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Comparison of estimated core body temperature measured with the BioHarness and rectal temperature under several heat stress conditions

Yongsuk Seo,

Travis DiLeo,

Jeffrey B. Powell,

Jung-Hyun Kim,

Raymond J. Roberge,

Aitor Coca

National Personal Protective Technology Laboratory, National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, Pittsburgh, Pennsylvania

Abstract

Monitoring and measuring core body temperature is important to prevent or minimize physiological strain and cognitive dysfunction for workers such as first responders (e.g., firefighters) and military personnel. The purpose of this study is to compare estimated core body temperature (Tco-est), determined by heart rate (HR) data from a wearable chest strap physiology monitor, to standard rectal thermometry (Tre) under different conditions.

Tco-est and Tre measurements were obtained in thermoneutral and heat stress conditions (high temperature and relative humidity) during four different experiments including treadmill exercise, cycling exercise, passive heat stress, and treadmill exercise while wearing personal protective equipment (PPE).

Overall, the mean Tco-est did not differ significantly from Tre across the four conditions. During exercise at low-moderate work rates under heat stress conditions, Tco-est was consistently higher than Tre at all-time points. Tco-est underestimated temperature compared to Tre at rest in heat stress conditions and at a low work rate under heat stress while wearing PPE. The mean differences between the two measurements ranged from −0.1 ± 0.4 to 0.3 ± 0.4°C and Tco-est correlated well with HR (r = 0.795 – 0.849) and mean body temperature (r = 0.637 – 0.861).

These results indicate that, the comparison of Tco-est to Tre may result in over- or underestimation which could possibly lead to heat-related illness during monitoring in certain conditions. Modifications to the current algorithm should be considered to address such issues.

CONTACT Aitor Coca esq6@cdc.gov National Personal Protective Technology Laboratory, 626 Cochrans Mill Road, Pittsburgh, PA 15236.

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Keywords

Estimated core body temperature; exercise; heat stress; rectal temperature

Introduction

Monitoring and measuring core body temperature (Tco) is important to prevent or minimize physiological strain (e.g., hyperthermia and related heat illness) and cognitive dysfunction for workers such as first responders (e.g., firefighters) and military personnel. Personal protective equipment (PPE), often used by first responders and healthcare workers, can contribute to increased heat stress through decreased dissipation of heat and increased metabolic heat production. Heat stress (external heat stimuli) can induce physiological strain (e.g., cardiovascular, thermoregulatory, metabolic, and neuromuscular function) that can lead to potentially life-threatening and clinical impairments.[1,2] Resulting hyperthermia or dehydration has been shown to be related to reduce the time to physical exhaustion and decreased mental performance (working memory, retention of visual information, and information processing).[2–6]

Standard measurements of Tco, implementing rectal thermistors, esophageal probes, and ingestible thermometer pills, are invasive and not practical in the field. Rectal and esophageal probes are typically reported as uncomfortable to the user[7,8] and impractical for ambulatory settings. The ingestible thermometer pills are limited by gastrointestinal transit times and motility and electromagnetic interference with data reception. Due to these limitations, a safer, more comfortable, and more valid measurement of Tco is needed for researching and monitoring of occupational workers who perform their daily tasks in hot/humid environments. Recently, wearable physiological devices have been developed and displayed in a variety of applications, including personal health management, physical training, and military uses.[9] The BioHarness (Zephyr Technology Corporation, Annapolis, MD) is an FDA-approved wireless, ambulatory physiological monitoring device that provides estimated Tco based on the Kalman Filter (KF) algorithm[10] constructed from a large set of ambulatory heart rate (HR) data. The BioHarness consists of a chest strap and an electronics module that collects and transmits vital sign data, such as HR and respiratory rate (RR). A previous study reported that the BioHarness was reasonably accurate for HR and RR measurements compared with standard laboratory spirometry during a graded exercise test in normothermia and prolonged exercise in heat.[11] Human thermoregulatory models have been investigated to estimate Tco using information that includes metabolic rate, individual characteristics, environmental factors, and clothing parameters.[12–15] However, this aforementioned information is not always available in the field setting. Recently, thermoregulatory heat transfer models, based on HR, have demonstrated some accuracy in estimating Tco in a variety of environmental and clothing conditions.[15–17] As such, the purpose of this study is to directly compare estimated Tco (Tco-est) using the BioHarness to standard rectal thermometry, under different conditions.

Methods and materials

Design and subjects

This study compiles data from four different experiments that mimic the physical activity and work in various environmental conditions; Treadmill exercise heat stress (Experiment 1), passive heat stress (Experiment 2), cycling exercise heat stress (Experiment 3), and treadmill exercise wearing PPE heat stress (Experiment 4). Data collected during these experiments were summarized and analyzed for the purpose of this study with the focus of comparing Tco. All experiments included in this study were approved by the National Institute for Occupational Safety and Health (NIOSH) Institutional Review Board and both oral and written informed consent were obtained from each subject prior to participation.

