Richmond et al., 2015) (Yang et al., 2017).

The Cosinuss[°] C-med (Cosinuss[°] GmbH, München, Germany) is a new wearable, non-obstructive and commercially available inner-ear thermometer that could be useful to monitor T_c continuously and in a non-invasive manner. This sensor system could provide more detailed and long-term insight in the change in T_c during firefighting activities, as

* Corresponding author. A. Deusinglaan 1, FB33 (3215.1105), 9713 AV, Groningen, the Netherlands.
E-mail address: c.c.roossien@umcg.nl (C.C. Roossien).

well as the role of different types of protective clothing (Barr et al., 2010), either as an individual measuring system or in combination with multiple variables (Richmond et al., 2015). In research of Chaglla (Chaglla et al., 2018) the Cosinuss[®] One demonstrated a deviation of -1.5°C in comparison to inner-ear infrared (IR) thermometry. The correlation of the Cosinuss[®] C-med and compared to the research standard of gastrointestinal temperature is unknown (Towey et al., 2017) (Langridge et al., 2012) (Gonzalez-Alonso et al., 1999).

The objective of this study is to investigate the validity of the Cosinuss[®] to monitor changes in core temperature during realistic physical active firefighting simulation tasks instead of standard lab controlled treadmill protocols to mimic the real-life situation as well as possible (Havenith and Heus, 2004). The aim of this study was (1) to test the validity and reliability of a wearable non-invasive T_c sensor, Cosinuss[®], in rest in comparison to an invasive temperature sensor pill and standard inner-ear IR thermometer and (2) during realistic firefighting simulation tasks in comparison to an invasive temperature sensor pill, and (3) to compare the change in T_c recorded with the Cosinuss[®] and an invasive temperature sensor pill of firefighters during realistic firefighting simulation tasks in two types (traditional turnout gear versus a new concept) of protective clothing.

2. Materials and methods

2.1. Subjects

The subjects participated voluntarily and were recruited by distributing flyers and during an information meeting organized by the fire department via the local safety region. Inclusion criteria were firefighters with an age between 18 and 67 years who passed the Periodic Preventive Medical Examination (PPMO). Exclusion criteria were body weights lower than 40 kg, problems or complaints with the gastrointestinal tract and/or infestation of proreflex, and needing to undergo Nuclear Magnetic Resonance Imaging or Magnetic Resonance Imaging in the next 24 h after swallowing the thermometer pill (HQ Inc., 2018a, b). Subject information was protected by double-blinding the data; the fire department gave every subject a letter and the researchers coupled a number to this letter using a random number generator.

The Medical Ethics Committee of the University Medical Center Groningen, the Netherlands, issued a waiver for this study, stating that it does not involve medical research under Dutch law and approved the study (M17.209969).

2.2. Materials

2.2.1. Cosinuss[®]

The Cosinuss[®] type C-med (Cosinuss[®] GmbH, München, Germany) is a wearable core thermometer which measures the temperature in the inner-ear. This hearing-aid shaped thermometer can be used in working conditions of -15 to 55°C . According to Cosinuss[®] (Cosinuss[®], 2016) the sample frequency is 100 Hz and the accuracy is $\pm 0.1^{\circ}\text{C}$.

2.2.2. CorTemp[®]

The CorTemp[®] HT150002 is an ingestible core body temperature sensor (dimensions: 2.4×10.7 mm) that has been approved by the US Food and Drug Administration (no. K880639) (HQ Inc, 2018a,b). This thermometer sensor pill has a temperature range 30 to 40°C and an accuracy of $\pm 0.1^{\circ}\text{C}$ (HQ Inc, 2018a,b). The pill data was continuously collected using the CorTemp[®] Data Recorder (dimensions $120 \times 60 \times 25$ mm, 193 g) with a sampling rate of 10 s (HQ Inc, 2018a,b). The data recorder used CorTrack[™] II Software version 2.7 (HQ Inc., 2006) and needed to be worn around the hips.

2.2.3. Inner-ear infrared thermometer

The Braun ThermoScan[®] 7 type IRT 6520 (Braun GmbH, Kornberg, Germany) is an inner-ear IR thermometer. Due to its fast, easy to use and

non-invasive nature, inner-ear IR thermometry is being used as a clinical standard (Garcia-Souto and Dabnicki, 2016) (Nederlands Huisartsen Genootschap, 2016) (Kocoglu et al., 2002). The Braun ThermoScan[®] has an measurement range temperature of 35 to 42°C with an accuracy of $\pm 0.2^{\circ}\text{C}$ compared to rectal temperature measurements in an operating T_a of 10 to 40°C (Braun GmbH, sd) (Moran-Nabarro et al., 2018).

2.2.4. Ambient conditions box

To measure the ambient temperature (T_a) and relative humidity (RH) (SHT15 Breakout, Sensirion, Staefa ZH, Switzerland) inside the protective clothing, an ambient conditions box was worn. The box was positioned on the chest using elastic belts and was worn over the first layer of clothing (a cotton t-shirt) and below the fire suit measuring the microclimate inside the personal protective clothing. The temperature inside the clothing was described as T_{cli} (Lotens, 1993). The T_{cli} sensor has an accuracy of $\pm 0.3^{\circ}\text{C}$ and the RH sensor has an accuracy of $\pm 2.0\%$ at a range of 10–90% RH (Sensirion, 2010). The response time was 5–20 s and the operating temperature was -40 to 120°C (Sensirion, 2010).

2.2.5. Personal protective clothing

Two types of personal protective clothing were used; suit A and B. Suit A is traditional turnout gear composed of a trouser with jacket (see Fig. 1 left). Both trouser and jacket contained three layers; (1) outer fabric made of XT5 Nomex[®] Delta T; (2) moisture barrier made of MO3 Gore-tex[®] fireblocker; and (3) thermal barrier and inner layer made of Q01 thermal felt quilted to Nomex[®] viscose (standard EN469:2005) (Bristol Uniforms, 2007). This suit has a water vapor resistance of 28m2Pa/W, a thermal heat insulation (HTI) resistance HTI 24 of 21.3s and HTI 24-12 of 6.3s, and a radiation thermal heat insulation (RHTI) RHTI 24 of 26.2s and RHTI 24-12 of 7.1s. Suit B is a new protective clothing concept composed of a coverall with jacket (see Fig. 1 right). The jacket contained two layers; (1) an outer fabric made of TenCate Millenia[™] Mi 9200 and (2) an inner layer made of TenCate Defender[™] CZ 760. The coverall contains three layers; (1) an outer fabric made of TenCate Millenia[™] MI 9200 and Tecasafe[®] Plus XL 9700; (2) an inner layer of TenCate Defender[™] CZ760 (upper part) and DM9180 (lower part); and (3) a thermal barrier of TenCate thermal membrane CX 140 (Safety Masters, 2017). This suit has a water vapor resistance of 12.6m2Pa/W, a thermal heat insulation (HTI) resistance HTI 24 of 17.4s and HTI 24-12 of 5.3s, and a radiation thermal heat insulation (RHTI) RHTI 24 of 21.0s and RHTI 24-12 of 7.4s.

The main difference between suit A and B was the clothing ensembles and its protection level. Suit A (traditional turnout gear) contains a trouser and jacket which both need to be worn during firefighting work with protection level 2 according to the standard EN469 (EN 469:2005/A1:2006 Protective clothing for firefighters – Performance requirements for protective clothing for firefighting). Suit B (new protective clothing concept) contains a coverall with jacket of which the jacket only is mandatory during indoor fire-extinguishing work to provide protection level 2 of the standard EN469. The coverall without the jacket provided only protection level 1. The difference in design of the clothing ensemble (amount of layers) was expected to influence the ventilation and release of heat and so the rise in T_c during the performance of the work.

