

Biophysical, psychrometric and physiological limits for continuous liquid and air-based personal cooling systems in working men: A case for amending ASTM2300-10(2016)

Item Type	Journal article
Authors	Bach, Aaron JE;Borg, David N;Minett, Geoffrey M;Maley, Matthew J;Stewart, Ian B
Citation	Bach, A.J.E., Borg, D.N., Minett, G.M., Maley, M.J. and Stewart, I.B. (2020) Biophysical, psychrometric and physiological limits for continuous liquid and air-based personal cooling systems in working men: A case for amending ASTM2300-10(2016), Safety Science, 132, 104980.
DOI	10.1016/j.ssci.2020.104980
Publisher	Elsevier
Journal	Safety Science
Download date	2025-05-17 18:11:26
License	https://creativecommons.org/licenses/by-nc-nd/4.0/
Link to Item	http://hdl.handle.net/2436/623685

Title: Biophysical, psychrometric and physiological limits for continuous liquid and air-based personal cooling systems in working men: A case for amending ASTM2300-10(2016)

Authors: Aaron JE Bach¹, David N Borg², Geoffrey M Minett³, Matthew J Maley⁴, Ian B Stewart³

Affiliations:

¹National Climate Change Adaption Research Facility (NCCARF), Griffith University, Gold Coast, QLD, Australia.

²The Hopkins Centre, Menzies Health Institute Queensland, Griffith University, Brisbane, QLD, Australia.

³Institute of Health and Biomedical Innovation, School of Exercise and Nutrition Sciences, Queensland University of Technology, Brisbane, QLD, Australia

⁴Department of Sport, Institute of Human Sciences, University of Wolverhampton, Walsall, UK

Corresponding Author

Dr Aaron J.E. Bach

Office 4.24, Building G39

Engineering Drive, Southport

National Climate Change Adaptation Research Facility

Griffith University

4215, QLD, Australia

Email: a.bach@griffith.edu.au

Keywords: heat balance; partitional calorimetry; standard procedures; heat stress, heat transfer

Abstract

The ASTM F2300-10 standard testing protocol was implemented for two continuous personal cooling systems (venturi air vest and cold-water perfused vest) with theoretically similar cooling capacities. Secondly, we used the same systems in step-wise increments of either temperature or relative humidity in order to define the upper limit of the prescriptive zone for each (i.e., critical environmental limits method). ASTM F2300-10 standard protocol saw both vests equally effective in reducing cardiovascular and thermal strain relative to a no cooling control. The critical environmental limits method saw the upper limit for humidity significantly increase in both vests, with no differences between the vests. However, the upper limit for temperature was increased in the cold-water vest, with the venturi air vest being no more beneficial than the control. Overall, this study used an evidence-based approach to demonstrate that a single environment, as per ASTM F2300-10, failed to delineate differences between continuous cooling systems promoting discrete mechanisms of heat loss. Most notably, relative to no cooling, the use of the air vest provided no additional evaporative cooling in a low humidity environment, and therefore no increase in the upper limits of critical temperature. This should highlight to end users not to assume that one size fits all for effective personal cooling systems if applied outside of the environment it was tested. Based on these findings, we suggest a range of environments be recommended by the ASTM F2300-10 standard for the evaluation of cooling systems to ensure systems ineffective in certain environments can be identified.

Abbreviations

AV	air vest	H_{res}	total respiratory heat loss
CON	control	K_{skin}	conductive heat exchange at the skin
C_{skin}	convective heat loss through respiration	LV	liquid vest
D_{max}	maximal distance between the linear equation and quadratic equation	P_a	partial pressure of water vapour in air
E_{max}	maximum evaporative potential per unit area	P_{crit}	critical water vapour pressure
E_{req}	required evaporative loss per unit area for heat balance	RPE	rating of perceived exertion
H_{dry_skin}	net sensible dry heat exchange at the skin	t_b	mean body temperature
H_{evap_skin}	latent evaporative heat loss at the skin	T_{crit}	critical dry bulb temperature of air
H_{prod}	net metabolic heat produced	t_{db}	dry bulb temperature
HR	heart rate	t_{re}	rectal temperature
H_{res}	net heat loss through respiration	t_{sk}	mean skin temperature
		USG	urine specific gravity
		ϕ	relative humidity

1. Introduction

The relative risks of heat related illness present in many labour intensive occupations is well known by workers, administrators and policy makers alike (Bach et al., 2018; Jacklitsch et al., 2019; Lao et al., 2016; Samaniego-Rascón et al., 2019). Occupational safety standards require the consideration of heat loss mechanisms for the effective implementation of administrative controls aimed to reduce or eliminate employees' risk of heat stress. Of interest to administrators and researchers when developing heat exposure guidance are calculations pertaining to the rate(s) of body heat storage, measured, estimated or derived from metabolic cost tables (Ainsworth et al., 2011; International Organization for Standardization, 2004b), individual (Moran et al., 1998; Shapiro et al., 1982) and environmental heat stress indices (Belding and Hatch, 1955; International Organization for Standardization, 2017; Jendritzky et al., 2012; Lind and Hellon, 1957; Yaglou and Minaed, 1957), and their subsequent heat exposure limits. The determination of human heat exchange can be measured directly through whole body calorimetry (Kenny and Jay, 2011), thermal manikin modelling (ASTM International, 2016a), but more commonly it is predicted through partitioned

calorimetry likely using the heat balance equation (Cramer and Jay, 2018), or estimated via metabolic cost tables (American College of Sports Medicine, 2006; International Organization for Standardization, 2004b). These principles shape many decision aid tools and public policy that span a number of disciplines, from managing public safety during heat waves (Queensland Government, 2015; World Health Organization, 2017), athletic performance and health (National Rugby League, 2019; World Rugby, 2019), to occupational risk thresholds during work in the heat (American Conference of Governmental Industrial Hygienists, 2017; International Organization for Standardization, 2004a; Jacklitsch B et al., 2018).

In occupations where personal protective clothing is required, diurnal and seasonal variations exist, and/or the work intensity and duration is not always predictable, the ability to obtain specific policy and administrative controls for heat related illness can be limited. Inherently, personal protective clothing is a means to reduce employee risk in a given job. Often, protective clothing reduces the extrinsic risk of a specific hazard, and substitutes it with the risk for heat related illness due to the compromised heat loss pathways of an encapsulated individual (Horn et al., 2019). As such, despite the need for interventions that enhance heat loss capacity, minimal opportunity exists for alterations in standardised uniforms, as the protection from a distinct threat (e.g., biological protection) is of greatest priority. Any alterations, through research and development in textiles technology, which may improve the removal of body heat through reduced insulation, improved vapour pressure and/or radiative resistance, occurs over medium to long-term timelines involving many garment iterations. The integration of personal cooling strategies may provide an immediate solution to maintaining occupant protection, whilst mitigating the direct and indirect risks to workplace illness and injury in the presence of heat stress (Varghese et al., 2018). The use of personal cooling may permit operation at a higher metabolic load in the same environment compared to no cooling; or maintain the capability for heat balance for the same metabolic rate at higher critical environmental limits. This is imperative as an ineffective cooling system assumed to benefit the end user could expose workers to

a higher risk of heat stress. With an increase to the individual's load carriage, plus the potential to overestimate heat exposure times or work rates, and/or further impair regular avenues of human heat loss (e.g., reduced evaporation via insulation). The absence of a cooling system altogether may in fact be more advantageous than that of an untested system assumed to be effective in all conditions.

Traditionally, two methodologies have been undertaken when comparing rates of heat exchange between people varying in fitness, body composition, gender, age, acclimatisation status, work environments and clothing ensembles. The first being that of a '*standard test method*', that evaluates net heat storage between conditions by imposing uncompensable heat stress upon the individual through fixing both the environmental condition(s) and metabolic rate until a safe exposure time (i.e., tolerance time) is quantified. This method has been adopted for a human research testing standard for personal cooling systems, F2300-10 (ASTM International, 2016b). F2300-10 aims to quantify the effectiveness of various cooling systems and to ensure the conclusions drawn from results are "*accurate, robust and comparable*" (ASTM International, 2016b). However, a key limitation of the standard is that tolerance is only required to be tested in a single environment - in this case, 35 °C and 50% relative humidity. Although single environment testing enables more direct comparisons between studies of similar methodology, it also gives the reader the implicit assumption that the performance of cooling systems in this environment are transferable to other 'hot' conditions. Given the inherent differences by which various cooling systems extract heat/facilitate heat loss, it is logical to suggest that different systems will perform differently outside of the single F2300-10 prescribed environment.

The second method, *critical environmental limits testing*, defines the upper environmental bounds of heat balance by prescribing a compensable metabolic rate and environment, allowing deep body temperature to equilibrate to the conditions. After deep body temperature equilibrium, either ambient temperature or water vapour pressure remains fixed whilst the other follows small stepwise

increments to find the threshold environment(s) where a homeostatic disturbance in deep body temperature is seen. The environment(s) below this threshold is known as the 'prescriptive zone' (Lind, 1963) with any further increases in temperature (or vapour pressure) signalling a net gain in heat balance, noted by an inflection in deep body temperature, that is indicative of the individual transitioning from compensable to uncompensable heat strain. The determination of the prescriptive zone and the corresponding critical temperature (T_{crit}) or critical water vapour pressure (P_{crit}) was first implemented by Kamon and Belding (1971). Subsequently, the method was adopted by a number of seminal investigations into how these limits can shift according to protective clothing (Kenney et al., 1988; Kenney et al., 1987) and air velocities (Kamon and Avellini, 1979). More recent work has utilised this method to differentiate upper critical limits between men and women (Ashley et al., 2008; Kenney and Zeman, 2002), lean and obese heat acclimated boys (Dougherty et al., 2010), practice and game day American Football uniforms (Kulka and Kenney, 2002), fan cooling versus no fan cooling during passive rest (Ravanelli et al., 2017b), various metabolic work rates (Ashley et al., 2008), and the influence of shifts in blood volume and hydration status (Cramer et al., 2017).

The purpose of this investigation was subsequently twofold. First, the ASTM F2300-10 standard testing protocol (ASTM International, 2016b) was implemented for two continuous cooling systems with theoretically similar cooling capacities, though prioritising different mechanisms of heat loss. Secondly, the same systems were worn during step-wise increments of environmental conditions in order to define the upper limit of the prescriptive zone for both temperature and water vapour pressure (i.e., humidity). By doing this, it could be known if there is the potential for misleading end users of the effectiveness of personal cooling systems in environments that fall outside that of the current single environmental test method of ASTM F2300-10.

2. Methods

2.1. Participants

This study was carried out in accordance with the recommendations of the National Statement on Ethical Conduct in Human Research. The protocol was approved by the Queensland University of Technology Human Research Ethics Committee (EC00171). Participants were pre-screened and provided written informed consent. The study procedures adhered to the latest version of the Declaration of Helsinki, excluding pre-trial registration in a database. Twelve healthy males participated in the study and their mean (standard deviation, [SD]) characteristics are displayed in [Table 1](#).