The number of subjects studied were 12 healthy men for *Experiments 1* and *2* (age = 23 ± 1 year, mass = 76.9 ± 10 kg, height = 180 ± 10cm, BMI = 23.3 ± 2.2 kg/m2, HRmax = 186.4 ± 7.2, VO2max = 56.8 ± 6.2 ml·kg·min-1), 10 healthy men for Experiment 3 (age: 23 ± 2 years, mass: 80.3 ± 9.9 kg, height: 180 ± 10cm, BMI = 23.8 ± 2.8 kg/m2, HRmax = 188.3 ± 5.4, VO2max = 56.9 ± 5.1 mL·kg·min-1), and five healthy men for Experiment 4 (age: 24 ± 2 years, mass: 76.6 ± 10.1 kg, height: 180 ± 10cm, BMI = 23.9 ± 2.8 kg/m2, HRmax = 184.4 ± 5.6,VO2max = 56.2 ± 8.9 mL·kg·min-1). Prior to partaking in the study, subjects underwent a medical examination by a licensed physician. Subjects were excluded from this study if they smoked or had a positive history of cardiovascular or metabolic diseases. All experimental trials were conducted in the morning hours, with each trial separated by at least 48 hr. The subjects were instructed to avoid strenuous exercise and alcohol consumption for 24 hr prior to a study participation as well as avoid caffeine consumption on the morning of the study participation, but were instructed to eat a light breakfast.

Instrumentation

For all experiments, rectal temperature (Tre) was measured using a rectal probe (REF-4491, YSI temperature, Dayton, OH) inserted 13 cm beyond the anal sphincter. Tco-est constructed from HR data using Kalman Filter algorithm[10] was measured by the BioHarness. Skin thermistors (T-type copper/constantan, Concept Engineering, Old Saybrook, CT) were affixed with a transparent dressing film (Tegaderm, 3M, St. Paul, MN) onto four body sites (chest, shoulder, thigh, and calf) to monitor skin temperatures and subsequently calculate weighted mean skin temperature (Tsk) according to Ramanathan.[18] Mean body temperature (Tb) was calculated by the equation of Burton:[19] Tb = (0.64*Tre) +(0.36*Tsk). All data were recorded simultaneously throughout each experimental trial and summarized as 1 minute averages at baseline, and at 0.5, 1.0, and 1.5°C elevation in Tre above baseline.

Procedures

Prior to the study participation, all subjects performed a treadmill graded exercise test (GXT) utilizing a ramped Bruce protocol in thermoneutral conditions (22°C, 50% RH) to determine cardiovascular capacity and maximal oxygen uptake (VO_{2max}). Test termination criteria for all experiments were Tre of 1.5°C above baseline, Tre>39°C, or expressed volitional fatigue. Specific procedures for each experiment are summarized below.

Experiment 1. Treadmill exercise heat stress (TEH).—Upon arrival at the laboratory, the subjects changed into athletic shorts, t-shirt, and shoes, were instrumented with sensors, and underwent a 10 min resting stabilization under thermoneutral conditions (20°C, RH 50%). Following the baseline measurements after the stabilization, the subjects performed a treadmill exercise at approximately 50% of their VO_2max under heat stress conditions (45°C, 30%RH).

Experiment 2. Passive heat stress (PH).—Following the sensor instrumentation and stabilization as described above, subjects donned a liquid heating garment with sweat pants and hooded sweatshirt over the garment. After baseline measurements were obtained, subjects were seated at rest under heat stress conditions (45°C, 30%RH) while warmed water (45°C) was circulated through the liquid garment to generate passive heating.

Experiment 3. Cycling exercise heat stress (CEH).—Following the same procedures for sensor instrumentation, stabilization, and baseline measurements as described in TEH, the subjects performed cycling exercise on an electronically braked cycle ergometer (VIAsprint™ 150P, CareFusion, Hochberg, Germany) at approximately 50% VO_2max, with a pedal rate maintained between 60–70 RPM under heat stress conditions (45°C, 50%RH).

Experiment 4. Treadmill exercise wearing PPE heat stress (TEH+PPE).—Following the sensor instrumentation and stabilization, subjects donned a healthcare PPE ensemble comparable with that currently used in the West Africa Ebola response (MSF (Médecins Sans Frontières [Doctors Without Borders]), which consist of medical scrubs, socks, boots, Tychem® QC coverall (Dupont, Wilmington, DE), rubber apron, splash resistant goggles, surgical nitrile inner gloves, heavy duty nitrile outer gloves, N95 filtering facepiece respirator (Kimberly Clark model 46828), and fluid-resistant surgical cap (Kimberly Clark KCH69240). Baseline measurements were taken upon the completion of PPE donning, and then subjects performed treadmill exercise at 4.0 km/hr under heat stress conditions (32°C, 90%RH).

