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The Zero Heat Flux Method and Sweat Loss Modeling in Sports: Attempts of Next Generation Sports Information Systems

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Abstract

Today professional and amateur endurance athletes commonly use biofeedback systems to monitor their training and competition pace. Body core temperature and sweat loss are crucial factors influencing physical capabilities. Unfortunately, current gold standards are invasive and therefore impractical in active situations. Several non-intrusive technologies or models have been proposed, but partially are still unsuitable for active applications, not user friendly or lack knowledge on physiological relations. This paper is a first attempt for new information systems in sports and primarily assesses the Zero Heat Flux Method (ZHF) compared to aural temperatures during activity in two environments and four body sites. Furthermore, sweat loss has been analysed in various controlled experiments presented as simple modelling approach. Results showed that during activity in this set up, optimally 66% of differences in the zero heat flux method were within common core temperature deviations of ±0.5°C. Deviations varied highly across sites, the two conditions and individuals. The same is reflected from relations between body core temperature and sweat loss, since correlation coefficients increase with a more detailed subgrouping. In conclusion, it seems that slight modifications on the sensor assembly e.g. on insulation and size could partially solve remaining deviations. On contrast it´s likely that skin wetness remains a problem. Due to manifold individual and environmental influences on sweat rate, insufficient technologies and impracticable models, it remains unclear how sweat loss could be reliably measured or predicted. From today’s knowledge a further attempt could be using local sweat composition as predictor of blood sodium levels that potentially could describe hypo- and even hyper-hydration.

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Keywords: Monitoring; Thermal Stress; Human Modeling

1. Introduction

In the last decades, wearables technologies, such as smart phones, smart watches, wrist bands or the like intensively progressed and provided people with numerous functionalities making daily life more comfortable [1]. Especially in sports, e.g. monitoring heart rate has provided a useful tool structuring training or controlling competition pace for a long time. Scientifically, the value of this single parameter, concerning an athletes physical state, is clearly debatable. Common sense is,

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much more variables are necessary to assess this holistically. During physical activity body core temperatures and sweat loss are of immanent relevance to endure physical performance. In both cases, any deviation from homeostasis causes the human body to compensate via physiological mechanisms; but this within small borders. Although, core temperatures of 41°C have been observed in endurance runners, “fatigue generally coincides with core temperatures between 38 and 40°C and modest fluid losses of 2% body mass” [2]. Some literature [3, 4] has shown that humans lack the ability accurately identifying critical situations in time. Therefore, real time monitoring could provide the opportunity to react preventively if impairments of physical performance are likely. Current gold standards assessing core temperature or sweat loss [5, 6] are invasive and/or impractical in active situations. Several non-intrusive technologies [7, 8] or models [9-13] have been proposed, but partially are still unsuitable for active applications, not user friendly, lack knowledge on physiological relations or are not available.

On contrast the zero heat flux method, first described in the 70´s [14], has been patented [15] and i.a. commercially been sold by 3M as SpotON™; but primarily for clinical use. Its principle is to create a perfect insulation on human skin so that an isothermal tunnel from the inside is developed to measure core temperature superficially. Teunissen et al. (2011) described good agreement for measurements at the forehead in warm conditions. Other localizations and conditions will be assessed in this paper.

Concerning sweat loss, a review by Taylor and Machado-Moreira (2013) [16] described highly individual, but well established relations between core temperatures and sweat rate to “indeed arrive such approximations” of sweat loss. In their paper they only referred to a study for six, fully hydrated, and unacclimated females. More subgroups will be described in this paper.

Therefore, the rational of the studies was to explore the validity of the ZHF in active situations. Additionally, following Taylor and Machado-Moreira, results of various environmentally and individually controlled experiments concerning the relations between sweat loss and body temperatures are presented as simple modeling approach as basis for new monitoring systems.

2. Methodology

2.1. Sample & Data sets

Firstly, ten healthy and active male volunteers (Age: 24±3 years; Height: 184cm±9; Weight: 81.1 kg±10.7) participated in the study on ZHF. To control physiological influences (e.g. anthropometry, body composition) on thermoregulation according to Teunissen et al. (2011), a rather homogeneous sample was chosen.