Table 1. Participant Characteristics ($n = 12$)

VARIABLES	VALUES
Age (y)	25.5 ± 4.8
Body Mass (kg)	78.3 ± 10.6
Height (m)	1.78 ± 0.06
BSA (m ²)	1.901 ± 0.298
Fat Mass (%)	14.7 ± 5.7
Fat Free Mass (%)	85.3 ± 5.7
Total Body Volume (L)	73.42 ± 10.2
Body Density (kg·L ⁻¹)	1.066 ± 0.014
$\dot{V}O_{2peak}$ (ml·kg ⁻¹ ·min ⁻¹)	51 ± 5

Note. Data are presented as mean ± standard deviation

2.2 Pre-Test Procedures

Instructions pertaining to pre-test standardisation were given to individuals including no moderate-high intensity exercise in the 24 h prior to sessions and no stimulants or diuretics (e.g. caffeine or alcohol) 12 h prior to sessions. Participants were also asked to consume at least 40 mL·kg⁻¹ of water the day before the trial and 500 mL of water 2 h before arrival to the laboratory. All testing was conducted in a sub-tropical locality during the southern hemispheres spring season (September through November) when the 09:00 and 15:00 average outdoor dry-bulb temperature (t_{db}) and relative humidity (ϕ) were recorded as 22.4 ± 2.7 °C, 23.5 ± 3.1 °C and 61 ± 15%, 60 ± 15%, respectively (Australian Government Bureau of Meteorology, 2019). Testing was conducted in a

climate-controlled chamber (4 x 3 x 2.5 m; length, width, height), with conditions independently monitored using a wet bulb globe station (QUESTemp 36, 3M, USA) positioned at participants' hip height. Body composition was measured via an air displacement plethysmograph (BodPod, Cosmed, Italy) followed by a treadmill-based athletic protocol for aerobic capacity testing ($\dot{V}O_{2\text{peak}}$) via indirect calorimetry (TrueOne 2400, Parvo Medics, USA). Prior to commencement of the investigation, participants were required to be sized, fitted and familiarised with testing procedures, equipment and environmental conditions through at least one 40 min walking trial ($5 \text{ km}\cdot\text{h}^{-1}$, 1% grade) in full ensemble in t_{db} and ϕ set to $35 \text{ }^{\circ}\text{C}$ and 50%, respectively.

2.3. Experimental Procedures

Participants visited the laboratory on nine separate occasions, at the same time of day to control for variance in circadian rhythm and thermoregulation (Mills, 1966). On average, trials were separated by 7 ± 3 days. To mitigate any effects of fatigue and acclimation, a minimum separation period between trials of 48 h, and a maximum separation period of two sessions per week was set. Testing was conducted in two testing blocks, counter balanced (Latin Square); 1) the ASTM F2300-10 *standard test method*; and 2) a *critical environmental limits method*, both of which are described in detail in the subsequent sections. Irrespective of the method used, participants arrived with a first void mid-stream urine sample that was assessed for specific gravity (USG) (PAL-10S, Atago, Japan). A single 5 mL venous blood sample was collected from the median cubital vein for the attainment of serum-osmolality using the freezing point depression technique (Osmomat 030, Gonotec, Germany).

Participants self-inserted a single-use rectal thermistor (YSI 400, DeRoyal, USA) 12 cm past the anal sphincter to measure rectal temperature (t_{re}) (International Organization for Standardization, 2004c), and connected to a wireless logger programmed at 1 Hz (T-TEC7, Temperature Technology, Australia). Eight site (International Organization for Standardization, 2004c) mean skin temperature (t_{sk}) was measured with thermocron loggers set at 0.2 Hz (DS1971-F5 iButton, Maxim Integrated,

USA) and held in place with a single piece of adhesive tape (Premium Sportstape, Leuko, Germany). Mean body temperature (t_b) was calculated as per [Equation 7, Appendix A](#). Participants were then fitted with a chest strap and heart rate (HR) monitor (Team², Polar, Finland).

2.4. Clothing and Cooling Systems

Participants were provided with standard under and outer garments throughout all testing and wore their same footwear (athletic shoes) each session. Under garments consisted of a t-shirt (65% polyester, 35% cotton) and shorts (60% cotton, 38% polyester, 2% elastin; Hard Yakka, Australia), while outer garments consisted of a trouser and long sleeve single piece coverall (65% polyester, 35% cotton; Hard Yakka, Australia). This baseline ensemble, used as the control (CON) had an effective clothing insulation of 1.0 clo (International Organization for Standardization, 2007), and an intrinsic evaporative heat transfer resistance of $0.017 \text{ m}^2 \cdot \text{kPa} \cdot \text{W}^{-1}$ (International Organization for Standardization, 2007).

Two active personal cooling systems were utilised, capable of providing consistent and uninterrupted cooling for at least 150 min. Both cooling systems were worn as the first layer of clothing, immediately superficial to the skin with the undergarment t-shirt and outer garment coverall on top. The first system comprised an open circuit air-cooled venturi vest (AV) (0.23 m^2) (PN8450, Allegro Industries, USA) connected to an air compressor (free air delivery, $326 \text{ L} \cdot \text{min}^{-1}$, 11.5 cfm) (BC20-100L, Böss Compressors, Australia). Due to the air diffusion across the AV, as designed, it was difficult to measure continuous outgoing air temperature whilst in human operation. Pilot testing of the whole system in a modified Douglas bag (with one-way overflow valve) measured outflow air at $18 \text{ }^\circ\text{C } t_{db}$ and $30\% \phi$. The theoretical maximal cooling capacity of the AV was 413 W (dry convective cooling = 68 W, [Equation 1, Appendix A](#); evaporative cooling = 345 W, [Equation 2, Appendix A](#)).

The second system, a liquid-perfused vest (LV) (0.25 m²; KewlFit, Model 6626-PEV, TechNiche, USA), utilised a closed system cooling unit (iCool Compact+, iCoolsport, Australia) chilling water in an insulated reservoir at (14 °C). The chilled water was pumped into the vest at a rate of 0.45 L·min⁻¹ (AP1050, AquaPro, Australia) with inlet and outlet water temperatures independently monitored with a general purpose thermistor (YSI 400, DeRoyal, USA) via an associated data logger (Squirrel 2020 series, Grant Instruments, UK). The theoretical maximal (conductive) cooling capacity of the water-perfused vest was 409 W ([Equation 3, Appendix A](#)).

2.5. Testing via the ASTM F2300-10 Standard Test Method (Trials 1-3)

The three trials consisted of continuous walking on a motorised treadmill at both an individualised moderate work rate, defined by F2300-10 (ASTM International, 2016b) as 250-400 W (387 ± 35 W; 4.5 ± 0.3 km·h⁻¹), as well as a fixed relative heat production (5.0 ± 0.4 W·kg⁻¹) to account for any differences in body surface area within the sample (Ravanelli et al., 2017a). In the familiarisation trials, required work rates (i.e., treadmill speed and gradient) were approximated. Treadmill speed and gradient were then maintained for the subsequent *standard test method* trials. Trials were conducted in a uniform environment of 34.8 ± 0.2 °C t_{db} , 53 ± 2% ϕ , $v < 1.0$ m·s⁻¹. As per F2300-10, standardised termination criteria were applied: 1) t_{re} exceeding 39.0 °C (0 incidents), 2) HR exceeding 90% maximum (0 incidents), 3) volitional cessation (0 incidents), or 4) a time limit of 120 min (36 incidents). Throughout the entire 120 min trials, metabolic rate was continuously recorded through indirect calorimetry (TrueOne 2400, Parvo Medics, USA). A baseline recording of thermal sensation (Gagge et al., 1969) was collected inside the chamber in the minute immediately prior to walking. Every 15 min, perceived thermal sensation on a 13-point Taylor categorical scale (Lee et al., 2010), and rating of perceived exertion (RPE) on a 15-point scale (Borg, 1982) were recorded.

2.6. Determining the Critical Environmental Limits (Trials 4-9)

Work rates were required to permit compensable heat strain (317 ± 27 W; 3.7 ± 0.2 km·h⁻¹) - producing a fixed relative heat production of 4.1 ± 0.3 W·kg⁻¹. This allowed for the quantification of the critical environmental limits, where net heat storage begins, denoted by the individuals shift from a compensable to uncompensable state in the presence of increasing t_{db} or water vapour pressure (P_a). Each of the three ensemble conditions required two separate trials to determine T_{crit} and P_{crit} . In one trial, to derive P_{crit} , t_{db} was held constant (35.0 ± 0.1 °C) and after 40 min equalisation period, P_a was systematically increased by 0.16 kPa every 5 min. In the second trial, P_a was held constant (1.22 ± 0.05 kPa, ϕ 21.7 ± 0.8%) and after 40 min equalisation period, t_{db} was systematically increased by 0.7 °C every 5 min to establish T_{crit} . This method has been demonstrated to have a intraclass correlation coefficient of .99 (Dougherty et al., 2010).

Oxygen kinematics were continually monitored for the first 20 min of walking in trials 4 through 9. Due to the observed stability of key variables in the uncompensable conditions of trials 1–3, $\dot{V}O_2$ and RER were assumed to remain stable from 20 min, allowing the removal of the face-mask and mitigating any effect the facemask might have on the respective critical environmental limits.

To increase objectivity in identifying the inflection point of t_{re} , mathematical formula ([Equation 4](#), [Appendix A](#)) were used as per the method outlined in Kenney et al. (1993). Firstly, this required the selection of a window of between 40 and 60 min of the t_{re} data with the visual estimation of the inflection positioned in the middle of the window. Two lines of best fit are then applied the data, a linear regression through the beginning and end of the window, and a quadratic regression fit through all the window data. The point of maximum distance (D_{max}) between these two lines, set at perpendicular to the slope of the linear equation, was quantified as the inflection point with the corresponding environment representing either T_{crit} or P_{crit} .

2.7. Data Analysis

All analyses were performed in R (Version 3.5.0) using the RStudio environment (Version 1.2.1335). The sample size was determined a priori ($\beta = .80$, $\alpha = .05$, $f = 1.1$) using the ‘WebPower’ package (Zhang and Mai, 2018) and was informed from previous similar studies (Bernard et al., 2010; Kenney et al., 1988; Kulka and Kenney, 2002). The final sample of 12 participants surpassed the F2300-10 requisite sample size, “a minimum of five different participants” (ASTM International, 2016b).

Nude mass, blood osmolality, USG, RPE, thermal sensation, and final HR, t_{re} , t_{sk} , and t_b , and partitioned calorimetry variables were analysed using linear mixed-effects models - fit with restricted maximum likelihood estimation. Models were implemented in ‘lmerTest’ (Kuznetsova et al., 2017). Baseline or single time point models included condition as a fixed factor, and a random intercept for each participant. Exercise models (i.e., HR, t_{sk} , t_{re} and t_b) included time, condition and time by condition as fixed factors, and a random intercept for each participant. Candidate exercise models also considered non-linear terms for time (i.e., $time^{0.5}$, $time^2$, and $time^3$) and their interactions with condition. The final model was selected based on the smallest Bayesian Information Criterion value. Where there was evidence of statistical differences in baseline variables (i.e., nude mass, blood osmolality, USG), the respective variable was included as a standardised covariate, of no interest. Covariates were transformed using [Equation 12, Appendix A](#), where ‘ \bar{x} ’ is the sample mean, ‘ s ’ the sample standard deviation (SD), and ‘ y ’ the observed value.