2.3. Study design

The protocol contained the following three stages: (1) concurrent validation measurement; (2) performance of realistic firefighting simulation tasks; (3) concurrent validation measurement. In the concurrent validation measurements in stage 1 and 3, the T_c of the subjects was measured five times at rest with a frequency of one measurement per minute. The T_c was recorded using the Cosinuss[®] (in one ear) and using the CorTemp[®] and an inner-ear IR thermometer (in other ear) as references. These concurrent validation measurement were performed in a room with a constant T_a of $20.0 \pm 2.0^{\circ}\text{C}$ and RH of $45.0 \pm 5.0\%$. Stage 2 contained a simulation of two realistic firefighting simulations tasks of

approximately 15 min per task. First, a selection of standardized tasks were performed selected from the Periodic Preventive Medical Examination (PPMO) protocol namely:

- track including rolling out and up a fire hose of 15 m;
- climbing and descending a ladder (96 steps) with a fire hose of 20 kg over the shoulder;
- crawling through two tunnels (tunnel of 3 m long and 1.2 m height with 3 m between the two tunnels) with a fire hose;
- a demolition operation where a ball of 5 kg needs to be hit the upper side of a basket ten times with a stick of 6 kg on a height of 2.5 m;
- and punching a door with a forcible entry tool of 16 kg.

The PPMO was performed in a room with a constant T_a of 20.0 ± 2.0 °C and RH of $45.0 \pm 5.0\%$. Secondly, a hot fire-extinguishing task while wearing self-contained breathing apparatus (SCBA) including:

- extinguishing a fire,
- searching for victim,
- and kneeling in front of a fire of 220 a 225 °C.

The T_c of the subjects was recorded continuously using the Cosinuss° (one measurement per second) and using the CorTemp® (one measurement per 10 s) as reference. Due to the non-wearable character of the inner-ear thermometer this thermometer could not be included in stage 2. The hot fire-extinguishing task was performed in a practice building with a fireplace of 220 a 225 °C. The task started outdoor with a T_a of 13.0 ± 2.0 °C, RH of $72.0 \pm 5.0\%$ and mean wind speed of 3.2 m/s. The estimated heat radiations was about 4 kW/m².

In all three stages the subjects wore suit A (trouser and jacket) or suit B (coverall with jacket). After the first round of stage 2 the subject changed suit and performed this stage again in the second suit. To avoid order effects, the order in which the suits were worn alternated per subject. Both measurements in the different suits were performed on the same day in the same order: a concurrent validation measurement, the

PPMO, the hot fire-extinguishing task and a concurrent validation measurement. The PPMO test was done before the hot fire-extinguishing task, because according to regulations after the hot fire-extinguishing task the subjects needed to clean their clothing. Between the three stages, the two tasks and between the measurements in suit A and B, the subjects had time to acclimatize or cool down by passive sitting and drinking water for a period of 10 min. In Table 1, this study design is presented.

To test the in-vivo validity and reliability of the Cosinuss° in rest (aim 1), in the concurrent validity study of stage 1 and 3 the Cosinuss° was compared to the references CorTemp® and an inner-ear IR thermometer. To test the in-vivo validity and reliability of the Cosinuss° during work (aim 2), in stage 2 the Cosinuss° was compared to the reference CorTemp®. To explore the change in individual T_c , T_{cli} and RH of the subjects (aim 3), during stage 2 the T_c was continuously recorded with the Cosinuss° and CorTemp® and T_{cli} and RH were continuously recorded using the ambient conditions box (measurement frequency of one measurement per second). To compare the change in T_c , T_{cli} and RH in the two types of protective clothing, the two tasks in stage 2 were performed twice; once in suit A and once in suit B.

2.4. Data analysis

Field calibration to correct the Cosinuss° was explored and conducted based on both the CorTemp® and the inner-ear IR thermometer during stage 1. To correct the Cosinuss° the second measurement of stage 1 was used; per subject in one ear the T_c was recorded with the Cosinuss° and compared to the T_c recorded with the CorTemp® and the inner-ear IR thermometer in the other ear. The difference between the measured T_c of the Cosinuss° and CorTemp® or inner-ear thermometer was considered as the individual correction factor of the Cosinuss°. The CorTemp® sensors were factory calibrated and the HQ Inc data loggers were calibrated according to the user instructions.

To test the aims, statistical analysis was performed using IBM SPSS Statistic 25. To test the validity and reliability of the Cosinuss° in rest (aim 1), of stage 1 and 3 the fourth concurrent validation measurement

Table 1

Study design; study design including stages 1–3. NB. Stage 2 was performed twice (once wearing suit A, once wearing suit B) with the order counterbalanced between subjects.

Stage	Activity	Measurement	Task	Thermometers	Measurement frequency	Duration
0	Dress up	-	Put on suit A	• CorTemp®	-	-
1	Acclimatization	-	Passive sitting and drinking water	• Cosinuss°	-	10 min
	Measurement	Concurrent validity	Rest (passive sitting)	• CorTemp®	Once per minute	5 min
				• Cosinuss°		
				• CorTemp®		
2	Measurement	Performance of job simulation	Periodic Preventive Medical Examination	• Inner-ear	Continuously during task	15 min
				• Cosinuss°		
				• CorTemp®		
	Cool down	-	Passive sitting and drinking water	• Cosinuss°	-	10 min
				• CorTemp®		
	Measurement	Performance of job simulation	Fire-extinguishing task	• Cosinuss°	Continuously during task	15 min
				• CorTemp®		
	Cool down	-	Passive sitting and drinking water	• Cosinuss°	-	10 min
				• CorTemp®		
	Dress up	-	Put off suit A, put on suit B	• CorTemp®		
	Acclimatization	-	Passive sitting and drinking water	• Cosinuss°	-	10 min
				• CorTemp®		
	Measurement	Performance of job simulation	Periodic Preventive Medical Examination	• Cosinuss°	Continuously during task	15 min
				• CorTemp®		
	Cool down	-	Passive sitting and drinking water	• Cosinuss°	-	10 min
				• CorTemp®		
	Measurement	Performance of job simulation	Fire-extinguishing task	• Cosinuss°	Continuously during task	15 min
				• CorTemp®		
	Cool down	-	Passive sitting and drinking water	• Cosinuss°	-	10 min
				• CorTemp®		
3	Measurement	Concurrent validity	Rest (passive sitting)	• Cosinuss°	Once per minute	5 min
				• CorTemp®		
				• Inner-ear		

was used, including the T_c recorded with the Cosinuss[°], CorTemp[®] and inner-ear thermometer. To test the validity and reliability of the Cosinuss[°] during work (aim 2), of stage 2 the mean T_c per task and of both tasks recorded with the Cosinuss and CorTemp[®] was used. To compare the development of T_c while working in two types of protective clothing (aim 3), per subject two datasets were generated, one in suit A and one in suit B. Of stage 2 the mean T_c , T_{cli} and RH per task and of both tasks per suit was used. Sensitivity analysis was performed to test differences between the fourth and fifth measurement (stage 1 and 3) and the mean of all measurements (all stages), in addition to being performed on only complete datasets (all stages). These sensitivity analyses were performed to verify if the fourth measurement and incomplete datasets are representative.

Parametric data were analyzed using the paired *t*-test and by calculating the intraclass correlation coefficient (ICC, two-way random model). Non-parametric data were analyzed with the Wilcoxon signed rank test. The results are shown with mean or the mean difference (MD) and standard deviation (SD) (mean \pm SD). P-values ≤ 0.05 were considered statistically significant. The interpretation of the ICC: ICC < 0.39 is poor, $0.40 > \text{ICC} > 0.59$ is moderate, $0.60 > \text{ICC} > 0.79$ is good and ICC ≥ 0.80 is excellent (Cicchetti, 1994). The Limits of Agreement (LoA), calculated as $\pm 1.96 \times \text{SD difference}$, has an acceptable level of LoA ≤ 0.50 (Bland and Altman, 1999). To illustrate if the magnitude of the difference was related to the mean performance, Bland-Altman plots were made (Bland and Altman, 1999). The individual difference were plotted against the individual mean of the stages (Bland and Altman, 1999).