Statistical analyses

All experimental data were summarized as 1-min average values (mean ± SD) and Tre and Tco-est in all trials were summarized at baseline, and at increases of 0.5, 1.0, and 1.5°C above baseline for statistical analyses. A repeated measure ANOVA was carried out to determine significant mean differences between Tre and Tco-est over the time of the experiment. When the ANOVA indicated significant main effect, post-hoc paired sample t-test was utilized to determine where those differences existed. Pearson's correlation was performed to determine the strength of association between Tco-est and HR as well as Tco-est and Tb. In addition, Bland-Altman plots[20] were created using SigmaPlot (v.12, Systat Software Inc., San Jose, CA) in order to assess the degree of agreement between Tre and Tco-est (95% limits of agreement [LoA] = mean difference ± 1.96 SD). Also, a simple linear regression was calculated to predict Tco-est based on Tre, Tb, and HR. A statistical significance was accepted when $p<0.05$ and all analyses were performed using the Statistical Package for Social Sciences (v.19.0, IBM, Somers, NY).

Results

A repeated measure ANOVA was conducted to compare the estimated Tco (Tco-est) using the BioHarness to standard rectal thermometry under four different conditions.

A repeated measure ANOVA demonstrated a significant main effect for time ($F = 375.970$, $p < 0.001$), main effect for condition ($F = 10.790$, $p = 0.009$), and significant interaction ($F = 4.109$, $p = 0.016$) during TEH. A repeated measure ANOVA demonstrated a significant main effect for time ($F = 418.356$, $p < 0.001$), no main effect for condition ($F = 2.099$, $p = 0.185$), and a significant interaction ($F = 53.573$, $p < 0.001$) during PH. A repeated measure ANOVA demonstrated a significant main effect for time ($F = 179.391$, $p < 0.001$) and main effect for condition ($F = 5.788$, $p = 0.040$), but no interaction ($F = 0.933$, $p = 0.438$) during CEH. A repeated measure ANOVA demonstrated a main effect for time ($F = 45.972$, $p < 0.001$), but no main effect for condition ($F = 6.343$, $p = 0.086$) and no interaction ($F = 2.397$, $p = 0.136$) during TEH+PPE.

Table 1 shows that Tco-est was significantly higher at baseline ($p = 0.009$), 0.5 ($p = 0.003$), and 1.5°C ($p = 0.045$) than Tre during TEH, but Tco-est and Tre were not different at 1.0°C ($p = 0.071$). During CEH, Tco-est was significantly higher than Tre at 0.5 ($p = 0.006$), but the Tco-est and Tre was not significantly different at baseline ($p = 0.408$), 1.0°C ($p = 0.05$) and 1.5°C ($p = 0.08$). During PH, the Tco-est was significantly lower than Tre at 1.0 ($p=0.009$) and 1.5°C ($p=0.001$), but the Tco-est and Tre were not significantly different at baseline ($p=0.162$) and 0.5°C ($p = 0.766$). During TEH+PPE, the Tco-est was significantly lower than Tre at 1.5°C ($p = 0.031$), but the Tco-est and Tre were not significantly different at baseline ($p = 0.655$), 0.5 ($p = 0.315$), and 1.0°C ($p = 0.051$). Also, Table 3 shows the individual variability of percentage of over- and underestimated core temperature.

The overall mean differences between Tre and Tco-est for the four conditions, combining the four-time points, varied from−0.2 ± 0.4°C to 0.3 ± 0.4°C, with moderate-to-strong correlations ($r = 0.679 – 0.858$) that were statistically significant ($p \le 0.01$) (Table 2). Tco-est also correlated strongly with HR ($r = 0.795 – 0.849$) (Figure 1) and correlated moderately-to-strong with Tb ($r = 0.637 – 0.861$) (Figure 2) that all were statistically significant. Bland-Altman plots exhibited mean differences for the four trials that ranged from −0.2 ± 0.4°C to 0.3 ± 0.4°C and at least ≥ 92% of the temperature measurements fell within LoA (Figure 3). A simple linear regression indicated that Tre, Tb, and HR were significant predictors of Tco-est. The regression equation was ($F(1,38) = 105.902$, $p \le 0.001$, $R2 = 0.736$, $F(1,38) = 109.253$, $p \le 0.001$, $R2 = 0.742$, $F(1,38) = 98.081$, $p \le 0.001$, $R2 = 0.721$, respectively) during THE. A simple linear regression demonstrated that ($F(1,37) = 31.696$, $p \le 0.001$, $R2 = 0.461$, $F(1,37) = 25.292$, $p \le 0.001$, $R2 = 0.406$, $F(1,37) = 79.356$, $p \le 0.001$, $R2 = 0.682$, respectively) during PH. A simple linear regression demonstrated that ($F(1,38) = 80.088$, $p \le 0.001$, $R2 = 0.678$, $F(1,38) = 87.849$, $p \le 0.001$, $R2 = 0.698$, $F(1,38) = 146.883$, $p \le 0.001$, $R2 = 0.794$, respectively) during CEH. A simple linear regression demonstrated that ($F(1,17) = 23.836$, $p \le 0.001$, $R2 = 0.584$, $F(1,17) = 20.315$, $p \le 0.001$, $R2 = 0.544$, $F(1,17) = 29.126$, $p \le 0.001$, $R2 = 0.631$, respectively) during TEH+PPE.