Thermal sensation (1–13) and RPE (6–20) were modelled with a beta response distribution, using the ‘betareg’ package (Zeileis et al., 2010). The beta distribution is highly versatile and can accommodate a variety of distributional shapes and skewed errors often observed with bounded data (Smithson and Verkuilen, 2006). Before analysis, data were transformed to the (0, 1) beta interval using [Equation 13, Appendix A](#), where ‘ a ’ and ‘ b ’ are the smallest and largest possible scale values,

respectively, and 'y' is the observed value (Smithson and Verkuilen, 2006). Beta regression models included condition as a fixed factor.

Bonferroni corrected pairwise comparisons were made through 'emmeans' (Russell, 2018). For all variables except thermal sensation and RPE, the standardised difference, denoted d_r , between conditions (or time points) ' k ' and ' l ' was determined using [Equation 14, Appendix A](#), where ' d_{kl} ' is the mean difference between k and l , and ' s_{res} ' is the residual SD determined from the linear mixed model (Cohen, 1992; Rouder et al., 2012). The 95% CI of d_r was calculated using the 'psych' package (Revelle, 2015). Values of d_r were interpreted as small 0.20–0.49, medium 0.50–0.79, and large ≥ 0.80 (Cohen, 1992). Cliff's d , a non-parametric effect size measure, was utilised for RPE and thermal sensation. Cliff's d evaluates the probability of distributional differences between k and l , where values range from 1 (all values from $k > l$) to -1 (all values from $k < l$). A Cliff's d of zero would indicate perfectly overlapping distributions. Cliff's d and 95% CI were computed using the 'effsize' package (Torchiano and Torchiano, 2018), with values interpreted as small 0.147–0.329, medium 0.330–0.473, and large 0.474–1. Data are reported as the mean or mean difference (MD) and 95% CI.

3. Results

3.1. Standard Test Method

Baseline USG and blood osmolality were similar between conditions ([Table 2](#)). Parameter estimates from *standard test method* trials are shown in [Table 3](#) and [Table 4](#). Baseline nude mass was greater in LV versus CON (MD [95% CI] = 0.5 kg [0.1, 1.0]; $p = .03$; d_r [95% CI] = 1.18 [0.23, 2.10]). Because there was evidence that baseline nude mass was different, all exercise models adjusted for baseline nude mass. Final RPE was lower in LV versus CON (MD = -1.3 [-2.5, -0.2]; $p = .02$; Cliff's $d = -0.47$ [-0.77, -0.01]). Final thermal sensation was lower in AV versus CON (MD = -1.7 [-2.8, -0.7]; $p < .001$; Cliff's $d = -0.81$ [-0.93, -0.47]), and lower in LV versus CON (MD = -1.6 [-2.7, -0.6]; $p < .001$; Cliff's $d = -0.71$ [-0.89, -0.33]).

[Figure 1](#) shows HR, t_{re} , t_{sk} , and t_b during exercise. HR in AV versus CON was statistically higher at 0 min ($p = .007$; $d_r = 0.22$ [-0.59, 1.03]) and statistically lower from 40–120 min (all $p < .001$; $d_r = -2.82$ to -0.28). HR in LV versus CON was statistically higher at 0 min ($p < .001$; $d_r = 0.52$ [-0.32, 1.34]) and statistically lower from 40–120 min (all $p < .001$; $d_r = -2.85$ to -0.60). t_{re} was statistically lower in AV versus CON from 40–120 min ($p < .001$ to $p = .01$; $d_r = -2.15$ to -0.15). t_{re} was statistically higher in LV versus CON at 0 and 20 min ($p < .001$ for both; $d_r = 0.42$ [-0.40, 1.23] and 0.31 [-0.50, 1.12], respectively) and lower from 60–120 min ($p < .001$ to $p = .0035$; $d_r = -1.67$ to -0.19). t_{sk} was statistically lower across the entire 120 min in AV versus CON (all $p < .001$; $d_r = -3.27$ to -1.79), and LV versus CON (all $p < .001$; $d_r = -4.30$ to -2.49). t_{sk} was statistically lower in LV versus AV from 0–120 min (all $p < .001$; $d_r = -1.99$ to -0.70). t_b was statistically lower from 0–120 min in AV versus CON (all $p < .001$; $d_r = -3.64$ to -1.12), and LV versus CON (all $p < .001$; $d_r = -4.32$ to -1.10). t_b was statistically lower in LV versus AV from 20 min onwards (all $p \leq .001$; $d_r = -0.85$ to -0.23).

3.2. Critical Environmental Limits

Baseline and key variables at D_{\max} for T_{crit} and P_{crit} are shown in [Table 2](#), and [Table 3](#) displays the parameter estimates from these models. There was little evidence that baseline nude mass or USG were statistically different between any condition for T_{crit} and P_{crit} trials, or that baseline serum osmolality was statistically different between conditions for P_{crit} trials. Baseline serum osmolality for T_{crit} trials was statistically higher in LV compared to CON (MD [95% CI] = 5 mOsm·kg⁻¹ [1, 8]; $p = .007$; d_r [95% CI] = 1.76 [0.66, 2.82]). Because there was evidence that baseline serum osmolality was different between conditions, all T_{crit} final exercise value models adjusted for baseline serum osmolality. Critical upper limits for all conditions are displayed in [Figure 2](#). The critical upper limit of t_{db} (i.e., T_{crit}) was statistically higher LV versus CON (MD = 3.3 °C [1.9, 4.8]; $p < .001$; $d_r = 2.48$ [1.16, 3.75]) and versus AV (MD = 3.4 °C [2.0, 4.9]; $p < .001$; $d_r = 2.55$ [1.21, 3.84]). The critical upper limit of P_a (i.e., P_{crit}) was statistically higher in AV versus CON (MD = 0.67 kPa [0.37, 0.98]; $p < .001$; $d_r = 2.36$ [1.08, 3.59]), and LV versus CON (MD = 0.67 kPa [0.37, 0.97]; $p < .001$; $d_r = 2.35$ [1.07, 3.59]). As shown previously by others (Kamon and Avellini, 1979; Kamon et al., 1978; Kenney et al., 1988), a straight line joining T_{crit} and P_{crit} is an approximate representation of the limits across a psychrometric chart. A visual depiction of the critical limits is displayed in [Figure 3](#).

3.3. Partitional Calorimetry

Mean values of all biophysical parameters for each condition are displayed in [Table 5](#), and [Table 6](#) the parameter estimates from these models. The separation of C_{skin} and K_{skin} from their respective cooling vests was based on the assumption that they equalled the difference between the calculated E_{req} to maintain heat balance and the maximal evaporative potential (E_{max}) for the given clothing, environment, skin temperature and body surface area. So, C_{skin} or $K_{\text{skin}} = (E_{\text{req}} - E_{\text{max}}) + H_{\text{dry_skin}}$, where $H_{\text{dry_skin}} = C_{\text{amb}} + R_{\text{skin}} + K_{\text{amb}}$; with K_{amb} assumed to be zero for walking.

Analysis of the key parameters of partitional calorimetry showed statistically differences between the AV and LV in T_{crit} trials for $H_{\text{dry_skin}}$ (MD [95% CI] = -37.7 W [-48.5, -26.9]; $p < .001$; d_r [95% CI] = 3.70 [1.96, 5.40]), H_{res} (MD = -3.1 W [-4.8, -1.5]; $p < .001$; d_r = 1.98 [0.82, 3.11]), $H_{\text{evap_skin}}$ (MD = -42.4 W [-56.9, -27.9]; $p < .001$; d_r = 3.09 [1.57, 4.57]), C_{skin} or K_{skin} (MD = 80.6 W [56.0, 105.2]; $p < .001$; d_r = 3.46 [1.81, 5.08]), and E_{req} (MD = 38.2 W [31.99, 66.9]; $p < .001$, d_r = -2.32 [-3.54, -1.05]).

Differences were seen in the LV and CON at the end of T_{crit} trials for $H_{\text{dry_skin}}$ (MD [95% CI] = -42.2 W [-50.3, -34.0]; $p < .001$; d_r [95% CI] = 4.14 [2.24, 6.00]), H_{res} (MD = -2.6 W [-3.9, -1.3]; $p < .001$; d_r = 1.64 [0.57, 2.66]), $H_{\text{evap_skin}}$ (MD = -57.9 W [-68.9, -47.0]; $p < .001$; d_r = 4.22 [2.29, 6.11]), K_{skin} (MD = 107.3 W [88.8, 125.9]; $p < .001$; d_r = 4.61 [2.54, 6.66]), and E_{req} (MD = 49.4 W [36.3, 62.6]; $p < .001$; d_r = -3.00 [-4.45, -1.51]).

The AV and CON differed in P_{crit} trials for H_{prod} (MD [95% CI] = 21.3 W [9.6, 33.1]; $p = .005$; d_r [95% CI] = -1.45 [-2.43, -0.43]), $H_{\text{dry_skin}}$ (MD = -12.4 W [-16.8, -8.1]; $p < .001$; d_r = 2.30 [1.04, 3.52]), H_{res} (MD = -3.0 W [-4.4, -1.7]; $p < .001$; d_r = 1.80 [0.68, 2.87]), $H_{\text{evap_skin}}$ (MD = -94.8 W [-108.0, -81.7]; $p < .001$; d_r = 5.77 [3.25, 8.26]), C_{skin} (MD = 131.7 W [114.9, 148.4]; $p < .001$; d_r = 6.26 [3.55, 8.94]), and E_{req} (MD = 36.8 W [25.0, 48.6]; $p < .001$; d_r = -2.49 [-3.77, -1.17]).

Finally, for LV and CON in P_{crit} trials differences were present for H_{prod} (MD [95% CI] = -18.0 W [-22.3, -13.7]; $p < .001$; d_r [95% CI] = 3.33 [1.72, 4.90]), H_{res} (MD = -3.4 W [-4.7, -2.1]; $p < .001$; d_r = 2.02 [0.84, 3.15]), $H_{\text{evap_skin}}$ (MD = -109.2 W [-122.4, -96.1]; $p < .001$; d_r = 6.65 [3.79, 9.49]), K_{skin} (MD = 139.8 W [123.0, 156.6]; $p < .001$; d_r = 6.64 [3.78, 9.48]), and E_{req} (MD = 30.5 W [18.7, 42.3]; $p < .001$; d_r = -2.06 [-3.21, -0.87]).