3. Results

Eleven firefighters (10 male and one female) with a mean age of 40.1 ± 8.0 years participated in this study. One subject was not able to perform the study in the suit A and due to an error not all data of the Cosinuss[°] and ambient condition box datasets were stored. The usability and sample size of the incomplete datasets varies per aim. Per aim, table and figure the sample size is mentioned. Statistical analysis was performed on as well all available data and only complete datasets.

3.1. In-vivo validity and reliability in rest

During the concurrent validation measurements (stage 1 and 3) ($n = 11$), the mean T_c recorded with Cosinuss[°] was $36.0 \pm 0.8^\circ\text{C}$ with a mean SD within subjects of $0.1 \pm 0.1^\circ\text{C}$. The mean T_c recorded with CorTemp[®] was $37.5 \pm 0.4^\circ\text{C}$ with a mean SD within subjects of $0.1 \pm 0.2^\circ\text{C}$. The mean of T_c recorded with the inner-ear IR was $36.6 \pm 0.4^\circ\text{C}$ with a mean SD within subjects of $0.1 \pm 0.1^\circ\text{C}$. Individual correction (in stage 1) based on the CorTemp[®] resulted in an average correction factor of $1.5 \pm 0.7^\circ\text{C}$ and based on the inner-ear IR of $0.6 \pm 0.6^\circ\text{C}$. In Table 2 the MD of the T_c recorded with the Cosinuss[°] and compared to CorTemp[®] and inner-ear IR are shown.

In stage 1, significant acceptable differences were found between the Cosinuss[°] corrected and compared to CorTemp[®] (MD = 0.1 ± 0.1 , CI

[0.04; 0.18], $p = 0.006$) and the Cosinuss[°] corrected and compared to inner-ear IR (MD = 0.2 ± 0.2 , CI [0.11; 0.32], $p = 0.001$). The other combinations showed significantly high differences between the Cosinuss[°] and CorTemp[®]. In stage 3, significantly high differences were found in T_c recorded with the Cosinuss[°] and CorTemp[®] (MD ≥ -0.8 , $p \leq 0.013$). The Cosinuss[°] corrected and compared to CorTemp[®] showed an acceptable, but non-significant mean difference with a high SD (MD = 0.0 ± 1.0 , CI [-0.67; 0.65], $p = 0.976$). In Table 3 is shown the ICC for Cosinuss[°], CorTemp[®] and inner-ear IR.

In stage 1 and 3, without individual correction of the Cosinuss[°] no correlation between the Cosinuss[°] and CorTemp[®] was observed and a moderate correlation was observed between Cosinuss[°] and inner-ear with an unacceptably high LoA (ICC = 0.40, $p = 0.044$, LoA = ± 1.20). The Cosinuss[°] corrected with the CorTemp[®] (stage 1) resulted in an excellent correlation with an acceptable LoA compared to the CorTemp[®] (ICC = 0.94, $p = 0.000$, LoA = ± 0.20) and a poor correlation compared to the inner-ear IR (ICC = 0.19, $p = 0.007$, LoA = ± 0.68). The Cosinuss[°] corrected with the inner-ear IR resulted in a poor correlation compared to the CorTemp[®] (ICC = 0.30, $p = 0.005$, LoA = ± 0.61) and an excellent correlation with an acceptable LoA compared to the inner-ear IR (ICC = 0.84, $p = 0.000$, LoA = ± 0.30). No correlation or a poor correlation was found between the CorTemp[®] and inner-ear IR thermometer (ICC ≤ 0.24). In Fig. 2, the Bland-Altman plots before working (stage 1) are shown.

After working (stage 3), all correlations between the Cosinuss[°], CorTemp[®] and inner-ear IR were lowered to non-significant and poor with unacceptable LoA (ICC ≤ 0.38 , $p \geq 0.091$, LoA ≥ 1.71). In Fig. 3, the Bland-Altman plots after working (stage 3) are shown. Sensitivity analysis revealed similar results.

3.2. In-vivo validity and reliability during realistic firefighting simulation tasks

During the two realistic firefighting simulation tasks (stage 2) in both suits, the mean T_c recorded with Cosinuss[°] was $36.1 \pm 1.1^\circ\text{C}$ ($n = 17$). The mean T_c recorded with CorTemp[®] was $37.6 \pm 0.5^\circ\text{C}$. In Table 4 the MD of the T_c recorded with the Cosinuss[°] and compared to CorTemp[®] are shown.

In stage 2, the T_c recorded with the non-corrected Cosinuss[°] differs significantly compared to the CorTemp[®] (MD ≥ -0.7 , $p \leq 0.002$). The Cosinuss[°] corrected and compared to the CorTemp[®] showed an acceptable, but non-significant difference (MD ≤ 0.2 , $p \geq 0.534$). In Table 5 is shown the ICC for Cosinuss[°] and CorTemp[®].

During the realistic firefighting simulation tasks in stage 2, no correlations between the Cosinuss[°] and the CorTemp[®] were proven (ICC ≤ 0.26 , $p \geq 0.253$) with unacceptable high LoA's (LoA ≥ 2.20). Sensitivity analysis revealed similar results. In Fig. 4, the Bland-Altman plots during the both realistic firefighting simulation tasks are shown.

3.3. Comparison of the change in core temperature

During the two during realistic firefighting simulation tasks, every

Table 2

Mean difference (MD) in core temperature (T_c) ($^\circ\text{C}$) measurements in both suits ($n = 11$) of Cosinuss[°] C-med versus reference thermometers; CorTemp[®] and inner-ear infrared (IR).

	Thermometer	Stage 1 (before working)			Stage 3 (after working)		
		MD \pm SD	[CI]	p	MD \pm SD	[CI]	p
Non-corrected	Cosinuss [°] vs CorTemp [®]	-0.4 ± 0.7	[-1.84; -0.90]	0.000	-1.5 ± 1.2	[-2.28; -0.70]	0.002
	Cosinuss [°] vs IR	-0.5 ± 0.6	[-0.89; -0.07]	0.026	-0.3 ± 1.0	[-0.97; 0.30]	0.265
Corrected with CorTemp [®]	Cosinuss [°] vs CorTemp [®]	0.1 ± 0.1	[0.04; 0.18]	0.006	0.0 ± 1.0	[-0.67; 0.65]	0.976
	Cosinuss [°] vs IR	1.0 ± 0.4	[-0.88; 0.46]	0.000	1.2 ± 1.0	[0.42; 1.87]	0.006
Corrected with IR	Cosinuss [°] vs CorTemp [®]	-0.7 ± 0.3	[-0.88; -0.46]	0.000	-0.8 ± 0.9	[-1.38; -0.20]	0.013
	Cosinuss [°] vs IR	0.2 ± 0.2	[0.11; 0.32]	0.001	-0.4 ± 1.0	[-0.28; 1.00]	0.233
Non-corrected	CorTemp [®] vs IR	0.9 ± 0.3	[0.67; 1.12]	0.000	1.2 ± 0.9	[0.53; 1.78]	0.002

Table 3

Intraclass correlations (ICC) and Limits of Agreement (LoA) of T_c measurements in both suits ($n = 11$) of Cosinuss[®] C-med versus reference thermometers; CorTemp[®] and inner-ear infrared (IR).