Secondly, 143 data sets (41 variables), 59 subjects (Male: ~66%, Female: ~33%; Age: 24±3 years; Height: 177.2cm±8.6; Weight: 69.6kg±9.3) and more than 14 conditions were chosen to analyze the relations between body temperatures and sweat loss. A variety of individual and environmental data were collected (Table 1&2). Because all of the experiments took place in an environmental chamber radiation/globe temperature could be disregarded.

Table 1. Exemplary individual data.

Variable	Weight	Fat content	Fat free mass	Fitness level (VO2max, HFmax, Pmax)	Core temperature (rectal, aureal)	Duration
Unit	kg	%	kg	ml/kg/h; bpm; Watts, h/week	°C	min
Method	Scale	Caliper; Bioelectrical Impedance	Formula	Spirometry; Heart rate belt; Powermeter/Ergometer; Questionnaire	Thermistor; Thermo-element	Time watch
Range	52-93	6-33	39-83	39-53;185-196;199-325; 0-16	35.1-37.9	20-90

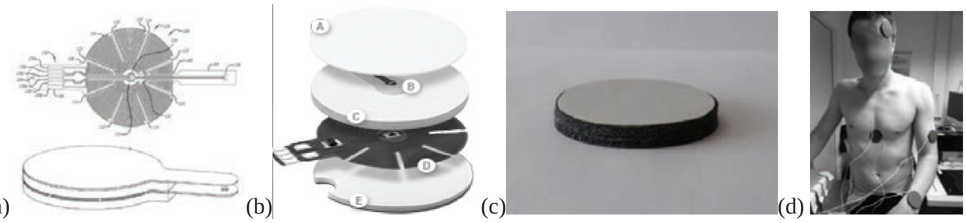
Variable	Activity/Intensity	Heart frequency	Clothing	Hydration status	Sweat loss
Unit	bpm; Watts	bpm	m²K/W; clo	mg/ml; none	g;ml; %
Method	Heart rate belt; Powermeter/Ergometer,	Heart rate belt	Norms	Refractometer; Colorscale	Balance; Patches
Range	110-153; 20-211	111-166	0.1-0.64	1.000-1.034;1-7	25-2355;.0-1.19

Table 2. Environmental data.

	Ambient temperature	Relative humidity	Wind speed	Globe temperature
Unit	°C	%	m/s	°C
Method	Thermistor, Thermoelement	Hygrometer	Anemometer	Globe thermometer
Range	10-29	40-78	0.1-4.2	-

2.2. Protocols

The ZHF experiments took place in two controlled environmental conditions (t_1=15°C; relative humidity= 50%; v_a= 0.1 m/s; t_2=25°C; relative humidity= 50%; v_a= 0.1 m/s). In both, subjects wore standardized clothing (shorts, 0.1 m²K/W) and were tested at ~60% of their individual threshold (Power: 146 Watts±34; relative Power: 1.81 Watts/kg±0.43) on an individually adjusted ergo meter. Further standardization of subjects was approached via recommendations of the American College of Sports Medicine not to participate in any physical activity or consume alcohol 24h before testing, as well as to stop eating or consumer caffeine 2 hours before the experiment. As reference for core temperature aural temperature (insulated) in the auditory channel was measured via the cosinuss™ [17] sensor (accuracy: 0.1°C, frequency: 1Hz). Although literature describes several restrictions (e.g. off-set; delay, ambient temperatures, wind) [5], insulation, as we did, can minimize the bias. The assumption of quick temperature change assessments via the aural temperature and practicability lead this choice. The ZHF sensors were placed at four different sites with medical tape; forehead (FH), sternum, upper arm (UA), and wrist and based on principle constructions according to an US patent by Bieberich et al. (2011) [15]. Our own design was combination of 6mm polyethylene foam and temperature sensors from MSR Electronics Switzerland (accuracy: 0.5°C), excluding a heating element and its regulation. The test started with an acclimatization phase of 10 minutes, subsequent 30 minutes of cycling followed by a recovery phase of 10 minutes.



(a) (b) (c) (d)

Fig. 1. (a) patent design; (b) 3M design (c) own design (d) sensor positions

The protocols on the 143 data sets follow the same structure and standardization. Table 1 and 2 show respective conditions, individual data, their assessment and gathered ranges.