Discussion

This study compared Tco-est to Tre during four different conditions. The results from Experiment 1 (TEH) demonstrated that Tco-est recorded slightly (but significantly) higher Tre at baseline, 0.5°C°, 1.5°C, and approached significance at 1.0°C (p = 0.07), which is similar to the slightly higher Tco-est for 0.5°C, 1.0°C, and 1.5°C (that approached significance [p = 0.08]) reported for Experiment 3 (CEH). The mean difference between Tco and Tre in both of these experiments was 0.3 ± 0.4°C, which may be related to the elevated HR in response to the increased metabolic demand at the onset of exercise. During Experiment 2 (PH) and Experiment 4 (TEH+PPE), the Tco-est slightly (but significantly) underestimated Tco compared to Tre at 1.0°C and 1.5°C, with mean differences of −0.2 ± 0.4°C and −0.1 ± 0.4°C. The underestimation of the Tco-est in PH and TEH+PPE likely resulted from a smaller increase in HR due to the sedentary state of Experiment 2 and the slower treadmill work rate of Experiment 4. There are several possible explanations that could account for the over- and underestimation of Tco-est as this measure is based on HR. First, during continuous submaximal exercise in the heat, central blood volume and stroke volume decreases and HR increases to maintain cardiac output during the redistribution of blood to the periphery. During exercise in the heat, dehydration induces a decrease in plasma volume over time. This decreased plasma volume results in a lower end diastolic volume and consequently a lower stroke volume. To maintain cardiac output at a constant workload, heart rate must increase slowly over time. The estimation of core temperature may not consider this adaptation to prolonged exercise in the heat.[21,22] Second, the adaptations described above occur within 10 min of starting exercise in a hot environment which may introduce error in the estimation of core temperature from HR. Dehydration from sweating during exercise in the heat will induce these changes earlier than in thermoneutral environments because of decreased blood volume.[23] Also, previous studies reported that Tre increased at a slower rate than esophageal temperature and aural canal temperature during exertional heat stress and recovery.[24] In detail, Tes is approximately 0.8°C higher than Tre at the end of exercise in the heat. Furthermore, Tes was approximately 0.3–0.4°C lower than jugular venous blood temperature.[25] Because of this delay, differences between Tre and Tco-est may have been detected at certain time points. Furthermore, Pearson's correlation coefficient indicated that Tco-est is moderately-to-strongly associated (0.637–0.861) with Tb in all four conditions. Tb is considered as an individual's thermal stress[26] and has been used for body heat storage calculation.[27] A previous study by Hall and Polte[27] reported a linear relationship between body heat storage and physiological heat strain index at the 1% level. The physiological heat strain index indicates the effect of the heat load and thermoregulatory response to heat stress. Although there was a slight difference between indices of temperature across the four different conditions, the results from Pearson's correlation coefficient suggested that Tco-est could be considered as a valid and reliable method to monitor Tco in various settings with improvement to the algorithm. Differences shown between Tco-est and Tre may also be contributed to variability across individuals. This must be considered if using this method in practice as over- and underestimation may be present (Table 3). Variability of the estimate across various workloads may result in greater variability of the estimation measurement. Measurement variability may have detrimental effects on workers in potentially hazardous and stressful occupational environments. It is hypothesized that variability may increase with increasing workload or HR, especially at maximal HR. As such, while this study used a fixed workload across all testing conditions, the results may be limited in the generalizability to other workloads.

Limitations of the current study include the small number of subjects in Experiment 4 (n = 5). Our adult subjects were all healthy and physically fit, so we cannot comment on the accuracy of Tco-est for individuals with medical disorders or lack of physical fitness or the elderly or children. Also, because no women were tested, we cannot comment on possible gender-related differences in Tco-est calculations. There are some advantages and disadvantages of the KF model. The advantage of KF to estimate Tco is that it needs only a single parameter, HR, while other thermoregulatory models need a multitude of data such as metabolic rate, environment condition, clothing characteristics, and individual anthropometrics[(28)]. However, there is a disadvantage of the KF model in that it would underestimate Tco when HR reaches its maximum; Tco could increase continuously, but, since the KF model estimates the Tco based on HR, it may not estimate Tco accurately. Workloads in the field are not stable and constant, and they also vary from prolonged low intensity to moderate and high intensity of physical demand.[29] To provide foundational data, this study focused on the comparison of the measurements in a controlled manner (i.e., at a fixed workload). Future research should find ways to reduce the individual variability in regard to monitoring of individual's safety and health. Current data show the results overestimating Tco-est by greater than 0.5°C in 10 out of 16 measurements and underestimating Tco-est by greater than 0.5°C in 5 out of 16 measurements. It also must consider variable workloads that are seen in real-world work environments. However, the simulation of real-world workload is technically challenging for a comparison between Tre and Tco-est. Measuring fixed and standard workloads would allow for this comparison to be made under specific conditions.

Conclusion

With respect to field activities (e.g., occupational activities), the slightly higher or lower Tco-est compared with Tre noted in the current study could possibly lead to heat-related illness in certain conditions. Therefore, caution should be taken in regard to monitoring of individuals' safety and health when using the BioHarness device under passive heat or while wearing PPE as it may over-or underestimate Tco and could potentially result in heat injuries or illness. Algorithm modifications should consider metabolic demands, HR, and individual variability in Tco responses to various heat stress conditions to improve the accuracy of this wearable monitoring device in the field.