Table 2. Mean [95% confidence interval] of variables before or during *standard test method* and *critical environmental limits* trials

VARIABLE	CON	AV	LV
STANDARD TEST METHOD			
BASELINE			
Nude mass (kg)	78.5 [71.8, 85.3]	78.7 [71.9, 85.5]	79.1 [72.3, 85.8]†
Serum osmolality (mOsm·kg ⁻¹)	288 [284, 291]	287 [283, 291]	288 [284, 292]
Urine specific gravity (au)	1.020 [1.015, 0.025]	1.019 [1.014, 1.024]	1.021 [1.016, 1.026]
EXERCISE			
Final HR (beats·min ⁻¹)	139 [122, 155]	120 [103, 136]†	120 [103, 136]†
Final t_{re} (°C)	38.3 [38.0, 38.6]	38.0 [37.7, 38.2]†	38.0 [37.7, 38.3]†
Final t_{sk} (°C)	35.9 [35.6, 36.1]	34.8 [34.5, 35.0]†	33.8 [33.6, 34.1]†‡
Final t_b (°C)	37.8 [37.5, 38.2]	37.3 [36.9, 37.7]†	37.2 [36.8, 37.6]†‡
Final RPE (6-20)	13 [12, 14]	12 [11, 13]	12 [11, 12]†
Final thermal sensation (1-13)	10 [10, 11]	8 [8, 9]†	9 [8, 9]†
CRITICAL ENVIRONMENTAL LIMITS			
T_{crit} BASELINE			
Nude mass (kg)	78.4 [71.7, 85.0]	78.4 [71.7, 85.0]	78.4 [71.7, 85.0]
Serum osmolality (mOsm·kg ⁻¹)	287 [285, 290]	289 [287, 292]	292 [290, 295]†
Urine specific gravity (au)	1.022 [1.018, 1.027]	1.021 [1.017, 1.026]	1.020 [1.016, 1.025]
T_{crit} EXERCISE			
HR at D_{max} (beats·min ⁻¹)	96 [89, 104]	97 [90, 104]	99 [91, 106]
t_{re} at D_{max} (°C)	37.7 [37.5, 37.8]	37.6 [37.5, 37.8]	37.8 [37.6, 37.9]
t_{sk} at D_{max} (°C)	35.5 [34.8, 36.3]	33.6 [33.0, 34.3]†	33.8 [33.0, 34.5]†
t_b at D_{max} (°C)	37.2 [37.0, 37.5]	36.8 [36.6, 37.0]†	37.0 [36.7, 37.2]
Final thermal sensation (1-13)	9 [9, 10]	9 [8, 10]	9 [8, 10]
P_{crit} BASELINE			
Nude mass (kg)	78.2 [71.6, 84.9]	78.4 [71.7, 85.0]	78.4 [71.8, 85.0]
Serum osmolality (mOsm·kg ⁻¹)	288 [285, 292]	288 [284, 292]	289 [285, 293]
Urine specific gravity (au)	1.023 [1.018, 1.027]	1.021 [1.017, 1.026]	1.019 [1.014, 1.023]
P_{crit} EXERCISE			
HR at D_{max} (beats·min ⁻¹)	97 [90, 104]	97 [90, 104]	98 [91, 105]
t_{re} at D_{max} (°C)	37.7 [37.5, 37.8]	37.8 [37.6, 37.9]	37.8 [37.6, 37.9]
t_{sk} at D_{max} (°C)	35.4 [35.0, 35.8]	33.8 [33.4, 34.2]†	33.2 [32.8, 33.6]†‡
t_b at D_{max} (°C)	37.2 [37.0, 37.4]	37.0 [36.8, 37.1]†	36.8 [36.7, 37.0]†
Final thermal sensation (1-13)	10 [9, 10]	9 [9, 10]	9 [9, 10]

Note. AV = air vest, CON = control, LV = liquid vest, T_{crit} = critical temperature, P_{crit} = critical vapour pressure, au = arbitrary units, HR = heart rate, t_{re} = rectal temperature, t_{sk} = mean skin temperature, t_b = mean body temperature, D_{max} = calculated point of inflection in rectal temperature. Statistical differences are shown in bold. † indicates statistically different to control ($p < .05$), ‡ indicates statistically different to AV ($p < .05$).

Table 3. Mean [95% confidence interval] parameter estimates for fixed effects from *standard test method* trials and *critical environmental limits* trials.

RESPONSE VARIABLE	β , AV	β , LV	β , COVARIATE
STANDARD TEST METHOD			
Pre nude mass (kg)	0.2 [-0.2, 0.5]	0.5 [0.2, 0.9]*	NA
Serum osmolality (mOsm·kg ⁻¹)	-0.4 [-5.4, 4.5]	0.5 [-4.5, 5.6]	NA
Urine specific gravity (au)	-0.001 [-0.007, 0.005]	0.001 [-0.005, 0.007]	NA
Final RPE ^a	-0.25 [-0.51, 0.01]	-0.4 [-0.6, -0.1]*	0.06 [-0.05, 0.17]
Final thermal sensation ^a	-0.6 [-0.9, -0.3]*	-0.6 [-0.8, -0.3]*	0.1 [-0.1, 0.2]
CRITICAL ENVIRONMENTAL LIMITS			
T_{crit} BASELINE			
Pre nude mass (kg)	0.00 [-0.47, 0.47]	-0.03 [-0.49, 0.44]	NA
Serum osmolality (mOsm·kg ⁻¹)	1.9 [-0.5, 4.5]	4.7 [2.3, 7.3]*	NA
Urine specific gravity (au)	-0.001 [-0.006, 0.003]	-0.002 [-0.006, 0.003]	NA
T_{crit} EXERCISE			
HR at D _{max} (beats·min ⁻¹)	0.4 [-4.9, 6.0]	2.2 [-4.4, 9.0]	-1.3 [-5.0, 2.2]
t _{re} at D _{max} (°C)	-0.04 [-0.14, 0.05]	0.10 [-0.02, 0.22]	-0.04 [-0.10, 0.03]
t _{sk} at D _{max} (°C)	-1.9 [-2.8, -1.1]*	-1.8 [-2.8, -0.8]*	0.2 [-0.3, 0.6]
t _b at D _{max} (°C)	-0.4 [-0.6, -0.2]*	-0.26 [-0.54, 0.00]	-0.02 [-0.15, 0.14]
Final thermal sensation ^a	-0.1 [-0.4, 0.2]	-0.1 [-0.4, 0.2]	0.1 [-0.1, 0.2]
P_{crit} BASELINE			
Pre nude mass (kg)	0.1 [-0.4, 0.7]	0.2 [-0.4, 0.7]	NA
Serum osmolality (mOsm·kg ⁻¹)	-0.3 [-4.7, 4.7]	-0.6 [-4.0, 5.7]	NA
Urine specific gravity (au)	-0.002 [-0.006, 0.002]	-0.004 [-0.008, 0.001]	NA
P_{crit} EXERCISE			
HR at D _{max} (beats·min ⁻¹)	0.6 [-2.9, 4.1]	1.1 [-2.4, 4.6]	NA
t _{re} at D _{max} (°C)	0.08 [-0.04, 0.20]	0.10 [-0.02, 0.22]	NA
t _{sk} at D _{max} (°C)	-1.6 [-2.0, -1.1]*	-2.2 [-2.7, -1.8]*	NA
t _b at D _{max} (°C)	-0.2 [-0.4, -0.1]*	-0.4 [-0.5, -0.2]*	NA
Final thermal sensation ^a	-0.1 [-0.3, 0.1]	-0.1 [-0.2, 0.1]	NA

Note. All variables fit with restricted likelihood estimation. Because there was evidence that nude mass at baseline was statistically higher in LV versus CON, all *standard test method* exercise models adjusted for baseline nude mass. au = arbitrary units, AV = air vest, CON = control, LV = liquid vest, RPE = rating of perceived exertion, ^a = (Logit-scale). Statistical differences are shown in bold. * indicates a statistically important effect ($p < .05$).

Table 4. Mean [95% confidence interval] parameter estimates for fixed effects from *standard test method* trials data models.

Model parameter	HR	t_{re}	t_{sk}	t_b
β , Intercept	97.8 [80.6, 115.0]*	37.9 [37.6, 38.1]*	35.5 [35.3, 35.8]*	37.4 [36.9, 37.8]*
β , Time	0.34 [0.33, 0.35]*	20.7 [20.2, 21.2]*	10.4 [8.8, 11.9]*	19.0 [18.5, 19.5]*
β , Time ²	NA	-2.9 [-3.4, -2.4]*	-16.4 [-18.0, -14.8]*	-5.2 [-5.7, -4.7]*
β , Time ³	NA	NA	16.2 [14.6, 17.8]*	3.7 [3.2, 4.2]*
β , AV	1.5 [0.5, 2.5]*	-0.10 [-0.11, -0.09]*	-1.19 [-1.23, -1.16]*	-0.34 [-0.35, -0.33]*
β , LV	3.4 [2.4, 4.5]*	-0.05 [-0.07, -0.04]*	-1.90 [-1.94, -1.87]*	-0.43 [-0.44, -0.42]*
β , Covariate	-27.6 [-33.3, -21.2]*	-0.4 [-0.5, -0.2]*	-0.04 [-0.33, 0.19]	-0.5 [-0.7, -0.4]*
β , Time x AV	-0.17 [-0.18, -0.16]*	-6.2 [-6.9, -5.4]*	10.3 [8.1, 12.6]*	-4.1 [-4.8, -3.4]*
β , Time x LV	-0.19 [-0.20, -0.17]*	-2.1 [-2.8, -1.3]*	7.1 [4.9, 9.4]*	-0.4 [-1.1, 0.3]
β , Time ² x AV	NA	-6.1 [-6.9, -5.4]*	-10.2 [-12.5, -8.0]*	-2.1 [-2.8, -1.4]*
β , Time ² x LV	NA	-1.3 [-2.0, -0.6]*	-2.5 [-4.7, -0.2]*	-6.6 [-7.3, -5.8]*
β , Time ³ x AV	NA	NA	9.4 [7.2, 11.7]*	0.75 [0.04, 1.47]*
β , Time ³ x LV	NA	NA	-9.4 [-11.6, -7.1]*	-1.8 [-2.5, -1.1]*

Note. AV = air vest, CON = control, LV = liquid vest, au = arbitrary units, HR = heart rate, t_{re} = rectal temperature, t_{sk} = mean skin temperature, t_b = mean body temperature. NA = Not applicable. Statistical differences are shown in bold. * indicates a statistically important effect ($p < .05$).

Table 5. Partitional Calorimetry – The effect of air or liquid cooling on human heat balance at point of rectal temperature inflection in *critical environmental limits* trials.

		t_{db} °C	P_a kPa	ϕ %	H_{prod} W	H_{dry_skin} W	H_{res} W	H_{evap_skin} W	C_{skin} or K_{skin} W	E_{req} W
T_{crit}	CON	39.5 [38.1, 40.8]	1.58 [1.47, 1.70]	22.0 [21.6, 22.4]	313 [297, 328]	-32 [-43, -22]	21 [20, 23]	324 [307, 341]	0 [-19, 19]	324 [305, 343]
	AV	39.4 [38.0, 40.7]	1.59 [1.47, 1.70]	22.2 [21.7, 22.6]	320 [305, 336]	-37 [-47, -27]	22 [20, 23]	309 [292, 325]	27 [8, 45]	335 [316, 354]
	LV	42.8†‡[41.4, 44.2]	1.84†‡[1.72, 1.96]	21.4 [21.0, 21.8]	318 [302, 333]	-75†‡[-85, -64]	19†‡[17, 20]	266†‡[249, 283]	107†‡[89, 126]	374†‡[355, 392]
P_{crit}	CON	34.9 [34.8, 35.0]	2.37 [2.13, 2.62]	42.4 [38.1, 46.7]	307 [289, 325]	5 [1, 9]	19 [17, 21]	267.6 [250, 285]	16 [3, 29]	283 [267, 299]
	AV	35.0 [34.9, 35.1]	3.09†[2.85, 3.33]	55.1†[50.8, 59.4]	328†[311, 346]	-7†[-11, -3]	16†[14, 18]	173†[155, 191]	147†[134, 160]	320†[304, 336]
	LV	34.9 [34.8, 35.0]	3.08†[2.84, 3.32]	55.0†[50.7, 59.3]	316.0 [298, 334]	-13†[-17, -9]	15†[13, 17]	158†[140, 176]	155†[142, 168]	314†[298, 330]

Note. Mean [95% confidence interval]. By definition at D_{max} heat storage (S) was assumed to be zero. T_{crit} = critical dry bulb trials, P_{crit} = critical vapour pressure trials, CON = control, AV = air vest, LV = liquid vest, t_{db} = dry bulb temperature, P_a = water vapour pressure, ϕ = relative humidity, H_{prod} = metabolic heat produced, H_{dry_skin} = net sensible dry heat exchange at the skin, H_{res} = net heat loss through respiration, H_{evap_skin} = assumed to be the maximal latent evaporative heat loss at the skin, E_{req} = resultant heat loss needed for a body heat storage of zero, C_{skin} = convective heat exchange at the skin (applicable for the AV condition) taken as the difference between E_{req} - H_{evap_skin} and then incorporated into H_{dry_skin} values, K_{skin} = conductive heat exchange at the skin (applicable for the LV condition) taken as the difference between E_{req} - H_{evap_skin} and then incorporated into H_{dry_skin} values. † = statistically different to control ($p < .05$), ‡ = statistically different to AV ($p < .05$).

