Heat Stress Degrades Hiking Performance

by

Joshua Linsell

A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved February 2019 by the
Graduate Supervisory Committee:

Floris Wardenaar, Chair
Christopher Berger
Erica Forzani
David Hondula

ARIZONA STATE UNIVERSITY

May 2019

ABSTRACT

This study investigated the effect of environmental heat stress on physiological and performance measures during a ~4 mi time trial (TT) mountain hike in the Phoenix metropolitan area. Participants (*n* = 12; 7M/5F; age 21.6 ± 2.47 [SD]) climbed ‘A’ mountain (~1 mi) four times on a hot day (HOT; wet bulb globe temperature [WBGT] = 31.6°C) and again on a moderate day (MOD; WBGT = 19.0°C). Physiological and performance measures were made before and throughout the course of each hike. Mean pre-hike hydration status (urine specific gravity [USG]) indicated that participants began both HOT and MOD trials in a euhydrated state (1.016 ± 0.010 and 1.010 ± 0.008, respectively) and means did not differ significantly between trials (*p* = .085). Time trial performance was impaired by -11% (11.1 minutes) in the HOT trial (105 ± 21.7 min), compared to MOD (93.9 ± 13.1 min) (*p* = .013). Peak core temperatures were significantly higher in HOT (38.5 ± 0.36°C) versus MOD (38.0 ± 0.30°C) with progressively increasing differences between trials over time (*p* < .001). Peak ratings of perceived exertion were significantly higher in HOT (14.2 ± 2.38) compared to MOD (11.9 ± 2.02) (*p* = .007). Relative intensity (percent of age-predicted maximal heart rate [HR]), estimated absolute intensity (metabolic equivalents [METs]), and estimated energy expenditure (MET-h) were all increased in HOT, but not significantly so. The HOT condition reduced predicted maximal aerobic capacity (CRFp) by 6% (*p* = .026). Sweat rates differed significantly between HOT (1.38 ± 0.53 L/h) and MOD (0.84 ± 0.27 L/h) (*p* = .01). Percent body mass loss (PBML) did not differ significantly between HOT (1.06 ± 0.95%) and MOD (0.98 ± 0.84%) (*p* = .869). All repeated measures variables showed significant between-subjects effects (*p* < .05), indicating individual differences in response to test conditions. Heat stress was shown to negatively affect physiological and performance measures in recreational mountain hikers. However, considerable variation exists between individuals, and the degree of physiological and performance impairment is probably due, in part, to differences in aerobic fitness and acclimatization status rather than pre- or during-performance hydration status.

TABLE OF CONTENTS

Page

APPENDIX

LIST OF TABLES

TABLE Page

LIST OF FIGURES

Chapter 1

INTRODUCTION

Overview

Hiking in the mountains is a popular recreational activity in the United States. Recreational mountain hiking is considered to be a leisurely pursuit, attracting a broad range of people in varying physical condition. People who perform physical activity in the wilderness, such as hikers, are likely to be exposed to more extreme environmental conditions due to the remoteness from shelter. Additionally, many hikers who travel abroad to different climates are not acclimatized and may not anticipate the additional physiological challenge from high summer temperatures in the desert.

Each year, over 200 recreational hikers are rescued from the mountains of the notoriously hot Phoenix metropolitan area in Arizona (Athena, 2017). Emergency medical providers in the area report anecdotally that many of these rescues are related to exertional heat illness (EHI), but the reasons for mountain rescues are not documented (Cassidy & McGlade, 2015). Mountain rescues are costly and public resource-intensive, oftentimes requiring multiple firefighter rescue crews or even helicopters to conduct an otherwise simple medical evacuation (Athena, 2017; Cassidy & McGlade, 2015). Public authorities have responded by collaborating to create the “Take a Hike – Do it Right” campaign to inform hikers on preventative safety measures (“Take a Hike - Do it Right,” 2015). The campaign infographic literature is posted at trailheads as well as online. The infographic encourages hikers to watch the weather, dress appropriately, bring water, carry a cell phone, team up, be honest, stay on designated trails, and to take responsibility. Despite the notion that a large number of these rescues are due to heat stress and its associated symptoms, the infographic takes a non-specific approach, and does not highlight the most important factors in lowering the risk for EHI such as proper hydration and heat acclimatization (Sawka et al., 2007).

Although hydration and heat acclimatization can delay the onset of EHI, it is important to note that heat stress generally degrades exercise performance before the development of heat illness (Sawka, Leon, Montain, & Sonna, 2011). Many studies on heat stress focus on performance rather than EHI because of the ethical obligation to terminate activity before severe hyperthermia ensues (Armstrong et al., 2007). Studies that do involve actual cases of heat illness are usually retrospective and the progression of the illness is not monitored or investigated. The degree of performance decrement and subsequent risk for EHI is dependent upon the individual and environmental factors (Pryor, Bennett, O’Connor, Young, & Asplund, 2015). Individual factors include hydration status, acclimatization status, the intensity and duration of activity, physical fitness, and medications, among others (Armstrong et al., 2007; Pryor et al., 2015). Environmental factors include the temperature, humidity, radiation, and wind speed (Lipman et al., 2014). Thermoregulation and heat tolerance are the physiological response to the interaction between these individual and environmental factors (Sawka et al., 2011). For hikers, this involves knowing the environmental factors (watching the weather) and their own preparedness for that environment (bringing water and knowing one’s limits).