2.3. Analysis

Descriptively, absolute deviations of ZHF to core temperatures are analyzed. Core temperature means of every last minute of acclimatization, cycling and recovery phase had been tested and corrected according to Bonferroni (α=0.05). To analyze the agreement between the measurement methods Bland Altman plots has been used. An acceptable agreement was chosen at ±0.5°C [19-22]. Resampling with 10.000 values was used to calculate the 95% confidence interval for ZHF values within ±0.5°C. To evaluate the reproducibility, the concordance correlation coefficient (CCC) according to Lin (1993) [23] was calculated. Due to time reasons, the ZHF method to reach thermal equilibrium only the cycling and recovery phase had been analyzed for agreement. To exclude individual fitness to influence ZFH measurements the product-moment correlation coefficient between relative power and share of differences within ±0.5°C has been analyzed. To analyze whether more homogeneous samples provide good relations between sweat loss and core temperature described by Taylor & Machado-Moreira [16], Pearson correlation coefficients and regressions have been assessed for different samples at various environmental conditions in absolute and relative values.

3. Results

ZHF

Results showed evident influence of environmental conditions on body core temperature and significant differences in local ZHF sites. Significantly lower temperatures could be observed in cold temperatures and more peripheral body parts. The forehead constantly showed slightly higher values (max. +0.58°C) and sternum slightly lower ones (max. -0.66°C) than our reference methods (Fig. 1). Fig. 2 shows Bland-Altman plots for forehead in cold and warm temperatures including cycling and recovery phase. Independent of environments the mean of differences between ZHF at the forehead and the reference method was 0.47°C. In 95% of all cases the ZHF method showed values 1.42°C higher or 2.36°C lower than the reference. Only 30% of all values were within ±0.5°C. In the cold the mean was 0.77°C with 43% and in the warm 0.16°C with 67% within ±0.5°C (Fig. 2b). Specifically, for active situations the same picture appeared between warm and cold with best agreement in the warm and active conditions at the forehead (mean difference: 0.19°C; LoA: 66% within ±0.5°C). Interestingly, each subject showed individual agreements and partially even very satisfying ones (e.g. Fig. 2b). A summary of all active observations can be seen in Table 3.

Concerning individual fitness, neither in cold (p=.149, r=.745) nor warm (p=.420, r=.420) conditions correlation coefficient showed significant results.

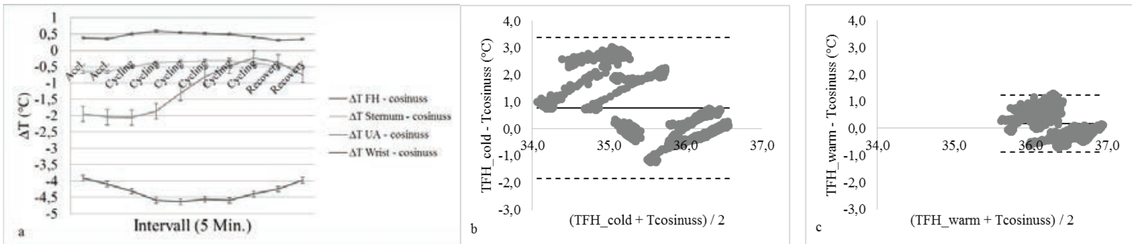


Fig. 2. (a) Mean deviations from reference method of the four measurement sites and Bland-Altman-Diagram for measurements at forehead (FH) at (b) cold (mean of differences .77°C; LoA ± 2,62°C) and (c) warm (mean of differences .16°C; LoA ± 1,01°C).

Table 3. Summary data of the Bland-Altman method for males actively cycling at 60% of individual threshold at different local sites in the warm and cold.