Table 6. Mean (95% confidence interval) parameter estimates for fixed effects from Partitional Calorimetry calculations.

RESPONSE VARIABLE	β , Intercept	β , AV	β , LV
<i>T</i>_{crit} TRIALS			
<i>t</i> _{db} (°C)	39.5 [38.2, 40.7]*	-0.1 [-1.2, 1.0]	3.3 [2.3, 4.4]*
<i>P</i> _a (kPa)	1.6 [1.5, 1.7]*	0.01 [-0.09, 0.10]	0.26 [0.16, 0.36]*
Φ (%)	22.0 [21.6, 22.4]*	0.2 [-0.3, 0.7]	-0.6 [-1.1, -0.1]*
<i>H</i> _{prod} (W)	312.8 [298.3, 327.4]*	7.3 [-4.8, 19.4]	4.7 [-7.4, 16.8]
<i>H</i> _{dry_skin} (W)	-32.4 [-42.1, -22.7]*	-4.5 [-12.6, 3.7]	-42.2 [-50.3, -34.0]*
<i>H</i> _{res} (W)	21.2 [19.7, 22.7]*	0.6 [-0.7, 1.8]	-2.6 [-3.9, -1.3]*
<i>H</i> _{evap_skin} (W)	324.1 [308.2, 340.0]*	-15.5 [-26.5, -4.6]*	-58.0 [-68.9, -47.0]*
<i>C</i> _{skin} or <i>K</i> _{skin} (W)	-0.03 [-17.7, 17.7]	26.7 [8.2, 45.3]*	107.3 [88.8, 125.9]*
<i>E</i> _{req} (W)	324.1 [306.4, 341.7]*	11.2 [-1.9, 24.4]	49.4 [36.3, 62.6]*
<i>P</i>_{crit} TRIALS			
<i>t</i> _{db} (°C)	34.9 [34.8, 35.0]*	0.1 [-0.1, 0.2]	0.02 [-0.10, 0.15]
<i>P</i> _a (kPa)	2.4 [2.1, 2.6]*	0.7 [0.5, 0.9]*	0.7 [0.5, 0.9]*
Φ (%)	42.4 [38.4, 46.4]*	12.7 [9.3, 16.1]*	12.6 [9.2, 16.0]*
<i>H</i> _{prod} (W)	306.9 [290.4, 323.4]*	21.4 [9.6, 33.3]*	9.1 [-2.6, 20.9]
<i>H</i> _{dry_skin} (W)	5.2 [1.4, 8.9]*	-12.4 [-16.8, -8.1]*	-18.0 [-22.3, -13.7]*
<i>H</i> _{res} (W)	18.7 [16.9, 20.4]*	-3.0 [-4.4, -1.7]*	-3.4 [-4.7, -2.1]*
<i>H</i> _{evap_skin} (W)	267.6 [250.8, 284.3]*	-94.8 [-108.0, -81.7]*	-109.2 [-122.4, -96.1]*
<i>C</i> _{skin} or <i>K</i> _{skin} (W)	15.6 [3.3, 27.8]*	131.7 [114.9, 148.4]*	139.8 [123.0, 156.6]*
<i>E</i> _{req} (W)	283.1 [268.0, 298.2]*	36.8 [25.0, 48.6]*	30.5 [18.7, 42.3]*

Note. *T*_{crit} = critical dry bulb trials, *P*_{crit} = critical vapour pressure trials, AV = air vest, LV = liquid vest, *t*_{db} = dry bulb temperature, *P*_a = water vapour pressure, ϕ = relative humidity, *H*_{prod} = metabolic heat produced, *H*_{dry_skin} = net sensible dry heat exchange at the skin, *H*_{res} = net heat loss through respiration, *H*_{evap_skin} = assumed to be the maximal latent evaporative heat loss at the skin, *E*_{req} = resultant heat loss needed for a body heat storage of zero, *C*_{skin} = convective heat exchange at the skin (applicable for the AV condition) taken as the difference between *E*_{req} - *H*_{evap_skin} and then incorporated into *H*_{dry_skin} values, *K*_{skin} = conductive heat exchange at the skin (applicable for the LV condition) taken as the difference between *E*_{req} - *H*_{evap_skin} and then incorporated into *H*_{dry_skin} values. Statistical differences are shown in bold. * indicates a statistically important effect (*p* < .05).

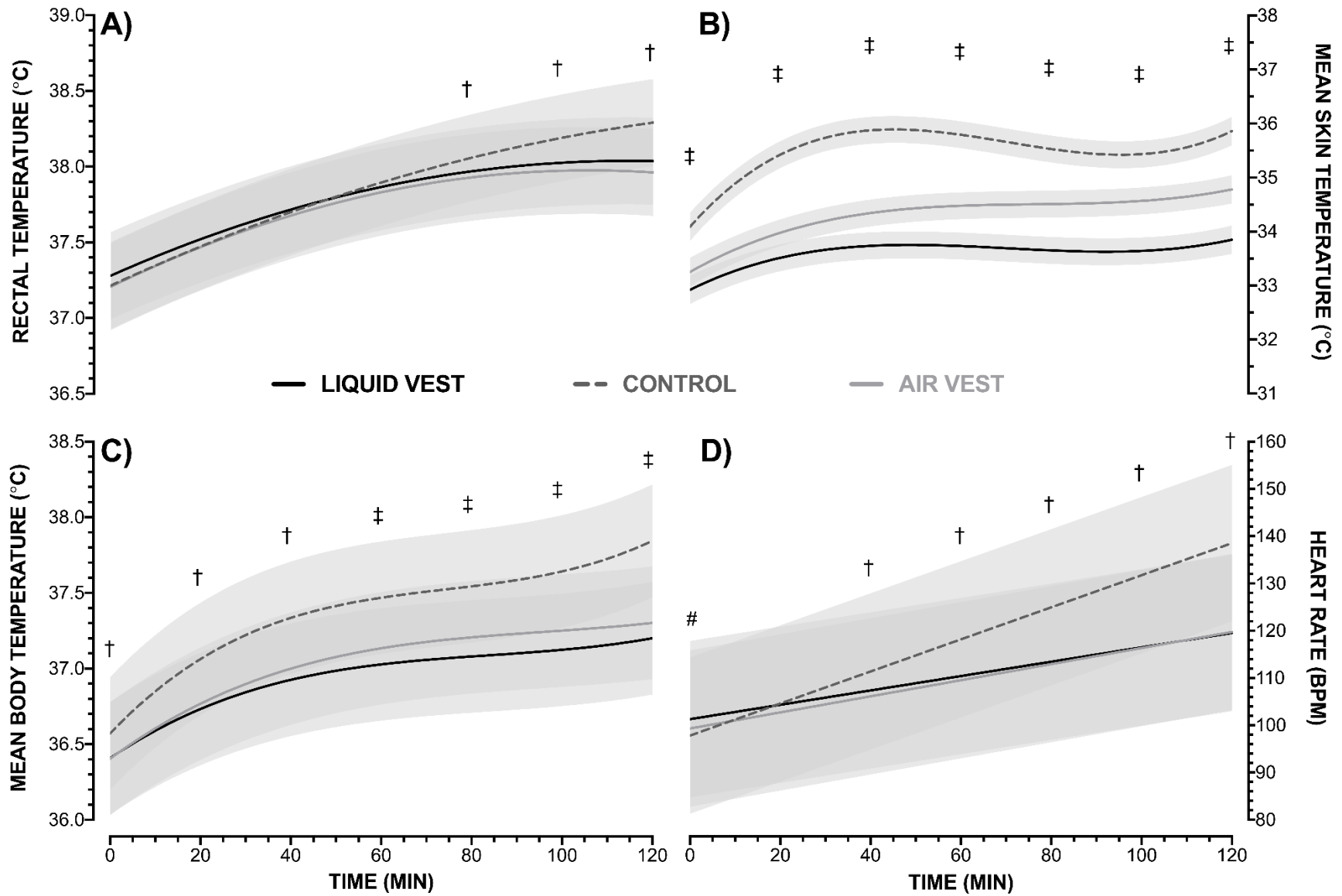


Figure 1. Mean (95% confidence interval) from models fit with restricted maximum likelihood estimation for A) rectal temperature, B) mean skin temperature, C) mean body temperature, and D) heart rate during *standard test method* trials. Symbols displayed for time points where both statistical differences ($p < .05$) and a medium effect size ($d_r > 0.5$) were present. Differences between control and liquid vest denoted as #; between control and both the liquid and air vest denoted as †; and between all three conditions denoted as ‡.