References

[1]. Hargreaves M: Physiological limits to exercise performance in the heat. J. Sci. Med. Sport 11(1): 66–71 (2008). [PubMed: 17720623]

[2]. Casa DJ: Exercise in the heat. I. Fundamentals of thermal physiology, performance implications, and dehydration. J. Athl. Train 34(3):246–252 (1999). [PubMed: 16558572]

[3]. Holmer I: Protective clothing in hot environments. Ind. Health 44(3):404–413 (2006). [PubMed: 16922184]

[4]. Cheung SS: Neuromuscular response to exercise heat stress. Med. Sport Sci 53:39–60 (2008). [PubMed: 19208998]

[5]. Gaoua N, Racinais S, Grantham J, and El Massioui F: Alterations in cognitive performance during passive hyperthermia are task dependent. Int. J. Hyperthermia 27(1):1–9 (2011). [PubMed: 21070137]

[6]. Hocking C, Silberstein RB, Lau WM, Stough C, and Roberts W: Evaluation of cognitive performance in the heat by functional brain imaging and psychometric testing. Comp. Biochem. Physiol. A Mol. Integr. Physiol 128(4):719–734 (2001). [PubMed: 11282316]

[7]. Gunga H-C, Sandsund M, Reinertsen RE, Sattler F, and Koch J: A non-invasive device to continuously determine heat strain in humans. J. Therm. Biol 33(5):297–307 (2008).

[8]. Teunissen L, de Haan A, de Koning J, and Daanen H: Telemetry pill versus rectal and esophageal temperature during extreme rates of exercise-induced core temperature change. Physiolog. Measure 33(6): 915 (2012).

[9]. Pantelopoulos A, and Bourbakis NG: A survey on wearable sensor-based systems for health monitoring and prognosis. Syst. Man Cybernet. Part C Applic. Rev. IEEE Trans 40(1):1–12 (2010).

[10]. Kalman RE: A new approach to linear filtering and prediction problems. J. Fluids Eng 82(1):35–45 (1960).

[11]. Kim J, Roberge R, Powell J, Shafer A, and Jon WW: Measurement accuracy of heart rate and respiratory rate during graded exercise and sustained exercise in the heat using the Zephyr BioHarness. Int. J. Sports Med 34(6):497–501 (2013). [PubMed: 23175181]

[12]. Fiala D, Lomas KJ, and Stohrer M: Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions. Int. J. Biometeorol 45(3):143–159 (2001). [PubMed: 11594634]

[13]. Havenith G: Individualized model of human thermoregulation for the simulation of heat stress response. J. Appl. Physiol (1985) 90(5):1943–1954 (2001). [PubMed: 11299289]

[14]. Kraning KK, and Gonzalez RR: A mechanistic computer simulation of human work in heat that accounts for physical and physiological effects of clothing, aerobic fitness, and progressive dehydration. J. Therm. Biol 22(4):331–342 (1997).

[15]. DeGroot DW, Goodman DA, Montain SJ, and Cheuvront SN: Validation of the ICDA Model for Predicting Body Core Temperature: 2056: Board# 27 May 30 9: 00 AM-10: 30 AM. Med. Sci. Sports. Exerc 40(5):S367 (2008).

[16]. Kim J-H, Williams WJ, Coca A, and Yokota M: Application of thermoregulatory modeling to predict core and skin temperatures in firefighters. Int. J. Industr. Ergon 43(1):115–120 (2013).

[17]. Williams WJ, Coca A, Kim J-H, and Roberge R: Repeatability of physiological responses during two repeated protective clothing performance tests under identical test conditions. Int. J. Industr. Ergon 44(5):793–799 (2014).

[18]. Ramanathan NL: A new weighting system for mean surface temperature of the human body. J. Appl. Physiol 19:531–533 (1964). [PubMed: 14173555]

[19]. Burton AC: Human calorimetry II. The average temperature of the tissues of the bodythree figures. J. Nutrit 9(3):261–280 (1935).

[20]. Bland JM, and Altman D: Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 327(8476):307–310 (1986).

[21]. Parsons K: Human Thermal Environments: The Effects of Hot, Moderate, and Cold Environments on Human Health, Comfort, and Performance. CRC Press, 2014.

[22]. Rowell LB: Human cardiovascular adjustments to exercise and thermal stress. Physiol. Rev 54(1):75–159 (1974). [PubMed: 4587247]

[23]. Wingo JE, Ganio MS, and Cureton KJ: Cardiovascular drift during heat stress: implications for exercise prescription. Exerc. Sport Sci. Rev 40(2):88–94 (2012). [PubMed: 22410803]

[24]. Gagnon D, Lemire BB, Jay O, and Kenny GP: Aural canal, esophageal, and rectal temperatures during exertional heat stress and the subsequent recovery period. J. Athl. Train 45(2):157 (2010). [PubMed: 20210619]

[25]. Nybo L, Secher NH, and Nielsen B: Inadequate heat release from the human brain during prolonged exercise with hyperthermia. J. Physiol 545(2):697–704 (2002). [PubMed: 12456844]