	Thermometer	Stage 1 (before working)			Stage 3 (after working)		
		ICC [95% CI]	p	LoA	ICC [95% CI]	p	LoA
Non-corrected	Cosinuss [®] vs CorTemp [®]	0.09 [-0.08; 0.43]	0.154	± 1.37	0.01 [-0.16; 0.37]	0.464	± 3.29
	Cosinuss [®] vs IR	0.40 [-0.10; 0.78]	0.044	± 1.20	0.27 [-0.32; 0.73]	0.193	± 1.85
Corrected with CorTemp [®]	Cosinuss [®] vs CorTemp [®]	0.94 [0.45; 0.99]	0.000	± 0.20	0.38 [-0.32; 0.79]	0.130	± 1.93
	Cosinuss [®] vs IR	0.19 [-0.05; 0.61]	0.007	± 0.68	0.05 [-0.19; 0.46]	0.374	± 2.12
Corrected with IR	Cosinuss [®] vs CorTemp [®]	0.30 [-0.08; 0.73]	0.005	± 0.61	0.29 [-0.15; 0.71]	0.091	± 1.71
	Cosinuss [®] vs IR	0.84 [0.00; 0.70]	0.000	± 0.30	0.18 [-0.39; 0.68]	0.280	± 1.86
Non-corrected	CorTemp [®] vs IR	0.24 [-0.06; 0.68]	0.004	± 0.66	0.01 [-0.17; 0.37]	0.474	± 1.82



Fig. 1. Left: Suit A, traditional turnout gear of Bristol Uniforms containing a trouser with jacket; Right: Suit B, a new protective clothing concept of Safety Masters containing a coverall combined with a separate outer jacket.

subject showed a different pattern in the change in T_c , T_{cli} and RH. The mean change in T_c in both suits recorded with the Cosinuss[®] was 0.06 ± 0.14 °C/minute and the mean change in T_c recorded the CorTemp[®] was 0.02 ± 0.10 °C/minutes. The mean T_{cli} in both suits increased with 0.4 ± 0.4 °C/minute with a mean T_{cli} of 29.7 ± 2.1 °C and the RH increased with $1.6 \pm 3.2\%$ /minute with a mean RH of $68.4 \pm 10.8\%$. In Table 6 the mean T_c recorded with the Cosinuss[®] and CorTemp[®] and T_{cli} and RH per task per suit are shown.

The maximum T_c recorded with the Cosinuss[®] was 40.1 °C and with the CorTemp[®] 38.4 °C (both during the fire-extinguishing task). However, on average the maximum T_c recorded with the Cosinuss[®] is significant lower compared to the CorTemp[®] during both tasks (during PPMO MD = 1.1 ± 1.2 , CI [0.45; 1.68], $p = 0.002$, during the fire-extinguishing task MD = 1.1 ± 1.1 , CI [0.51; 1.73], $p = 0.001$). In Table 7 the MD and ICC of the T_c recorded with the Cosinuss[®] CorTemp[®], T_{cli} and RH in both suits between the Periodic Preventive Medical Examination (PPMO) and hot fire-extinguishing task are shown.

During the fire-extinguishing task (stage 2), T_c recorded with the CorTemp[®] was significantly higher compared to the PPMO (MD = 0.4 ± 0.4 °C, CI [0.19; 0.56], $p = 0.000$), as well as T_{cli} (MD = 3.3 ± 1.2 °C, CI [2.66; 3.94], $p = 0.000$) and RH (MD = $12.0 \pm 13.7\%$, CI [4.39; 19.59], $p = 0.004$). T_c recorded with the Cosinuss[®] did not differ significantly ($p = 0.285$) and an excellent correlation between the PPMO and fire-extinguishing tasks was found (ICC = 0.88, CI [0.66; 0.96], $p = 0.000$). However, it increased significantly faster during the hot task compared to the PPMO (MD = 0.11 ± 0.18 °C/minute, CI [0.01; 0.21], $p = 0.033$). The T_{cli} also increased more rapidly during the hot task, but this was non-significant (MD = 0.27 ± 0.54 °C/min, CI [-0.03; 0.57], $p = 0.077$). In Table 8 the MD of the T_c recorded with the Cosinuss[®] or CorTemp[®], T_{cli} and RH per task of suit A compared to suit B are shown.

The T_{cli} in suit B was significant higher compared to suit A (during PPMO MD = 1.9 ± 1.5 °C, CI [0.47; 3.27], $p = 0.017$, during the hot task MD = 2.6 ± 2.5 °C, CI [0.00; 5.16], $p = 0.050$) and during the PPMO no

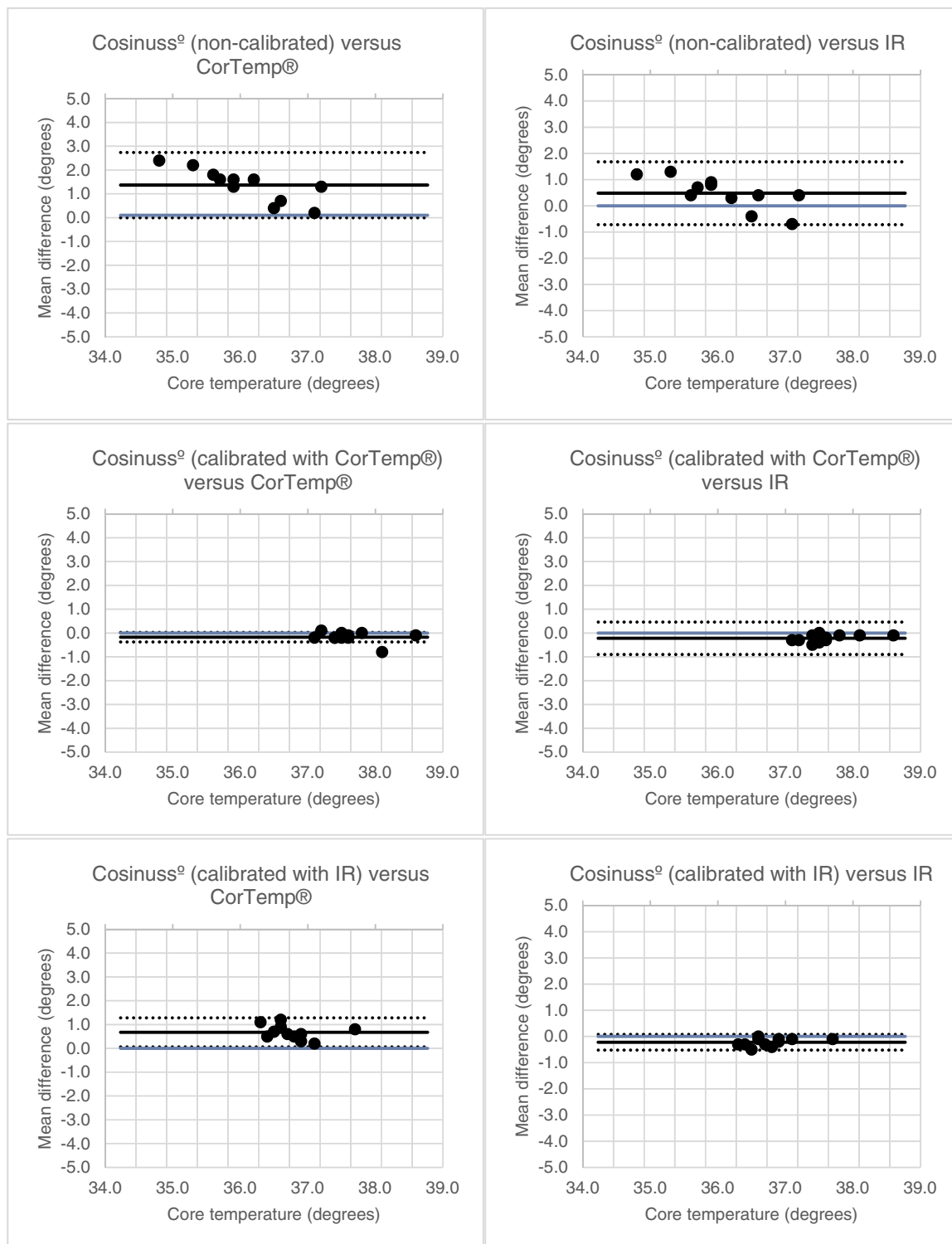


Fig. 2. Bland-Altman plots of the mean core temperature versus the mean temperature difference before working (stage 1) in both suits between the non-corrected and corrected Cosinuss° compared to the CorTemp® and inner-ear IR with mean (black line) and upper and lower Limit of Agreement (LoA) (black dotted line) and zero-line (blue line), $n = 11$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