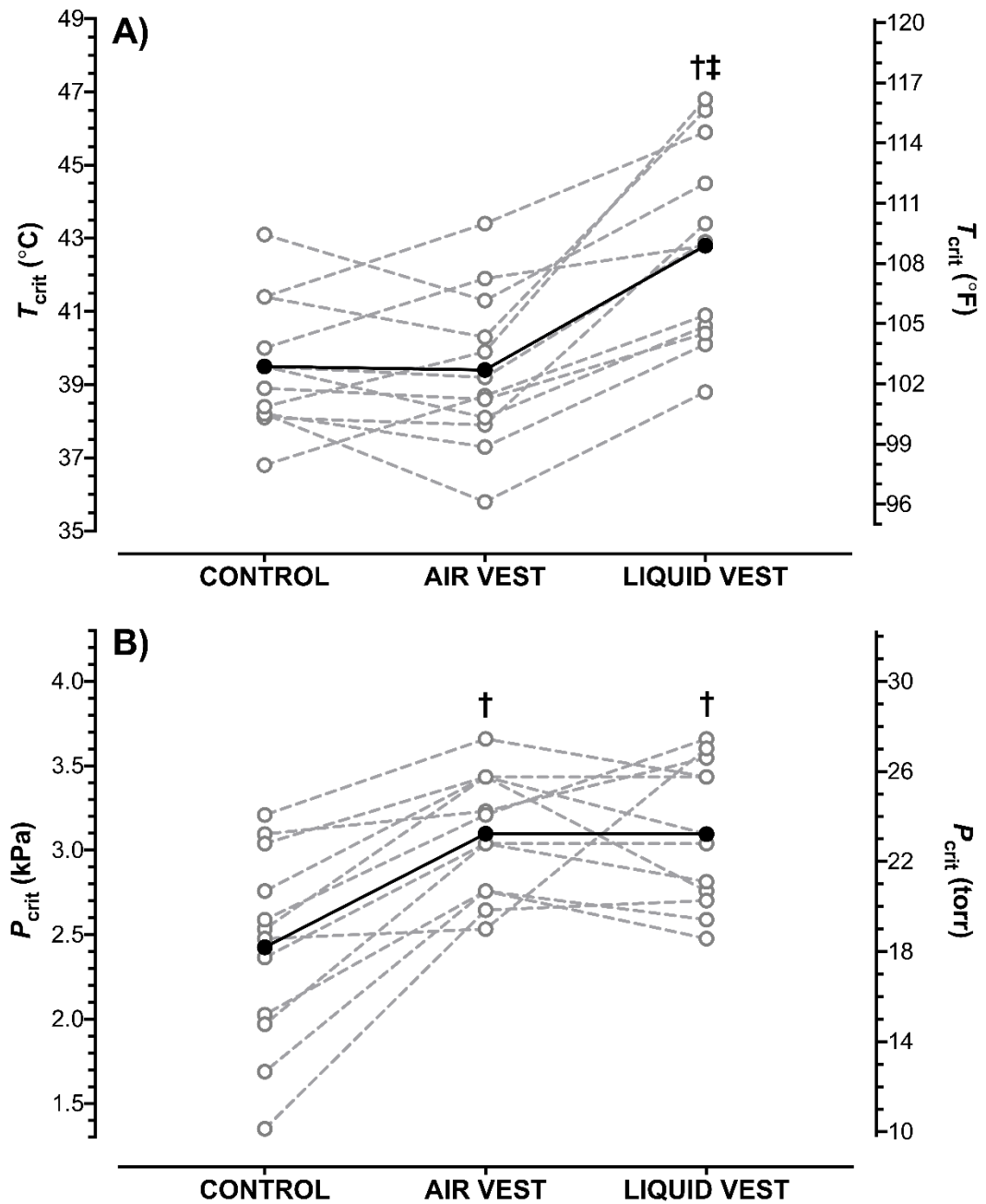


Figure 2. Individual critical environmental limits for control, the air vest and liquid vest. A) critical temperature (T_{crit}), B) critical vapour pressure (P_{crit}). † = statistically different to control ($p < .05$), ‡ = statistically different to AV ($p < .05$).

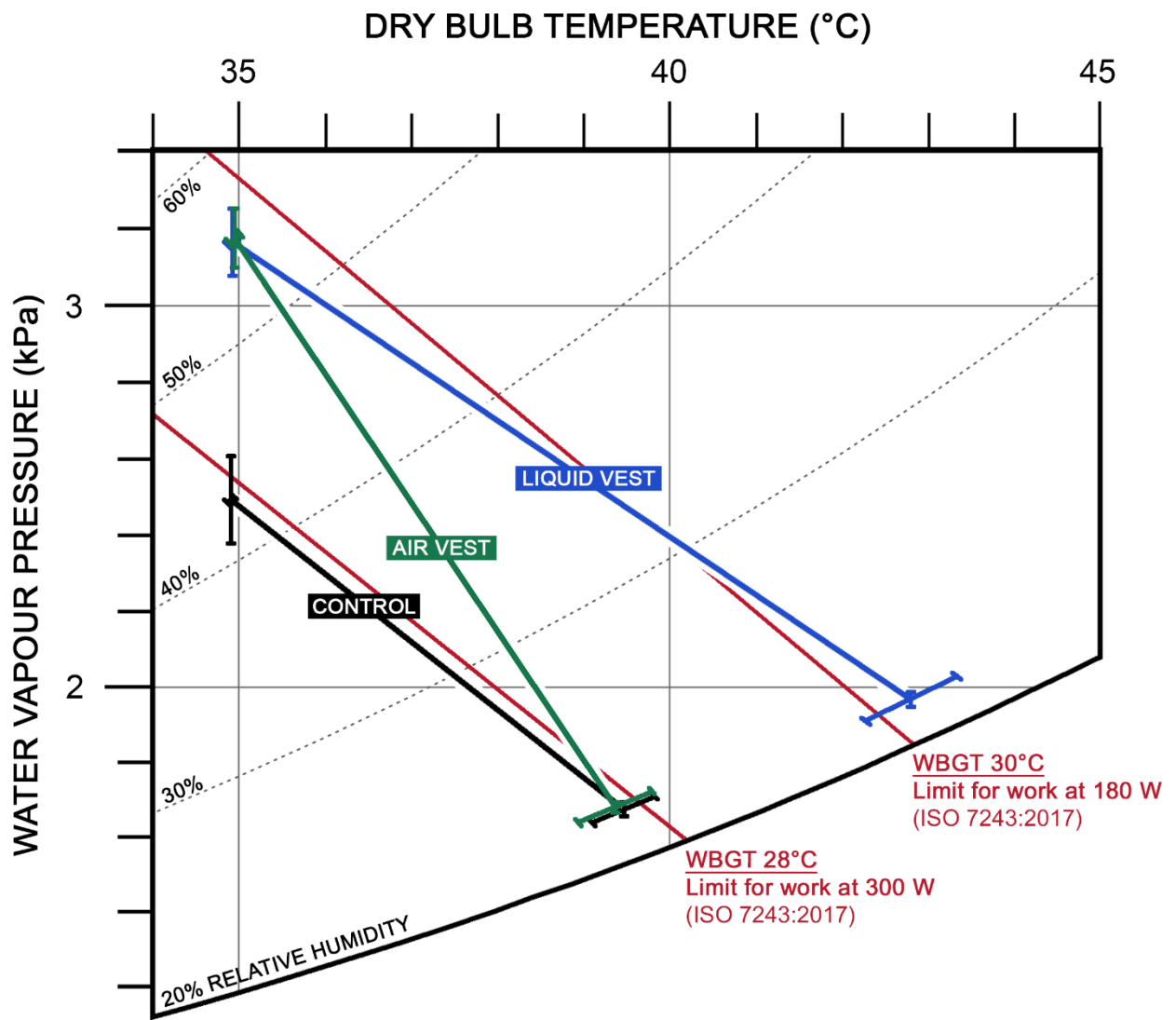


Figure 3. Psychrometric representation of the critical environmental limits of control, the air vest and liquid vest. Red lines represent the wet bulb globe temperature limit for work rates of 300 W and 180 W per ISO 7243:2017. Data displayed as mean and 95% confidence interval.

4. Discussion

The present investigation established that single environmental testing, as per the F2300-10 *standard test method*, was unable to delineate significant or meaningful differences in the key physiological variables of cardiovascular strain and deep body temperature between two continuous cooling systems utilising different heat loss mechanisms but matched in theoretical cooling capacity. With regards to trials defining the *critical environmental limits*, compiling biophysical data was able to identify significant differences in efficiency between the cooling systems. Illustrated by a delay in positive heat storage and thus, a rightward shift in T_{crit} and P_{crit} for the LV on a psychrometric chart relative to CON. In contrast, the AV T_{crit} was no greater than that of CON, with only AV P_{crit} denoting an improvement analogous to the LV condition. Partitioning the components of heat transfer further elucidated key differences in heat transfer mechanisms for a given environment. One of those being, no appreciable addition of evaporative cooling at the skin with the AV in the hot, dry, T_{crit} trials.

An earlier investigation by Vallerand and colleagues (1991) demonstrated air and liquid perfused cooling vests, matched for cooling power, can be equally effective in reducing heat strain while wearing chemical protective clothing (50:50 work rest protocol for 150 min). Similarly, the current investigation saw all participants, in all conditions, able to complete the entire 120 min of continuous work as per the *standard test method*. Both the AV and LV reduced cardiovascular strain and t_{rec} relative to CON ([Figure 1](#)). Predictably, significant differences in t_{sk} and subsequently calculated t_b were observed due to the different operating temperatures of the AV (18 °C) and LV (13.5 °C). Considering the ASTM F2300-10 *standard test method* dictates a single fixed environment of 35 °C t_{db} and 50% ϕ , it is clearly not representative of the wide range of possible conditions encountered by first responders, military personnel or industrial workers (Hanna et al., 2011). Viewing the findings from the *standard test method* in isolation may lead administrators to wrongfully assume the two cooling systems to be equal across a range of ensembles, occupations and/or environments.

The implementation of the *critical environmental limits* protocol saw that during T_{crit} trials, where t_{db} was incrementally increased, low water vapour pressures facilitated high evaporative heat loss, until maximal sweat rate became insufficient to maintain heat balance. This is apparent when parsing the components of the heat balance equation between conditions ([Table 6](#)). Given the reasonably permeable nature of the base ensemble (evaporative resistance of clothing = $0.016 \text{ m}^2 \cdot \text{kPa} \cdot \text{W}^{-1}$), the AV was unable to provide any additional evaporative potential ($308 \pm 28 \text{ W}$ at $39.4 \text{ }^\circ\text{C}$) compared to CON ($324 \pm 30 \text{ W}$ at $39.5 \text{ }^\circ\text{C}$). Conversely, the LV was able to supplement cooling via conduction ($107 \pm 36 \text{ W}$) in addition to readily apparent evaporative cooling ($266 \pm 25 \text{ W}$) that translated to a higher T_{crit} (42.8 ± 1.5 vs. $39.4 \pm 1.2^\circ\text{C}$). Regarding the P_{crit} trials, both cooling interventions became more advantageous than CON during the progressive restriction of latent evaporative heat loss ([Table 6](#)). Given evaporation of sweat is the primary means of heat loss during most activity based scenarios, accounting for up to 90% of total heat loss during exercise (American College of Sports Medicine, 2007), the AV provided cool, dry air around the torso improving evaporation and convection and thus maintained heat balance for a higher P_{crit} relative to CON. The LV circulating cold-water provided an enhanced avenue for conductive cooling across the torso leading to analogous improvements in P_{crit} as in the AV.