[26]. Lenhardt R, and Sessler DI: Estimation of mean body temperature from mean skin and core temperature. Anesthesiology 105(6):1117–1121 (2006). [PubMed: 17122574]

[27]. Hall JF Jr., and Polte JW: Physiological index of strain and body heat storage in hyperthermia. J. Appl. Physiol 15:1027–1030 (1960). [PubMed: 13710780]

[28]. Buller MJ, Tharion WJ, Hoyt RW, and Jenkins OC: Estimation of Human Internal Temperature From Wearable Physiological Sensors. In Proceedings of Twenty-Second Innovative Applications of Artificial Intelligence, Rychtyckyj N and Shapiro D (eds.). Menlo Park, CA: The AAAI Press, 2010. pp. 1763–1768.

[29]. Bos J, Mol E, Visser B, and Frings-Dresen MH: The physical demands upon (Dutch) fire-fighters in relation to the maximum acceptable energetic workload. Ergonomics 47(4):446–460 (2004). [PubMed: 14681000]

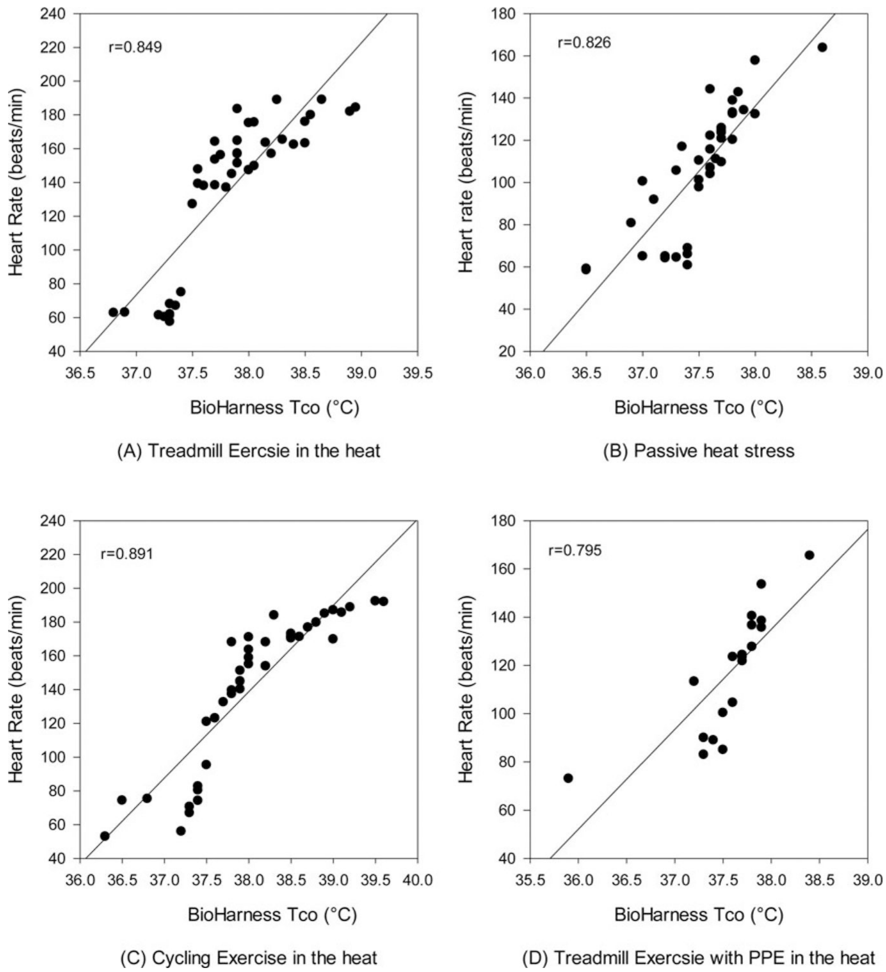

Figure 1.

Relationship between heart rate and BioHarness Tco across four conditions.