Comparison T_{ZHF} minus $T_{cosinuss}$	Mean (SD) (°C)	95% Confidence interval (CI)	Percent of differences within 0,5°C (95% CI; LoA)	CCC acc. to Lin (95% KI)	T_{ZHF} Min., Max.	$T_{cosinuss}$ Min., Max.
Forehead_total	0.46 (0.94)	-1.39, 2.31	0.52 (0.50, 0.54)	0.33 (0.29, 0.37)	34.56, 37.00	33.52, 36.93
Forehead _cold	0.73 (1.21)	-1.64, 3.10	0.38 (0.35, 0.41)	0.11 (0.06, 0.16)	34.56, 36.87	33.52, 36.51
Forehead _warm	0.19 (0.56)	-0.91, 1.30	0.66 (0.63, 0.69)	0.07 (0.01, 0.13)	35.68, 37.00	35.63, 36.93
Sternum_total	-0.61 (1.34)	-3.23, 2.01	0.28 (0.26, 0.30)	0.14 (0.10, 0.17)	33.12, 36.87	33.52, 36.93
Sternum_cold	-0.52 (1.82)	-4.08, 3.04	0.19 (0.16, 0.21)	-0.25 (-0.29, -0.21)	33.12, 36.37	33.52, 36.51
Sternum_warm	-0.71 (0.77)	-2.22, 0.81	0.37 (0.34, 0.40)	0.04 (0.00, 0.07)	34,43, 36,87	35.63, 36.93
Upper arm_total	-1.13 (1.58)	-4.22, 1.97	0.27 (0.25, 0.29)	0.18 (0.16, 0.21)	31.31, 37.00	33.52, 36.93
Upper arm_cold	-1.26 (2.03)	-5.23, 2.71	0.27 (0.24, 0.29)	-0.13 (-0.17, -0.09)	31.31, 36.37	33.52, 36.51
Upper arm_warm	-0.99 (1.14)	-4.21, 1.24	0.27 (0.24, 0.30)	0.17 (0.14, 0.19)	33.37, 37.00	35.63, 36.93
Wrist_total	-4.51 (2.57)	-9.54, 0.51	0.03 (0.02, 0.04)	0.09 (0.08, 0.10)	25.68, 35.68	33.52, 36.93
Wrist_cold	-6.26 (2.50)	-11.16, -1.36	0.00 (0.00, 0.00)	-0.02 (-0.02, -0.01)	25.68, 31.87	33.52, 36.51
Wrist_warm	-2.77 (0.90)	-4.52, -1.01	0.06 (0.04, 0.07)	0.03 (0.02, 0.03)	32.00, 35.68	35.63, 36.93

The 95% Limits of agreement (LoA) have been calculated by the Bland- Altmann method.

The 95% Confidence intervals have been estimated via resampling of 10.000 resamples.

Relations between core temperature and sweat loss

Relations over all various conditions (cf. Table 1&2) showed highly significant but low positive correlations (r=.37**; α=.01). Better ones appear with more discrete situations and homogenized samples. Table 4 shows a selection of deduced parameters in means and standard deviations with respective correlations.

Table 4. Summary data of the Bland-Altman method for males actively cycling at 60% of individual threshold at different local sites in the warm and cold.

	Ambient temperature (°C)	Relative humidity (%)	Wind speed (m/s)	Weight (kg)	Height (cm)	Fat content (%)	Fitness level (ml/kg/h; bpm; Watts, h/week)	Clothing (clo)	Hydration status (mg/ml; Colorscale;1-7))	Activity/Intensity (bpm; Watts)	**r**
Condition 1 (n=8)	25(±.5)	50(±5)	.15 (-)	69.1(±10.8)	174.1(±11.6)	24.7(±8.5)	3.2(±1.9)	0.38 (±0)	1-2 *(fully hydrated)*	134.1(±2)	**.92****
Condition 2 (n=6)	25(±.5)	60(±10)	.15 (-)	69(±13.1)	173(±10.3)	22.8(±5.7)	2(±1.5)	0.38 (±0)	4-5 *(slightly dehydrated)*	135.8(±.7)	**.82***
Condition 3 (n=6)	25(±.5)	50(±5)	.15 (-)	66.1(±11.7)	170.8(±9.2)	26.2(±6.5)	3.1(±1.7)	0.38 (±0)	1-2 *(fully hydrated)*	133.9(±1.8)	**.94****
Condition 4 (n=10)	10(±.5)	40(±5)	.15 (-)	76.8(±6.6)	185.8(±5.9)	14.4(±2.4)	-	0.48(±.2)	-	140(±.8)	**.72****
Condition 5 (n=5)	10(±.5)	40(±5)	.15 (-)	76.8(±6.6)	185.8(±5.9)	14.4(±2.4)	-	0.31(±0)	-	140(±.8)	**.98****

* α=.05

**α=.01

For instance, linear regressions of condition 3 and 5 show R^2´s of .87 and .97 with respective water loss deviations of maximum ~200 ml and ~50ml.

In both warm and cold conditions high and significant correlations could be observed as well with highest in conditions 3 and 5.