An ability to maintain a thermal equilibrium at higher environmental extremes is of great value in many labour-intensive occupations. The results depicted in [Figure 3](#) show an ability of the LV to functionally shift the upper wet bulb globe temperature (WBGT) limit for work at 300 W to a greater environmental intensity for the same metabolic cost, i.e., a higher WBGT limit normally reserved for work performed at a lower intensity (180 W) (International Organization for Standardization, 2017). The same shift was not seen in the AV for P_{crit} trials, with the AV being no more superior to CON. To put this in context, imagine a scenario where personal cooling was implemented upon the basis of a known upper threshold of $30 \text{ }^\circ\text{C}$ WBGT ($43 \text{ }^\circ\text{C}$ t_{db} , $20\% \phi$). An air-based cooling system is used to help aid

in reducing thermal strain on the employees as previous research has defined its potential cooling to be as effective as a similar water-based system (Vallerand et al., 1991). As per policy recommendations, work-rest schedules, exposure times and prescribed work rates are adjusted to improve productivity of the workers. Despite the administrators' best intentions, the evaporative efficiency in the hot/dry work setting is already high, approaching maximal, and the now higher relative work rates and increased exposure times place workers at a greater risk of heat illness or injury than providing no cooling at all. However, much like a yet to be defined '*ideal*' heat stress index would aim to quantify the total heat stress imposed on an individual regardless of the composition of environmental variables, the effectiveness of cooling systems should be known to end users across a range of ambient fractions. Therefore, removing the potential to under or overestimate the efficacy of systems in for example, hot-dry versus warm-wet environments. The use of a single fixed environment allows for simple comparisons between different cooling system technologies, but as shown in this study, performance evaluation outcomes should not be extrapolated to other environments. Based upon first principles, any substantial variation in air temperature, humidity and air velocity could influence the effectiveness of systems. Regarding the greatest influences, it is important to be cognisant of any factors that may inhibit evaporative pathways. Whether that be the unfavourable effects of increased evaporative resistance from uniforms (Kulka and Kenney, 2002) or protective clothing (Kenney et al., 1988), reductions in air velocities (Kamon and Avellini, 1979; Morrison et al., 2014) or lowered skin and ambient vapour pressure gradients (Maughan et al., 2012).

The application of a single environment to test cooling systems may highlight a larger failure within broader heat management standards and policy. The absence of specificity and individualisation has been highlighted as a concern in climate public policy for cooling practices needed for infants, elderly and clinical populations (Jay and Capon, 2018). Current policies may oversimplify the key measures of environmental parameters and indices in order

to facilitate a wider adoption from a more general audience. To cloud the issue further, even within the same respective field (e.g., public health, occupational and athletics), policy can provide different values for the upper limits of a given environmental index (International Organization for Standardization, 2017; Jacklitsch B et al., 2018). Recently, leading health administrations, the World Health Organisation (2017), the U.S. Environmental Protection Agency (2016) and the U.S. Centre for Disease Control (2017) heatwave policies have been critiqued for overly simplifying and misinterpreting the science associated with human heat exchange (Morris et al., 2019; Ravanelli et al., 2015). Specifically, for their advice not to use electric fans for personal cooling when $t_{db} > 35$ °C (Morris et al., 2019; Ravanelli et al., 2015) or using a heat index as a means to determine relative risk (Morris et al., 2019). The key misinterpretation being, that if ambient temperatures begin to exceed that of the skin (e.g., >35 °C) heat gain will be precipitated with fan use via conduction. This recommendation seems to have been made in the absence of any substantiating evidence (Jay and Capon, 2018). Nor does it account for 1) different combinations of temperature and vapour pressure, 2) the opportunity for improved evaporative potential, or 3) the reduced convective heat gain due to (protective) clothing.

5. Conclusion

Overall, this study used an evidence-based approach to demonstrate that a single environment, as per the ASTM F2300-10 standard test method, failed to delineate differences between two continuous cooling systems promoting discrete mechanisms of heat loss. When in fact, relative to no cooling, the use of the air-based cooling vest provides no additional evaporative cooling in a low water vapour pressure environment, and therefore no increase in the upper limits of critical temperature. This should highlight to administrators and end users not assume that one size fits all for effective personal cooling systems if applied outside of the environment it was tested. Based on these findings, it is suggested that more specific recommendations be adopted by the ASTM F2300-10 standard in relation to the evaluation of

cooling ensembles. Rather than prescribing a single environment ($35\text{ }^{\circ}\text{C}$ t_{db} , 50% ϕ), we suggest a range of environments be recommended for the evaluation of personal cooling systems to ensure systems that are ineffective in certain ambient conditions can be identified.

Author Contributions

The authors declare that the research was conducted in the absence of any commercial or financial relationships and have no competing interests. All authors approved the final version of the manuscript, agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved, and all persons that qualify for authorship are listed.

Appendix A. Calculations

Cooling System Equations

$$C_{AV} = \frac{[(Q_{air} \cdot \rho_{air}) \cdot C_p \cdot (t_{AV} - t_{sk})]}{60} \quad [1]$$

where,

C_{AV} = convective cooling capacity (W)

Q_{air} = air flow rate ($L \cdot \min^{-1}$)

ρ_{air} = air density at 18 °C ($kg \cdot m^{-3}$)

C_p = isobaric heat capacity of air ($kJ \cdot kg^{-1} \cdot C^{-1}$)

t_{AV} = temperature of air from the vest (°C)

t_{sk} = right scapular skin temperature (°C)

$$E_{AV} = \frac{[(Q_{air} \cdot \rho_{air}) \cdot C_p \cdot (AH_{AV} - AH_{sk})]}{60} \quad [2]$$

where,

E_{AV} = evaporative cooling capacity (W)

C_p = latent heat capacity of air ($kJ \cdot kg^{-1} \cdot C^{-1}$)

AH_{AV} = absolute humidity of AV outflow ($g \cdot m^{-3}$)

AH_{skin} = absolute humidity of saturated air at right scapula skin temperature ($g \cdot m^{-3}$)

$$K_{LV} = \frac{[(Q_{water} \cdot \rho) \cdot C_v \cdot (t_{LV_outlet} - t_{LV_inlet})]}{60} \quad [3]$$

where,

K_{LV} = conductive cooling capacity (W)

Q_{water} = water flow rate ($L \cdot \min^{-1}$)

ρ_{water} = water density at t_{LV_inlet} temperature ($m^3 \cdot kg$)

C_v = isochoric heat capacity of water ($kJ \cdot kg^{-1} \cdot C^{-1}$)

t_{LV_outlet} = water temperature from vest (28 °C)

t_{LV_inlet} = water temperature into vest (13 °C)

Physiological Equations

For each minute, subtracting the linear equation from the quadratic derived the furthest distance and therefore the inflection point in t_{rec} Kenney et al. (1993):

$$D_{max} = [(m \cdot x + c) - (a \cdot x^2 + b \cdot x + c)] \quad [4]$$

Body surface area, originally described by Du Bois and Du Bois (1916), was estimated from:

$$A_D = 0.202 \cdot (l^{0.725} \cdot m^{0.425}) \quad [5]$$

where,

A_D = body surface area (m²)

l = height (m)

m = body mass (kg)

Mean skin temperature was calculated from a weighted 8-site equation (International Organization for Standardization, 2004c).

$$t_{sk} = 0.07 \cdot t_{forehead} + 0.175 \cdot t_{left\ chest} + 0.175 \cdot t_{right\ scapula} + 0.07 \cdot t_{right\ upper\ arm} \\ + 0.07 \cdot t_{left\ lower\ arm} + 0.05 \cdot t_{left\ hand} + 0.19 \cdot t_{right\ anterior\ thigh} + 0.2 \cdot t_{left\ calf} \quad [6]$$

where,

t_{sk} = mean skin temperature (°C)

t_x = the specific site location

Mean body temperature (°C) was then derived using [Equation 7](#) (International Organization for Standardization, 2004c):

$$t_b = 0.8 \cdot t_{re} + 0.2 \cdot t_{sk} \quad [7]$$

where,

t_b = mean body temperature (°C)

t_{re} = rectal temperature (°C)

Each component of human heat exchange was calculated as outlined below, using the methods recently reviewed by Cramer and Jay (2018).

Metabolic energy expenditure:

$$H_{prod} = M - W \quad [8]$$

where,

H_{prod} = net metabolic heat produced (W)

Dry heat exchange:

$$H_{dry_skin} = C_{skin} + R_{skin} + K_{skin} \quad [9]$$

where,

H_{dry_skin} = net sensible dry heat exchange at the skin (W)

C_{skin} = convective heat exchange at the skin (W)

R_{skin} = radiative heat exchange at the skin (W)

K_{skin} = conductive heat exchange at the skin (W)

Heat loss via respiration:

$$H_{\text{res}} = C_{\text{res}} + E_{\text{res}} \quad [10]$$

where,

H_{res} = net heat loss through respiration (W)

C_{res} = convective heat loss through respiration (W)

E_{res} = latent evaporative heat loss through respiration (W)

At the time point of t_{re} inflection, it is assumed that heat storage is zero. As such, the equation can be rearranged as follows to solve for the remaining evaporative cooling at the skin.

$$H_{\text{evap_skin}} = H_{\text{prod}} - H_{\text{dry_skin}} - H_{\text{res}} - S \quad [11]$$

where,

$H_{\text{evap_skin}}$ = latent evaporative heat loss at the skin (W)

Data Analysis Equations

Covariate standardisation.

$$y' = (y - \bar{x}) / s \quad [12]$$

Transformation for variables modelled with a beta-response distribution.

$$y' = (y - a) / (b - a) \quad [13]$$

The standardised difference between conditions or time points.

$$d_r = d_{\text{kl}} / s_{\text{res}} \quad [14]$$

References

- Ainsworth, B.E., Haskell, W.L., Herrmann, S.D., Meckes, N., Bassett Jr, D.R., Tudor-Locke, et al., 2011. 2011 Compendium of physical activities: a second update of codes and MET values. *Med. Sci. Sports Exerc.* 43, 1575-1581.
- American College of Sports Medicine, 2006. ACSM's metabolic calculations handbook. Lippincott Williams & Wilkins, Baltimore, MD.
- American College of Sports Medicine, 2007. ACSM's primary care sports medicine. Lippincott Williams & Wilkins, Baltimore, MD.
- American Conference of Governmental Industrial Hygienists, 2017. Heat stress, TLVs and BEIs: threshold limit values for chemical substances and physical agents & biological exposure indices. ACGIH Cincinnati, OH.
- Ashley, C.D., Luecke, C.L., Schwartz, S.S., Islam, M.Z., Bernard, T.E., 2008. Heat strain at the critical WBGT and the effects of gender, clothing and metabolic rate. *Int. J. Ind. Ergon.* 38 (7-8), 640-644.
- ASTM International, 2016a. ASTM F1291-16 standard test method for measuring the thermal insulation of clothing using a heated manikin. ASTM International, West Conshohocken, PA.
- ASTM International, 2016b. ASTM F2300-10(2016) standard test method for measuring the performance of personal cooling systems using physiological testing. ASTM International, West Conshohocken, PA.
- Australian Government Bureau of Meteorology, 2019. Daily weather observations. Brisbane Airport, Queensland.
<http://www.bom.gov.au/climate/dwo/201809/html/IDCJDW4020.201809.shtml>
Accessed 10 December 2018.
- Bach, A.J.E., Maley, M.J., Minett, G.M., Stewart, I., 2018. Occupational cooling practices of emergency first responders in the United States: a survey. *Temperature*, 5 (4), 348-358.
- Belding, H., Hatch, T., 1955. Index for evaluating heat stress in terms of resulting physiological strains. *Heat. Piping Air. Cond.* 27 (8), 129-136.
- Bernard, T., Ashley, C., Trentacosta, J., Kapur, V., Tew, S., 2010. Critical heat stress evaluation of clothing ensembles with different levels of porosity. *Ergonomics* 53, 1048-1058.
- Borg, G.A., 1982. Psychophysical bases of perceived exertion. *Med. Sci. Sports Exerc.* 14 (5), 377-381.
- Cohen, J., 1992. A power primer. *Psychol. Bull.* 112 (1), 155-159.
- Cramer, M.N., Gagnon, D., Crandall, C.G., Jay, O., 2017. Does attenuated skin blood flow lower sweat rate and the critical environmental limit for heat balance during severe heat exposure? *Exp. Physiol.* 102 (2), 202-213.
- Cramer, M.N., Jay, O., 2018. Partitioned calorimetry. *J. Appl. Physiol.* 126 (2), 267-277.