correlation was found between the T_{cli} of suit A and B ($ICC = 0.74$, $CI [0.06; 0.96]$, $p = 0.017$, $n = 8$). No other significant differences were found between suit A and B with a good to excellent correlation between the T_c recorded with Cosinuss° ($ICC \geq 0.74$, $p \leq 0.017$, $n = 7$). Additionally, no significant difference in the T_c , T_{cli} and RH change between the suits during the tasks was found ($p \geq 0.308$). Sensitivity analysis revealed similar results.

4. Discussion

The T_c of the non-corrected Cosinuss° showed no correlations with the CorTemp® and a poor to moderate correlation with inner-ear IR thermometry, indicating the impact of individual correction. Individual correction resulted in excellent correlations. However it should be noted that this depends on the calibration method and it is unknown if

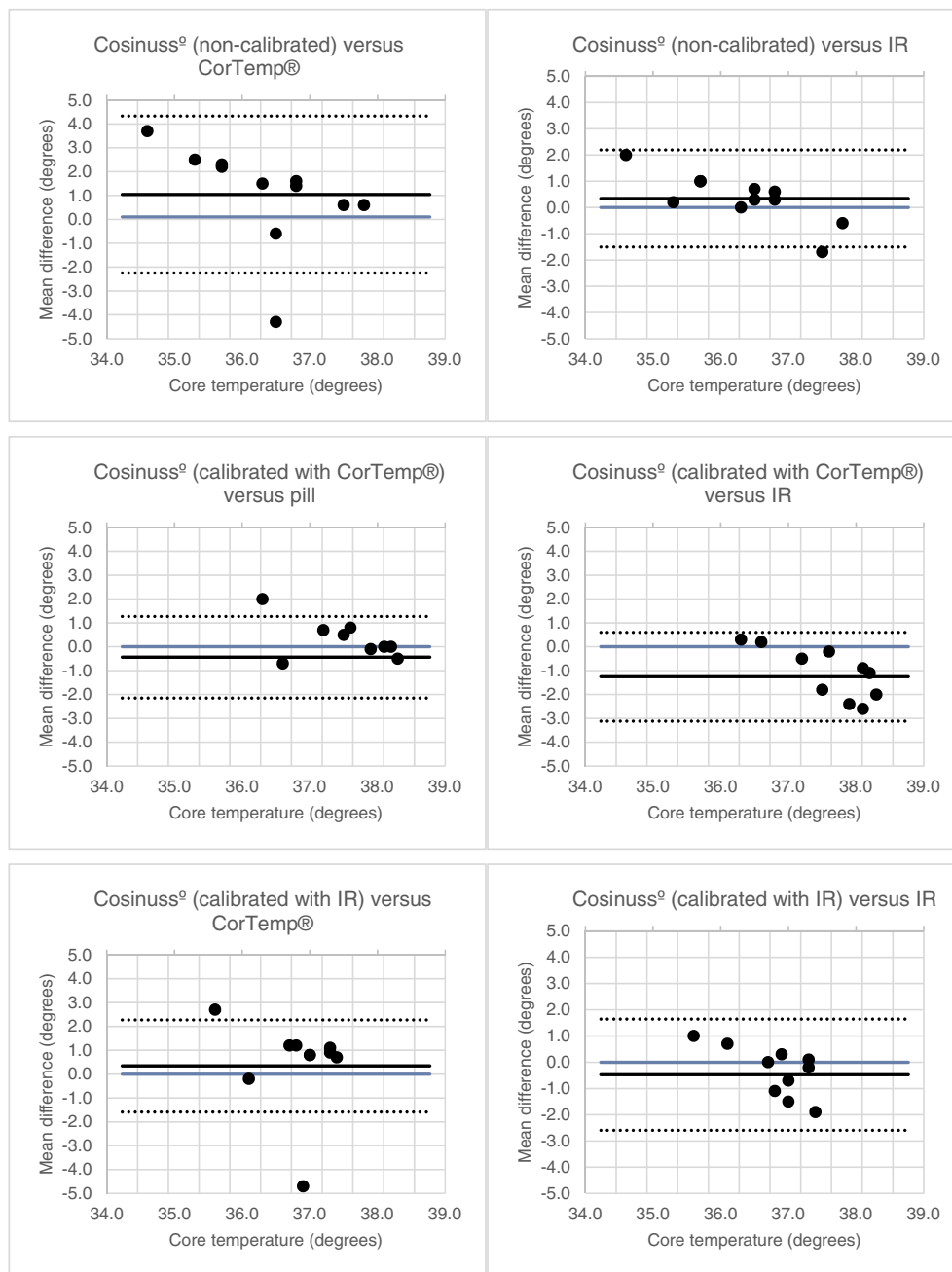


Fig. 3. Bland-Altman plots of the mean core temperature versus the mean temperature difference after working (stage 3) in both suits between the non-corrected and corrected Cosinuss° compared to the CorTemp® and inner-ear IR with mean (black line) and upper and lower Limit of Agreement (LoA) (black dotted line) and zero-line (blue line), $n = 11$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 4

Mean difference (MD) in core temperature (T_c) ($^{\circ}\text{C}$) measurements in both suits ($n = 17$) of Cosinuss° C-med versus reference thermometers; CorTemp® and inner-ear infrared (IR).

	Thermometer	Task	Stage 2 (during working)		
			MD \pm SD	[CI]	p
Non-corrected	Cosinuss° vs CorTemp®	Both	-1.4 ± 1.5	$[-2.09; -0.60]$	0.002
		PPMO	-1.4 ± 1.3	$[-2.07; -0.64]$	0.001
		Fire-extinguishing	-1.5 ± 1.2	$[-2.20; -0.90]$	0.000
Corrected with CorTemp®	Cosinuss° vs CorTemp®	Both	0.2 ± 1.5	$[-0.55; 1.02]$	0.534
		PPMO	0.2 ± 1.3	$[-0.51; 0.91]$	0.559
		Fire-extinguishing	0.0 ± 1.2	$[-0.62; 0.67]$	0.931
Corrected with IR	Cosinuss° vs CorTemp®	Both	-0.5 ± 1.4	$[-1.26; 0.18]$	0.129
		PPMO	-0.5 ± 1.3	$[-1.22; 0.13]$	0.108
		Fire-extinguishing	-0.7 ± 1.2	$[-1.36; -0.02]$	0.045

Table 5

Intraclass correlations (ICC) and Limits of Agreement (LoA) of T_c measurements of Cosinuss° C-med versus reference thermometer; CorTemp®, in both suits.