During periods of compensable exertional heat stress, thermoregulation is leveraged against performance. Initially, a primary thermoregulatory response to heat is sweating, which exchanges body water for evaporative cooling (Sawka et al., 2011).

Without replenishing sufficient fluids, the resulting dehydration can decrease blood volume with a compensatory increase in heart rate (a measure of intensity) in an attempt to maintain cardiac output (Nybo, Rasmussen, & Sawka, 2014). In addition to hypohydration's effect on exercise intensity, it negates the heat tolerance benefits of cardiorespiratory fitness (CRF) and heat acclimatization, is associated with an elevated core temperature when exercising in moderate to hot climates (Sawka & Montain, 2000), and increases the risk for EHI (Sawka et al., 2007). Eventually, the exercise activity (e.g. hiking) must end in either exhaustion or continue into an uncompensable heat stress situation where thermoregulation is no longer possible and exertional heat illness begins to develop (Cheung, McLellan, & Tenaglia, 2000).

Heat strain and hypohydration are highly related and hypohydration can exacerbate heat strain (Nybo et al., 2014). Hypohydration's impairment of thermoregulation subsequently negatively affects maximal and submaximal aerobic performance and cognition in warm to hot environments (Sawka et al., 2011). Because of this profound interaction between the individual's hydration status and environmental heat stress, optimal hydration strategies become paramount as they represent a modifiable portion of that interaction (Sawka et al., 2007). Beyond water, additives such as electrolytes and carbohydrates have been shown to promote optimal rehydration through fluid retention and replenishment of sodium losses from excretion (Baker & Jeukendrup, 2014). The "Take a Hike" campaign neglects to address these beneficial nutrient additives.

Heat stress also alters carbohydrate metabolism by accelerating glycogen breakdown and carbohydrate oxidation (Hargreaves, Angus, Howlett, Conus, & Febbraio, 1996). One might then be tempted to reason that glycogen depletion could be a limiting factor to exercise in the heat, but research has consistently shown otherwise (Nielsen, Savard, Richter, Hargreaves, & Saltin, 1990; Parkin, Carey, Zhao, & Febbraio, 1999). While carbohydrates seem to improve performance in the heat compared to water alone (Carter, Jeukendrup, Mundel, & Jones, 2003), the benefit appears to be non-metabolic (i.e. neuropsychological) (Jeukendrup & Chambers, 2010). Despite the non-metabolic ergogenic effect of carbohydrate supplementation in the heat, current during-activity nutritional recommendations fail to consider environmental temperature as a modifier of the carbohydrate needs of athletes in general (Burke & Deakin, 2015), and much less for the recreational hiker.

Previous research examining heat stress and fluid recommendations is abundant, yet few studies include recreational hikers, and no study investigates the performances that give way to exertional heat illness in recreational hikers. The current study sought to address some of these questions and produce some physiological and performance data on hikers on a hot versus a moderate day in the Phoenix metropolitan area. In doing so, we intended to provide evidence for the physiology-related safety recommendations for hiking in a hot and arid climate set forth by local authorities.

Purpose of Study

The purpose of this study is to investigate the physiological and performance effects of heat stress on local recreational mountain hikers. Subsequently, we hope to gain a better understanding of the progression of heat strain in this specific population, to identify the most impactful determinants of a safe and successful hiking experience.

Definition of Key Terms

Acclimation. The physiological process of adapting to an experimentally controlled environmental condition (e.g. a temperature and humidity-controlled laboratory). Acclimation status refers to the state rather than the process of acclimation.

Acclimatization. In contrast to acclimation, acclimatization is the physiological process of adapting to a particular “natural” environmental condition (e.g. summer climate in Phoenix, AZ). Acclimatization status refers to the state rather than the process of acclimatization.

Dehydration. The physiological process of losing body water by any means other than urination.

Exertional heat illness (EHI). illness caused by individual and/or environmental heat stress while performing physical activity. Illnesses range in severity from heat edema to heat cramps, heat syncope, heat exhaustion, and finally heat stroke.

Heat strain. The physiological burden imposed by heat stress, relative to the individual’s heat tolerance and thermoregulatory capacity.

Heat stress. Stress from individual (internal) and/or environmental (external) factors that increase body temperature above normal resting values.

Hypohydration. The result of the physiological process of dehydration from a euhydrated state.

Recreational mountain hiking. The recreational physical activity of walking (as opposed to running) outdoors on a designated unpaved trail of varying gradation (i.e. hills) and terrain. This is typically done with minimal loads (as opposed to “backpacking” or “rucking”) for durations of up to several hours. Recreational hiking is in contrast to walking outdoors in a non-recreational capacity with occupational protective garments (e.g. wildland firefighting or military pursuits).