- Dougherty, K.A., Chow, M., Kenney, W.L., 2010. Critical environmental limits for exercising heat-acclimated lean and obese boys. *Eur. J. Appl. Physiol.* 108 (4), 779-789.
- Du Bois, D., Du Bois, E., 1916. Clinical calorimetry: tenth paper a formula to estimate the approximate surface area if height and weight be known. *Arch. Intern. Med.* 17 (6_2), 863-871.
- Gagge, A.P., Stolwijk, J., Saltin, B., 1969. Comfort and thermal sensations and associated physiological responses during exercise at various ambient temperatures. *Environ. Res.* 2 (3), 209-229.
- Hanna, E.G., Kjellstrom, T., Bennett, C., Dear, K., 2011. Climate change and rising heat: population health implications for working people in Australia. *Asia Pac. J. Public Health* 23 (2 Suppl), 14S-26S.
- Horn, G.P., Stewart, J.W., Kesler, R.M., DeBlois, J.P., Kerber, S., Fent, et al., 2019. Firefighter and fire instructor's physiological responses and safety in various training fire environments. *Saf. Sci.* 116, 287-294.
- International Organization for Standardization, 2004a. ISO 7993, Ergonomics of the thermal environment - Analytical determination and interpretation of heat stress using calculation of the predicted heat strain. Geneva, Switzerland.
- International Organization for Standardization, 2004b. ISO 8996:2004, Ergonomics of the thermal environment - Determination of metabolic rate. Geneva, Switzerland.
- International Organization for Standardization, 2004c. ISO 9886:2004 Ergonomics - Evaluation of thermal strain by physiological measurements. Geneva, Switzerland.
- International Organization for Standardization, 2007. ISO 9920:2007, Ergonomics of the thermal environment - Estimation of thermal insulation and water vapour resistance of a clothing ensemble. Geneva, Switzerland.
- International Organization for Standardization, 2017. ISO 7243:2017, Ergonomics of the thermal environment - Assessment of heat stress using the WBGT (wet bulb globe temperature) index. Geneva, Switzerland.
- Jacklitsch, B., Williams, W.J., Musolin, K., Coca, A., Kim, J-H., Turner, N., 2018. NIOSH criteria for a recommended standard: Occupational exposure to heat and hot environments. U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Cincinnati, OH.
- Jacklitsch, B.L., King, K.A., Vidourek, R.A., Merianos, A.L., 2019. Heat-related knowledge, perceptions, and barriers among oil spill cleanup responders. *Saf. Sci.* 120, 666-671.
- Jay, O., Capon, A., 2018. Use of physiological evidence for heatwave public policy. *Lancet Planet. Health*, 2 (1), e10.
- Jendritzky, G., de Dear, R., Havenith, G., 2012. UTCI—why another thermal index? *Int. J. Biometeorol.* 56 (3), 421-428.

- Kamon, E., Avellini, B., 1979. Wind speed limits to work under hot environments for clothed men. *J. Appl. Physiol. Respir. Environ. Exerc. Physiol.* 46 (2), 340-345.
- Kamon, E., Avellini, B., Krajewski, J., 1978. Physiological and biophysical limits to work in the heat for clothed men and women. *J. Appl. Physiol. Respir. Environ. Exerc. Physiol.* 44 (6), 918-925.
- Kamon, E., Belding, H.S., 1971. Heart rate and rectal temperature relationships during work in hot humid environments. *J. Appl. Physiol.* 31 (3), 472-477.
- Kenney, W., Lewis, D., Armstrong, C., Hyde, D., Dyksterhouse, T., Fowler, S., et al., 1988. Psychrometric limits to prolonged work in protective clothing ensembles. *Am. Ind. Hyg. Assoc. J.* 49 (8), 390-395.
- Kenney, W., Lewis, D., Hyde, D., Dyksterhouse, T., Armstrong, C., Fowler, S., et al., 1987. Physiologically derived critical evaporative coefficients for protective clothing ensembles. *J. Appl. Physiol.* 63 (3), 1095-1099.
- Kenney, W., Mikita, D.J., Havenith, G., Puhl, S.M., Crosby, P., 1993. Simultaneous derivation of clothing-specific heat exchange coefficients. *Med. Sci. Sports Exerc.* 25 (2), 283-289.
- Kenney, W.L., Zeman, M.J., 2002. Psychrometric limits and critical evaporative coefficients for unacclimated men and women. *J. Appl. Physiol.* 92 (6), 2256-2263.
- Kenny, G.P., Jay, O., 2011. Thermometry, calorimetry, and mean body temperature during heat stress. *Compr. Physiol.* 3 (4), 1689-1719.
- Kulka, T.J., Kenney, W.L., 2002. Heat balance limits in football uniforms: how different uniform ensembles alter the equation. *Phys. Sportsmed.* 30 (7), 29-39.
- Kuznetsova, A., Brockhoff, P.B., Christensen, R.H.B., 2017. lmerTest package: tests in linear mixed effects models. *J. Stat. Softw.* 82 (13), 1-26.
- Lao, J., Hansen, A., Nitschke, M., Hanson-Easey, S., Pisaniello, D., 2016. Working smart: An exploration of council workers' experiences and perceptions of heat in Adelaide, South Australia. *Saf. Sci.* 82, 228-235.
- Lee, J.-Y., Stone, E.A., Wakabayashi, H., Tochihara, Y., 2010. Issues in combining the categorical and visual analog scale for the assessment of perceived thermal sensation: methodological and conceptual considerations. *Appl. Ergon.* 41 (2), 282-290.
- Lind, A., 1963. A physiological criterion for setting thermal environmental limits for everyday work. *J. Appl. Physiol.* 18, 51-56.
- Lind, A., Hellon, R., 1957. Assessment of physiological severity of hot climates. *J. Appl. Physiol.* 11 (1), 35-40.
- Maughan, R.J., Otani, H., Watson, P., 2012. Influence of relative humidity on prolonged exercise capacity in a warm environment. *Eur. J. Appl. Physiol.* 112 (6), 2313-2321.
- Mills, J.N., 1966. Human circadian rhythms. *Physiol. Rev.* 46 (1), 128-171.
- Moran, D.S., Shitzer, A., Pandolf, K.B., 1998. A physiological strain index to evaluate heat stress. *Am. J. Physiol.* 275 (1), R129-R134.

- Morris, N.B., English, T., Hospers, L., Capon, A., Jay, O., 2019. The effects of electric fan use under differing resting heat index conditions: A clinical trial. *Ann. Intern. Med.* 5, 675-677.
- Morrison, S.A., Cheung, S., Cotter, J.D., 2014. Importance of airflow for physiologic and ergogenic effects of precooling. *J. Athl. Train.* 49 (5), 632-639.
- National Rugby League, 2019. Heat Guidelines. Available from: https://www.playrugbyleague.com/media/1936/heat-guidelines_with-changes1.pdf
- Queensland Government, 2019. Heatwave management sub-plan June 2019, Queensland Health. Brisbane, QLD. Available from: https://www.health.qld.gov.au/__data/assets/pdf_file/0032/628268/heatwave-response-plan.pdf
- Ravanelli, N., Cramer, M., Imbeault, P., Jay, O., 2017a. The optimal exercise intensity for the unbiased comparison of thermoregulatory responses between groups unmatched for body size during uncompensable heat stress. *Physiol. Rep.* 5 (5), e13099.
- Ravanelli, N.M., Gagnon, D., Hodder, S.G., Havenith, G., Jay, O., 2017b. The biophysical and physiological basis for mitigated elevations in heart rate with electric fan use in extreme heat and humidity. *Int. J. Biometeorol.* 61 (2), 313-323.
- Ravanelli, N.M., Hodder, S.G., Havenith, G., Jay, O., 2015. Heart rate and body temperature responses to extreme heat and humidity with and without electric fans. *JAMA* 313 (7), 724-725.
- Revelle, W., 2015. Procedures for personality and psychological research. Northwestern University, Evanston, IL.
- Rouder, J.N., Morey, R.D., Speckman, P.L., Province, J.M., 2012. Default Bayes factors for ANOVA designs. *J. Math. Psychol.* 56 (5), 356-374.
- Russell, L., 2018. Emmeans: estimated marginal means, aka least-squares means. R package version 1. Available at: <https://github.com/rvlenth/emmeans>
- Samaniego-Rascón, D., da Silva, M.C.G., Ferreira, A.D., Cabanillas-Lopez, R.E., 2019. Solar energy industry workers under climate change: A risk assessment of the level of heat stress experienced by a worker based on measured data. *Saf. Sci.* 118, 33-47.
- Shapiro, Y., Pandolf, K.B., Goldman, R., 1982. Predicting sweat loss response to exercise, environment and clothing. *Eur. J. Appl. Physiol. Occup. Physiol.* 48 (1), 83-96.
- Smithson, M., Verkuilen, J., 2006. A better lemon squeezer? Maximum-likelihood regression with beta-distributed dependent variables. *Psychol. Methods* 11 (1), 54-71.
- Torchiano, M., Torchiano, M.M., 2018. Package 'effsize'. Available at: <https://github.com/mtorchiano/effsize/> Accessed
- U.S. Centers for Disease Control and Prevention, 2017. Natural disasters and severe weather - Hot weather tips. Available at: <https://www.cdc.gov/climateandhealth/pubs/extreme-heat-guidebook.pdf>

- U.S. Environmental Protection Agency, 2016. Extreme heat guidebook. Available at: <https://www.epa.gov/sites/production/files/2016-10/documents/extreme-heat-guidebook.pdf>
- Vallerand, A., Michas, R., Frim, J., Ackles, K., 1991. Heat balance of subjects wearing protective clothing with a liquid-or air-cooled vest. *Aviat. Space Environ. Med.* 62 (5), 383-391.
- Varghese, B.M., Hansen, A., Bi, P., Pisaniello, D., 2018. Are workers at risk of occupational injuries due to heat exposure? A comprehensive literature review. *Saf. Sci.* 110 (Part A), 380-392.
- World Health Organization, 2017. Public health advice on preventing health effect of heat. Available at: https://www.who.int/globalchange/publications/HeatstressAnnouncement_250818.pdf?ua=1
- World Rugby, 2019. Heat guideline. Available at: https://playerwelfare.worldrugby.org/content/getfile.php?h=21921e467635a2273ed2a636681fd953&p=pdfs/Heat_Guideline_EN.pdf
- Yaglou, C., Minaed, D., 1957. Control of heat casualties at military training centers. *AMA Arch. Indust. Health* 16 (4), 302-316.
- Zeileis, A., Cribari-Neto, F., Grün, B., Kosmidis, I., 2010. Beta regression in R. *J. Stat. Softw.* 34 (2), 1-24.
- Zhang, M., Mai, Y., 2018. WebPower: Basic and Advanced Statistical Power Analysis. R Package version 0.5 2. Available at: <https://cran.r-project.org/web/packages/WebPower/index.html>