	n	Task	Stage 2 (firefighting simulation tasks)		
			ICC [95% CI]	p	LoA
Non-corrected	17	Both	0.08 [-0.30; 0.49]	0.362	±2.22
	16	PPMO	0.06 [-0.44; 0.53]	0.409	±2.63
	15	Fire-extinguishing	0.00 [-0.32; 0.41]	0.512	±2.21
Corrected with CorTemp®	17	Both	0.24 [-1.34; 0.74]	0.310	±2.24
	16	PPMO	0.18 [-1.51; 0.72]	0.361	±2.62
	15	Fire-extinguishing	0.09 [-2.10; 0.71]	0.434	±2.29
Corrected with IR	17	Both	0.26 [-0.67; 0.71]	0.253	±2.20
	16	PPMO	0.22 [-0.90; 0.71]	0.302	±2.49
	15	Fire-extinguishing	0.05 [-1.02; 0.63]	0.451	±2.37

individual calibration using the CorTemp® performed once is valid over longer periods of time. Moreover, no correlation was found between the CorTemp® and inner-ear IR and no correlation or a poor correlation was found between the CorTemp® and Cosinuss° during the two tasks, indicating a difference due to the measurement method and location (Towey et al., 2017) (Taylor et al., 2014). The measured change in T_c by the Cosinuss°, as well as by inner-ear IR, is expected to be the local

temperature and/or caused by a preliminary or side effect (Levander and Grodzinsky, 2017) (Kuht and Farmery, 2014). Therefore calibration should be done using at least an invasive reference, such as CorTemp®, however calibration with a controlled thermostat bath at different temperatures is preferred. The correlations were poor after performance of the tasks. This is probably caused by a secondary human-device interaction factor, e.g., a shift of the sensor in the ear caused by movement. Overall, the Cosinuss° is an invalid method for measuring core temperature of firefighters during the performance of their job. The influence of the consumption of hot and cold food and drinks was noted by the research and clearly visible in the results of the CorTemp® (Collin et al., 2015).

The strength of this study is that validation of the T_c measurements was performed using the invasive (Mazgoaker et al., 2017) (Langridge et al., 2012) (Gonzalez-Alonso et al., 1999) as well as the inner-ear clinical standard (Moran-Nabarro et al., 2018) (Nederlands Huisartsen Genootschap, 2016) (Itani et al., 2018) (Ouahrani et al., 2017) (Nadipi Reddy et al., 2017). Furthermore this applied research was performed in a field situation with realistic firefighting tasks which are used to train and test firefighters (Havenith and Heus, 2004). Also, in addition to insight in the validity of the wearable thermometer, research was performed on two different types of protective suits and the difference in the development of heat stress between tasks was assessed. The main limitation was the duration of the tasks. The schedule was planned 30 min per task, but participants only took approximately 10 up to 15 min per task. This time span will result in only limited heating up of the body and less useful results. Especially in the case of exploring differences in heat development in the two types of protective clothing 10 min was not long enough to gain realistic insights and draw conclusions which are representing real-life firefighting tasks in protective

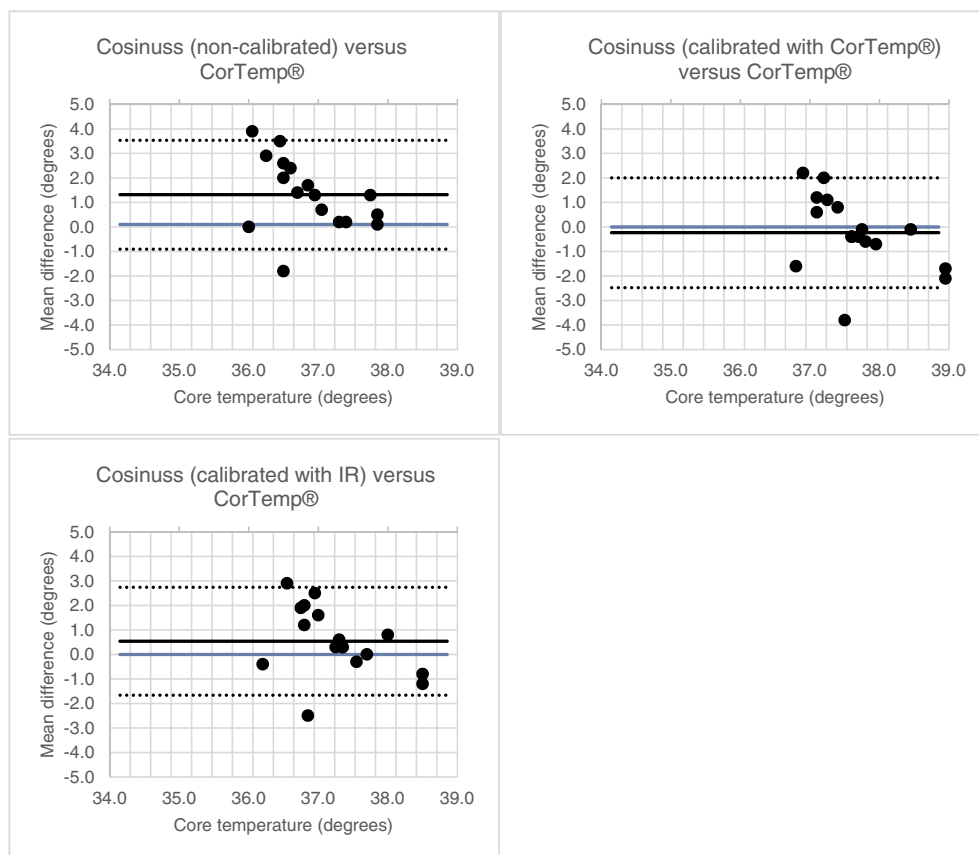


Fig. 4. Bland-Altman plots of the mean core temperature versus the mean temperature difference during both firefighting simulation tasks (stage 2) in both suits between the non-corrected and corrected Cosinuss° compared to the CorTemp® with mean (black line) and upper and lower Limit of Agreement (LoA) (black dotted line) and zero-line (blue line), $n = 17$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 6

Mean and maximum core temperature (T_c) (°C) recorded with the CorTemp® and (non-corrected) Cosinuss°, temperature inside de clothing (T_{cli}) (°C) and humidity (RH) (%) per (Periodic Preventive Medical Examination (PPMO) and hot fire-extinguishing task per suit A and B.

	PPMO			Fire-extinguishing task		
	n	Suit A	Suit B	n	Suit A	Suit B
Mean T_c CorTemp® (°C)	10	37.4 ± 0.4	37.3 ± 0.7	10	37.8 ± 0.3	37.7 ± 0.5
Mean T_c Cosinuss° (°C)	7	36.4 ± 1.6	37.0 ± 0.9	6	37.7 ± 1.4	37.9 ± 1.0
Mean T_{cli} (°C)	8	26.4 ± 1.9	29.0 ± 2.2	7	29.1 ± 3.3	32.5 ± 2.3
Mean RH (%)	8	59.9 ± 14.6	68.7 ± 12.1	7	72.1 ± 17.3	80.2 ± 11.9
Max T_c CorTemp® (°C)	10	38.1 ± 0.5	38.4 ± 0.6	10	38.3 ± 0.4	38.4 ± 0.4
Max T_c Cosinuss° (°C)	7	38.8 ± 1.5	38.9 ± 1.0	6	40.1 ± 1.2	39.8 ± 1.0
Max T_{cli} (°C)	8	39.3 ± 4.3	32.1 ± 2.9	7	33.0 ± 4.3	35.5 ± 3.2
Max RH (%)	8	84.9 ± 20.2	82.3 ± 15.6	7	92.9 ± 15.7	91.4 ± 15.3

Table 7

Mean difference in core temperature (T_c) (°C) recorded with the (non-corrected) Cosinuss° and the CorTemp®, temperature inside the clothing (T_{cli}) (°C), humidity (RH) and their change (Δ) between the Periodic Preventive Medical Examination (PPMO) and hot fire-extinguishing task in both suits.

	n	MD±SD	CI	p
Mean T_c CorTemp® (°C)	21	0.4 ± 0.4	[0.19; 0.56]	0.000
Mean T_c Cosinuss° (°C)	16	0.2 ± 0.8	[-0.21; 0.67]	0.285
Mean T_{cli} (°C)	16	3.3 ± 1.2	[2.66; 3.94]	0.000
Mean RH (%)	16	12.0 ± 13.7	[4.39; 19.59]	0.004
ΔT_c CorTemp® (°C/minute)	21	0.00 ± 0.12	[-0.52; 0.06]	0.900
ΔT_c Cosinuss° (°C/minute)	16	0.11 ± 0.18	[0.01; 0.21]	0.033
ΔT_{cli} (°C/minute)	16	0.27 ± 0.54	[-0.03; 0.57]	0.349
ΔRH (%/minute)	16	1.22 ± 4.89	[-1.49; 3.93]	0.077

Table 8

Mean difference in core temperature (T_c) (°C) recorded with the (non-corrected) Cosinuss° and the CorTemp®, temperature inside the clothing (T_{cli}) (°C), humidity (RH) and their change (Δ) per (Periodic Preventive Medical Examination (PPMO) and hot fire-extinguishing task between suit A and B.