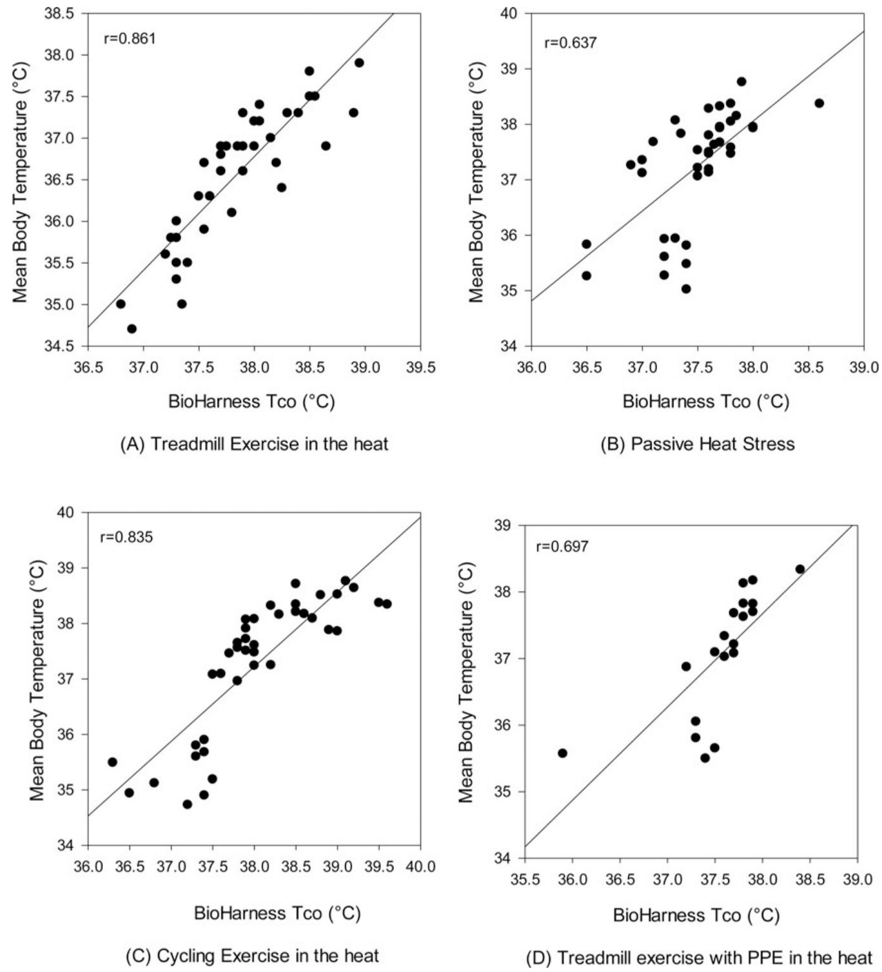

Figure 2.

Relationship between mean body temperature and BioHarness Tco across four conditions.

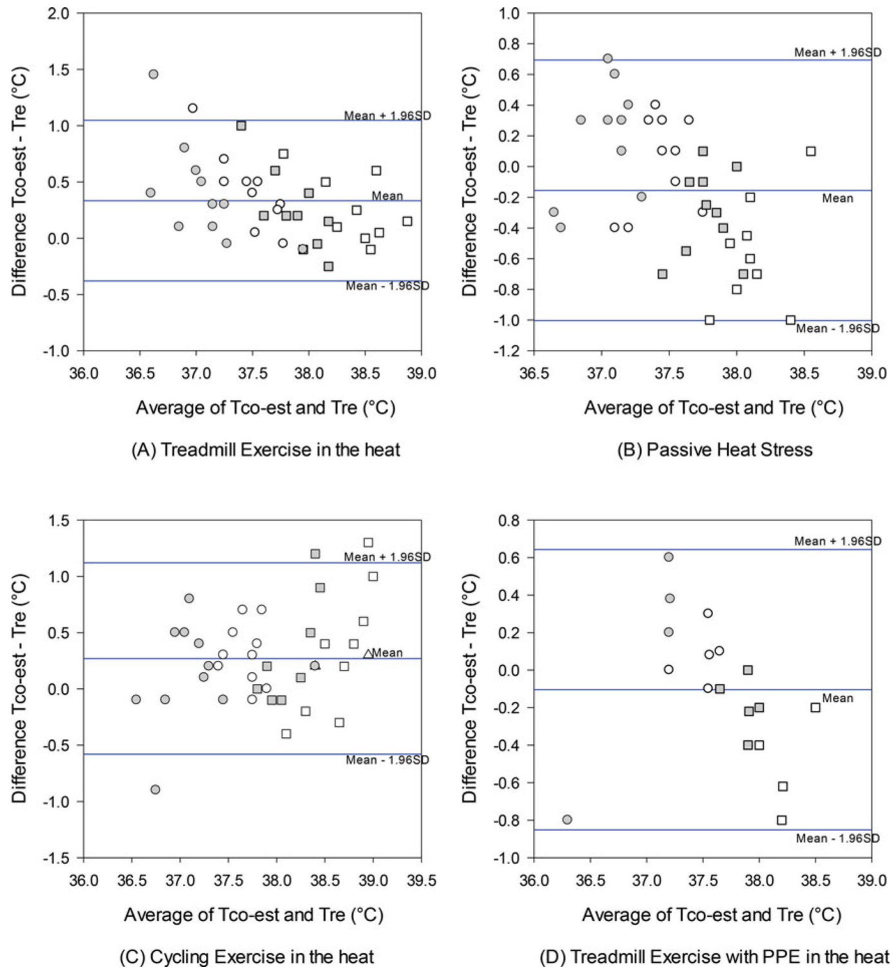

Figure 3.

Bland-Altman plots of inter-method (rectal temperature [Tre] vs. estimated core body temperature [Tco-est]) across four conditions. Filled circles represent an individual count of baseline, empty circles represent an individual count of 0.5°C, empty rectangles represent an individual count of 1.0°C, and closed rectangles represent an individual count of 1.5°C. (A: n = 40; B: n = 39; C: n = 40, D: n = 19). Upper and lower line: mean difference ± 1.96 SD (95% limits of agreement).

Table 1.