4. Discussion

Only partially the ZHF method was able to reflect the reference core temperature. As the auditory channel is clearly error prone, assessments of gold standards (e.g. rectal, esophageal) are obligatory. Nonetheless, in active situations a comfortable method of choice. It seems obvious that in described set up, colder temperatures and peripheral body sites physiologically do not apply for ZHF, since vasoconstriction helps to conserve body heat for vital body parts in those conditions. Therefore, even in active and more insulated situations and the use of an original temperature controlled ZHF Sensor (SpotON™, 3M); it's unlikely to grasp core temperature at those sites. On contrast sternum and forehead showed tendencies of valuable agreements in warm conditions. This is in line with former studies [21, 22], such as body sites with low subcutaneous fat and good perfusion are assumed to be more concordant. Unfortunately, in this study limits of agreement were rather unsatisfying, but in comparison to former research difficult to evaluate, because methodologies highly differ. In sum, systems integrated in common sports belts or helmets are supposable. As stated above and supported by Taylor et al. [5] the reference core temperature via the auditory channel needs a critical evaluation. Although it provides a comfortable alternative in exercise, some absolute values around 35°C and courses of core temperature seemed implausible. In a few cases it could be explained by environmental conditions or physiological responses to physical activity (i.e. sweating, to cool the human body), in other, it conflicts human thermoregulation. Clearly, it´s debatable which reference method to be best, but future research should consider additional reference methods. Additionally, in future one should use ZHF sensors bigger in surface, higher insulating and potentially with hydrophilic and/or reflecting materials to better control influences by individual (e.g. body composition, sweating) or environmental (cold temperatures, wind, radiation) factors. On contrast, a bigger surface may complicate fitting and disposition to human skin. In total, a best alternative between accuracy, simplicity and flexibility must be found. First results of follow up studies on modified ZHF show promising results.

Further discussions are indicated by the chosen sample. Generally positive was the independency of physical fitness on the measurements. Nonetheless, fitness is stated as influential factor on human thermoregulation, but others too might have an influence, such as body fat. Therefore, future studies need to specifically consider human composition.

In case future research and developments transfers this method into an applicable system, end users must be aware of a certain initializing phase, necessary an isothermal tunnel from the core to the skin to be built.

Found relations between core temperature and sweat loss supported assumptions by Taylor et al. [16] and many more, that physiological responses to exercise is highly situational and individual. Due to time restrictions the degressive behavior of sweat loss was not reached. Very good correlations underline the opportunity for simple modelling. Nonetheless, partially, also negative correlations appeared and as any core temperature and sweat loss relation- index, it describes the degree of thermoregulatory efficiency. The closer to proportional relations, the better the body is able to dissipate generated heat to the environment.

Due to this complexity a simple modeling approach, via potentially possible core temperature measurements seems applicable for new monitoring systems, but still requires a vast amount of input, such as environmental and personal data. It is unclear how accurate an average end user could reliably or generally generate that kind of data. For average end users this seems impractical, if not reliably automated. On contrast for keen athletes and professionals in sports or industries, it may provide an easy way to assess individual hydration regimes.

To the authors knowledge so far neither research is available that tried to cluster subjects` physiological responses, nor which variances of parameters are tolerable to still gain reliable predictions. If successful, it may reduce necessary input data to a realizable amount. These results currently support a rather difficult task to correctly assess or model sweat loss non-invasively in active situations.

Nonetheless, so far unmentioned, besides the importance of absolute sweat loss it´s composition and therefore lost amounts of potassium and sodium can be crucial, too [24]. In extreme cases unfavorable states of cell and blood osmolality can either lead to hyper- or hypo-hydrated situation, which both impair performance [25]. Relations between sweat and blood sodium had been described [26] and technology (ISE´s: Ione-selective electrodes; Horiba) exists to reliably measure former concentrations [27]. Although it is likely that sweat compositions and patterns are, as well, highly individual literature underlines it´s importance for hydration assessment.

5. Conclusion

To conclude, described research supports the potential of new non-invasive opportunities and modeling to monitor environmental and physical influences on the human body. To the authors opinion the implementation of body temperatures could be transferred shortly. On contrast, due to its manifold dependencies, the time horizon for noninvasive sweat rates assessment remains unclear.

Nonetheless new monitoring systems with ISE´s in combination with heart rate and ZHF sensors, and basing on the 4 well established relations between heart rate, oxygen consumption, core temperature, sweat loss and electrolyte loss [16], have the potential to better derive approximations of described parameters. A recently published paper by Gao et al. [28] support this idea.

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