Task		n	MD±SD	CI
PPMO	T_c CorTemp® (°C)	10	-0.3 ± 0.8	[-0.87; 0.33]
	T_c Cosinuss° (°C)	7	0.6 ± 0.9	[-0.28; 1.55]
	T_{cli} (°C)	8	1.9 ± 1.5	[0.47; 3.27]
	RH (%)	8	4.1 ± 15.8	[-10.6; 18.69]
	ΔT_c CorTemp® (°C/minute)	10	0.01 ± 0.17	[-0.11; 0.05]
	ΔT_c Cosinuss° (°C/minute)	7	-0.04 ± 0.09	[-0.14; 0.05]
	ΔT_{cli} (°C/minute)	8	0.63 ± 4.51	[-4.11; 5.37]
	ΔRH (%/minute)	8	-0.02 ± 0.48	[-0.52; 0.48]
	T_c CorTemp® (°C)	10	-0.1 ± 0.5	[-0.53; 0.31]
	T_c Cosinuss° (°C)	6	0.1 ± 0.4	[-0.43; 0.63]
Fire-extinguishing	T_{cli} (°C)	7	2.6 ± 2.5	[0.00; 5.16]
	RH (%)	7	6.5 ± 18.6	[-13.06; 26.06]
	ΔT_c CorTemp® (°C/minute)	10	0.00 ± 0.04	[-0.03; 0.03]
	ΔT_c Cosinuss° (°C/minute)	6	0.02 ± 0.06	[-0.06; 0.09]
	ΔT_{cli} (°C/minute)	7	0.20 ± 4.04	[-4.81; 5.21]
	ΔRH (%/minute)	7	-0.13 ± 0.44	[-0.68; 0.41]

clothing. Besides, it would have been interested to also include suit B without the jacket (only coverall with protection level 1) to explore the change in T_c , T_{cli} and RH during the PPMO task and to falsify is this new protective clothing concept is lowering the heat stress development during no firefighting activities. In addition, some datasets were incomplete. This resulted in a lower amount of data which could result in the risk over overestimating the results. In this case it was not a selective drop-out which significantly could have influence the data. Moreover, according to a power analysis and the two measurements (suits A and B) per subject, enough data was gathered for analysis

resulting in no need to replace these missing data. Besides, the failures of the systems provided useful input about the usability and weaknesses of the systems. Another limitation could be the difference in measurement frequency between the thermometers, although not much influence is expected since the temperature rise is only gradually.

To be able to apply the Cosinuss°, the system should be valid and reliable. The urge for individual calibration should be investigated, as well as using the Cosinuss° in a multivariable system to increase the accuracy of the T_c prediction. In addition, to improve the low correlation during and after performance of the tasks (stage 2 and 3), movements of the Cosinuss° should be limited. Further research should study the change in T_c over longer periods of time and with more participants. Furthermore, improvements are necessary to fix the device more stable in the ear. Without movement of the sensor relative to the ear its performance might be much improved. And the integration of the ear part with the ambient condition box would possibly improve the usability of this system. By eliminating the chest box, which was not experienced as very comfortable, a multivariable single-instrument system could be created. Above all, to make this system useable and safe in use for firefighters during their work, the system needs to be made heat- and fire-resistant. Currently the Cosinuss° is made of a thermoplastic with silicone developed to be used in ambient temperatures of -15 to 55 °C (Cosinuss°, 2016), which can cause burns during long-term use in heat exposure nor is fulfilling the safety standards.

If the reliability of the Cosinuss° can be improved, as part of a multivariable system (Richmond et al., 2015) the Cosinuss° could play a role in predicting T_c and heat storage. However, a reliable single-instrument system is preferred. A wearable thermometer could overcome the disadvantages of the temperature pill if it is an accurate, valid and reliable measurement system that does not underestimate the T_c . A wearable thermometer is non-invasive, useable for all body proportions, reusable with low costs and not influenced by food and liquid intake (Mazgoaker et al., 2017) (Saurabh et al., 2014) (Taylor et al., 2014) (Lim et al., 2008). In addition, it is immediately useable without a waiting time (Collin et al., 2015). Wearable non-invasive thermometers are of interest in multiple fields for (health) monitoring purposes (Chaglla et al., 2018) (Mazgoaker et al., 2017) (Li et al., 2019) (Diaz-Piedra et al., 2019) (Steck et al., 2011). Next to firefighters, other physical active workers are at risk of work-related overheating and are interested in such a device (Pancardo et al., 2015), including astronauts who want to launch wearables into space to monitor their health during their stay (Jones, 2006). However, the Cosinuss° in its present form is not suitable for this.

5. Conclusion

The validity of the Cosinuss° C-med was not confirmed in this study. Without individual correction, the Cosinuss° showed poor to moderate correlations resulting in an invalid, but reliable system. With individual correction, depending on the instruments used for field calibration in resting conditions an excellent correlation for measuring core temperature was found, resulting in a valid and reliable system. During and

after subject performance of the tasks, non-significant poor correlations were found. This is most likely caused by firstly the measurement location and secondly non-adequate fixation of the Cosinuss[°] causing a movement of the sensor relative to the ear. This indicates that Cosinuss[°] is an invalid method for measuring core temperature of firefighters during the performance of their job. The temperature inside the suit was significantly higher in the new protective clothing concept compared to the traditional turnout gear. No significant differences were found in the change in core temperature, temperature and humidity inside the suit.

Funding

This work, part of SPRINT@Work, was supported by the European Regional Development Fund, the province and municipality of Groningen, and the province of Drenthe [grant number T-3036, 2013]. Cosinuss[°] has supplied 6 Cosinuss[°] C-med during this study.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank 'Veiligheidsregio Groningen', in specific Bert Hindriks and Arie Smedinga, for the opportunity to perform this study and their infinite support. We appreciate the contribute of Negotica (Groningen, The Netherlands) during the development of the CORTES^{2/3}, and Pro-Care (Groningen, The Netherlands) for their effort with the temperature pills.