Summary of rectal temperature (Tre), estimated core temperature (Tco-est), average skin temperature (Tsk), and body temperature (Tb) during four time points across four conditions.

Conditions	Time Points	Tre	Tco-est	Tsk	Tb
TEH	Baseline	36.8 ± 0.4	37.2 ± 0.2 *	33.1 ± 0.9	35.5 ± 0.4
	0.5	37.3 ± 0.4	37.7 ± 0.1 *	35.3 ± 0.6	36.6 ± 0.3
	1.0	37.8 ± 0.4	38.0 ± 0.2	35.6 ± 0.8	37.0 ± 0.3
	1.5	38.3 ± 0.4	38.5 ± 0.3 *	35.8 ± 0.8	37.4 ± 0.3
PH	Baseline	36.9 ± 0.2	37.1 ± 0.3	33.6 ± 1.5	35.7 ± 0.5
	0.5	37.4 ± 0.2	37.5 ± 0.3	37.2 ± 0.3	37.3 ± 0.2
	1.0	37.9 ± 0.2	37.6 ± 0.2 *	37.5 ± 0.3	37.8 ± 0.2
	1.5	38.4 ± 0.2	37.8 ± 0.3 *	37.8 ± 0.3	38.2 ± 0.2
CEH	Baseline	37.0 ± 0.3	37.1 ± 0.4	32.4 ± 0.9	35.3 ± 0.4
	0.5	37.5 ± 0.2	37.8 ± 0.2 *	37.0 ± 0.4	37.3 ± 0.3
	1.0	38.0 ± 0.2	38.3 ± 0.4	37.9 ± 0.4	38.0 ± 0.3
	1.5	38.5 ± 0.2	38.8 ± 0.5	38.3 ± 0.4	38.4 ± 0.2
TEH+PPE	Baseline	37.0 ± 0.2	37.1 ± 0.7	33.5 ± 0.5	35.7 ± 0.2
	0.5	37.5 ± 0.2	37.5 ± 0.2	36.6 ± 0.2	37.1 ± 0.1
	1.0	38.0 ± 0.2	37.8 ± 0.1	37.0 ± 0.3	37.6 ± 0.2
	1.5	38.5 ± 0.2	38.0 ± 0.3 *	37.5 ± 0.3	38.1 ± 0.2

TEH: Treadmill Exercise in the heat, PH: Passive Heat, CEH: Cycling Exercise in the heat, TEH+PPE: treadmill exercise with PPE in the heat.

* $p < 0.05$ vs. Tre.

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Table 2.

Mean difference between the estimated core temperature (Tco-est) and rectal temperature (Tre).

Conditions	Mean Difference (°C)	Temperature measurements within LoA	95% LOA (°C)		
			Lower	Upper	r
TEH (n = 12)	0.3 ± 0.4 ($p \leq 0.01$)	38/40 (95%)	− 0.38	1.05	0.858
PH (n = 12)	−0.2 ± 0.4 ($p \leq 0.01$)	36/39 (92%)	−1.00	0.69	0.679
CEH (n = 10)	0.3 ± 0.4 ($p \leq 0.01$)	37/40 (92%)	− 0.58	1.12	0.824
TEH+PPE (n = 5)	−0.1 ± 0.4 ($p \leq 0.01$)	19/19 (100%)	− 0.85	0.64	0.764

TEH: Treadmill Exercise in the heat, PH: Passive Heat, CEH: Cycling Exercise in the heat, TEH+PPE: treadmill exercise with personal protective equipment (PPE) in the heat. r: correlation between the estimated core temperature (Tco-est) and rectal temperature (Tre).

Table 3.

Percentage of over- and underestimation of the estimated core temperature (Tco-est).

		Overestimation		Underestimation	
Conditions	**Range Time Points**	**Equal or Less than 0.5°C**	**Greater than 0.5°C**	**Equal or Less than 0.5°C**	**Greater than 0.5°C**
TEH	Baseline	60 (%)	30 (%)	N/A	N/A
	0.5	60 (%)	20 (%)	N/A	N/A
	1.0	20 (%)	50 (%)	10 (%)	N/A
	1.5	40 (%)	20 (%)	20 (%)	N/A
PH	Baseline	50 (%)	20 (%)	30 (%)	N/A
	0.5	60 (%)	N/A	30 (%)	N/A
	1.0	N/A	N/A	60 (%)	20 (%)
	1.5	N/A	N/A	40 (%)	50 (%)
CEH	Baseline	50 (%)	10 (%)	30 (%)	10 (%)
	0.5	60 (%)	20 (%)	10 (%)	N/A
	1.0	50 (%)	20 (%)	20 (%)	N/A
	1.5	50 (%)	20 (%)	30 (%)	N/A
TEH+PPE	Baseline	60 (%)	20 (%)	N/A	20 (%)
	0.5	60 (%)	N/A	20 (%)	N/A
	1.0	N/A	N/A	80 (%)	N/A
	1.5	N/A	N/A	40 (%)	40 (%)

TEH: Treadmill Exercise in the heat, PH: Passive Heat, CEH: Cycling Exercise in the heat, TEH+PPE: treadmill exercise with PPE in the heat.