References

- HQ Inc, 2006. CorTrack II Software - User Manual Rev 2.3 A. HQ Inc, Palmetto, Florida, USA.
- Barr, D., Gregson, W., Reilly, T., 2010. The thermal ergonomics of firefighting reviewed. *Appl. Ergon.* 41, 161–172.
- Bland, J., Altman, D., 1999. Measuring agreement in method comparison studies. *Stat. Methods Med. Res.* 8 (2), 135–160.
- Chaglla, J., Celik, N., Balanchandran, W., 2018. Measurement of core body temperature using graphene inked infrared thermopile sensor. *Sensors* 18 (10), 3315.
- Chang, C., Bernard, T., Logan, J., 2017. Effects of heat stress on risk perceptions and risk taking. *Appl. Ergon.* 62, 150–157.
- Cicchetti, D., 1994. Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instruments in psychology. *Psychol. Assess.* 284–290.
- Collin, A., et al., 2015. Study on visible-IR radiative properties of personal protective clothings for firefighting. *Fire Saf. J.* 71, 9–19.
- Cosinuss[°], 2016. Technisches Datenblatt Cosinuss[°] One. Cosinuss GmbH, Munchen, Germany.
- Costello, J., Stewart, K., Stewart, I., 2015. The effects of metabolic work rate and ambient environment on physiological tolerance times while wearing explosive and chemical personal protective equipment. *BioMed Res. Int.* 2015, 1–7.
- Cvirm, M., et al., 2019. The effects of hydration on cognitive performance during a simulated wildfire suppression shift in temperate and hot conditions. *Appl. Ergon.* 77, 9–15.
- Diaz-Piedra, C., Gomez-Milan, E., Di Stasi, L., 2019. Nasal skin temperature reveals changes in arousal levels due to time on task: an experimental thermal infrared imaging study. *Appl. Ergon.* 81, 102870.
- Epstein, Y., Moran, D., 2006. Thermal effects on the Heat Stress Indices. *Ind. Health* 2006, 388–398.
- Garcia-Souto, M., Dabnichki, P., 2016. Core and local skin temperature: 3e24 months old toddlers and comparison to adults. *Build. Environ.* 104, 286–295.
- Braun GmbH, n.d. ThermoScan[®] 7 met age Precision[®] - IRT6520-user manual. [Online] Available at: www.brauntherms.com/nl/producten/thermoscan-7-oor-thermometer-irt6520/ [Accessed 30 April 2017].
- Gonzalez-Alonso, J., et al., 1999. Influence of body temperature on the development of fatigue during prolonged exercise in the heat. *Hyperther. Fatigue* 1032–1039.
- Havenith, G., Heus, R., 2004. A test battery related to ergonomics of protective clothing. *Appl. Ergon.* 35 (1), 3–20.
- HQ Inc, 2018. CorTemp Core Body Temperature Monitors by HQ Inc. - Specifications. HQ Inc, Palmetto, Florida, USA.
- HQInc, 2018. CorTemp Core Body Temperature Monitoring System - User Manual Rev 4.3.1. HQ Inc, Lametto, FL, USA.
- Itani, M., et al., 2018. An optimal two-bout strategy with phase change material cooling vests to improve comfort in hot environment. *J. Therm. Biol.* 72, 10–25.
- Jones, W., 2006. Taking body temperature, inside out [body temperature monitoring]. *IEEE Spectr.* 43 (1), 13–15.
- Kocoglu, H., et al., 2002. Infrared tympanic thermometer can accurately measure the body temperature in children in an emergency room setting. *Int. J. Pediatr. Otorhinolaryngol.* 65 (1), 39–43.
- Kuht, J., Farmery, A., 2014. Body temperature and its regulation. *Anaesth. Intensive Care Med.* 15 (6), 273–278.
- Langridge, P., et al., 2012. Assessing the validity of tympanic temperature to predict core temperature of firefighters in different environmental conditions. *Proc. Bushfire CRC AFAC 2012 Conf. Res. Forum* 150–159.
- Levander, M., Grodzinsky, E., 2017. Variation in normal ear temperature. *Am. J. Med. Sci.* 354 (4), 370–378.
- Levels, K., et al., 2014. The effect of pre-warming on performance during simulated. *Appl. Ergon.* 45, 1504–1509.
- Li, J., Ma, Q., Chan, A., Man, S., 2019. Health monitoring through wearable technologies for older adults: smart wearables acceptance model. *Appl. Ergon.* 75, 162–169.
- Lim, C., Byrne, C., Lee, J., 2008. Human thermoregulation and measurement of body temperature in exercise and clinical settings. *Thermoregulation Sport. Exerc* 37 (4), 347–353.
- Lotens, W.A., 1993. Heat Transfer from Humans Wearing Clothing. Soesterberg, the Netherlands: TNO – Institute for Perception.
- Masters, Safety, 2017. Safety Masters Fire Equipment, Helmond, the Netherlands: Safety Masters B.V.
- Mazgoaker, S., et al., 2017. Measuring core body temperature with a non-invasive sensor. *J. Therm. Biol.* 66, 17–20.
- McInnes, J., et al., 2017. Association between high ambient temperature and acute work-related injury: a case-crossover analysis using workers' compensation claims data. *Scand. J. Work Environ. Health* 43 (1), 86–94.
- McQuerry, M., Barker, R., Denhartog, E., 2018. Relationship between novel design modifications and heat stress relief in structural firefighters' protective clothing. *Appl. Ergon.* 70, 260–268.
- Moran-Nabarro, R., et al., 2018. Validity of skin, oral and tympanic temperatures during exercise in the heat: effects of wind and sweat. *Ann. Biomed. Eng.* 1–15.
- Nadipati Reddy, P., et al., 2017. Walking cadence affects rate of plantar foot temperature change but not final temperature in younger and older adults. *Gait Posture* 52, 272–279.
- Nederlands Huisartsen Genootschap, 2016. NHG-werkgroep Standaard Kinderen met koorts (derde herziening). Huisarts Wet. 11, 484–491.
- Nunneley, S., 1989. Heat stress in protective clothing: interactions among physical and physiological factors. *Scand. J. Work Environ. Health* 15 (Suppl. 1), 52–57.
- Ouahrani, D., et al., 2017. Experimental study on using PCMs of different melting temperatures in one cooling vest to reduce its weight and improve comfort. *Energy Build.* 155, 533–545.
- Pancardo, P., et al., 2015. Real-time personalized monitoring to estimate occupational heat stress in ambient assisted working. *Sensors* 15 (7), 16956–16980.
- Richmond, V., Davey, S., Griggs, K., Havenith, G., 2015. Prediction of core body temperature from multiple variables. *Ann. Occup. Hyg.* 59 (9), 1168–1178.
- Saurabh, K., Rao, H., Amrutur, B., Sundarajan, A., 2014. Continuous core body temperature estimation via surface temperature measurements using wearable sensors: is it feasible?. In: *Biodevices (Conference Paper)*, pp. 181–186.
- Savage, R., et al., 2014. Firefighter feedback during active cooling: a useful tool for heat stress management? *J. Therm. Biol.* 46, 65–71.
- Sensirion, 2010. Datasheet SHT1x (SHT10, SHT11, SHT15) - Humidity and Temperature Sensor. Sensirion AG, Staefa ZH, Switzerland.
- Steck, L., Sparrow, E., Abraham, J., 2011. Non-invasive measurement of the human core temperature. *Int. J. Heat Mass Transf.* 54, 975–982.
- Taylor, N., Tipton, M., Kenny, G., 2014. Considerations for the measurement of core, skin and mean body temperatures. *J. Therm. Biol.* 46, 72–101.
- Towey, C., Easton, C., Simpson, R., Pedlar, C., 2017. Conventional and novel body temperature measurement during rest and exercise induced hyperthermia. *J. Therm. Biol.* 63, 124–130.
- Uniforms, Bristol, 2007. Structural. Bristol Uniforms Ltd, Bristol, UK.
- Uth, M., Koch, J., Sattler, F., 2016. Body core temperature sensing: challenges and new sensor technologies. *Proc. Eng.* 168, 89–92.
- Yang, J., Weng, W., Wang, F., Song, G., 2017. Integrating a human thermoregulatory model with a clothing model. *Appl. Ergon.* 61, 168–177.
- Yazdi, M., Sheikhzadeh, M., 2014. Personal cooling garments: a review. *J. Text. Inst.* 105 (12), 1231–1250.