Chapter 2

REVIEW OF LITERATURE

Phoenix Mountain Rescues: the Problem and the Current Solution

Annually, over 200 hikers are rescued from the notoriously hot and arid mountains of the Phoenix metropolitan area (Athena, 2017; “Take a Hike - Do it Right,” 2015). Local mountain rescuer and Captain in the Phoenix Fire Department, Larry Subervi, reported that roughly half of these mountain emergencies can be attributed to heat illness, and the other half to musculoskeletal injuries (*Hiking Safety Campaign - Take a Hike. Do it Right.*, 2015). While the musculoskeletal injuries are commonplace in outdoor recreation at large (Leemon & Schimelpfenig, 2003), heat illness is a particular concern in hot desert climates such as summer in Phoenix, Arizona (Backer & Shlim, 2013).

The Centers for Disease Control and Prevention (CDC) identifies at-risk individuals for heat illness as travelers from cooler climates who are not acclimatized to the heat and are in poor physical condition (Backer & Shlim, 2013). Tourist hiking hotspots in Phoenix include Camelback Mountain, Piestewa Peak, and South Mountain. Combine the at-risk population with desert heat and the steep and rocky terrain of those popular mountain trails, and the result is a recipe for emergency rescues. Indeed, these emergency situations are at best unfortunate for the individual, but the cost extends beyond the individual. The rescues involve publicly-funded resources such as teams of firefighters and emergency medical providers, and all of the things that they need to perform a mountain rescue: multiple rescue vehicles, or even a medical evacuation helicopter. Therefore, it is in the best interest of the taxpayer and public authorities to address how to reduce these resource-intensive mountain rescues.

In 2015, the City of Phoenix Parks and Recreation Department collaborated with local fire and police departments, the hotel industry, and the Maricopa County Department of Public Health to launch the “Take a Hike – Do it Right” campaign (“Take a Hike - Do it Right,” 2015). The educational campaign was in response to the growing number of mountain rescues being conducted every year in the Phoenix area. The campaign collaborators produced an infographic that has been posted online and at popular local trailheads (Figure 1).

Take a HIKE. Do it RIGHT.

More than **200** hikers annually are rescued from City of Phoenix desert and mountain parks and preserves. This simple checklist can help keep you from becoming a statistic.

Watch the Weather:
Yes, “it’s a dry heat” – but Arizona’s temperature can be deceiving and deadly. Hike when it’s cool outside, try early mornings and evenings when there’s more shade.

Dress Appropriately:
Wear proper shoes, clothing, hat and sunscreen.

Bring Water:
Hydrate before you go. Have plenty of water, more than you think you need. Turn around and head back to the trailhead before you drink half of your water.

Keep in Contact:
Carry a mobile phone.

Team Up:
Hike with others. If hiking solo, tell someone your start and end times, and location.

Be Honest:
Do you have a medical condition? Asthma, heart problems, diabetes, knee or back problems? Don’t push yourself! (Even trained athletes have been caught off guard by getting dehydrated on Arizona trails.)

Don’t Trailblaze:
Enjoy the Sonoran Desert’s beautiful and undeveloped landscape, but please stay on designated trails.

Take Responsibility:
Don’t be “that person” – the one who wasn’t prepared, shouldn’t have been there for health reasons or ignored safety guidelines. Be the responsible hiker, who takes a hike and does it right!

Figure 1. *Take a Hike – Do it Right Infographic*

The infographic highlights the statistics on the annual number of mountain rescues and then provides information on how best to prevent such a circumstance. The infographic encourages hikers to (1) watch the weather, (2) dress appropriately, (3) bring water, (4) carry a cell phone, (5) team up, (6) be honest, (7) stay on designated trails, and (8) to take responsibility.

Interestingly, hydration is given equal emphasis compared to the other seven recommendations, and heat acclimatization is not mentioned at all. This is concerning because hydration and acclimation are considered to be the most important preventative measures for exertional heat illness (Sawka et al., 2007). The hydration recommendations in the infographic are general, and they do not account for the modulating effect of environmental temperature on fluid requirements. There is no mention of carbohydrates or electrolytes, both of which can enhance rehydration during physical activity in the heat (Sawka et al., 2007).

However, the lack of specificity in the “Take a Hike – Do it Right” campaign is somewhat understandable because of the dearth of studies on recreational mountain hikers. Indeed, much of the research on heat stress, heat illness, and hydration in physical activity is focused on collegiate or professional athletes of various sports, or military professionals, and so one must question its generalizability to recreational mountain hikers and the general population. The following sections will delve into the pertinent physiological underpinnings of performance in the heat in an effort to inform hiking safety recommendations in the desert southwest. An additional goal of this review of literature is to highlight the gaps in literature and the need for more focused research studies.

Heat Stress and Effects on Physiology: Heat Strain and Exertional Heat Illness

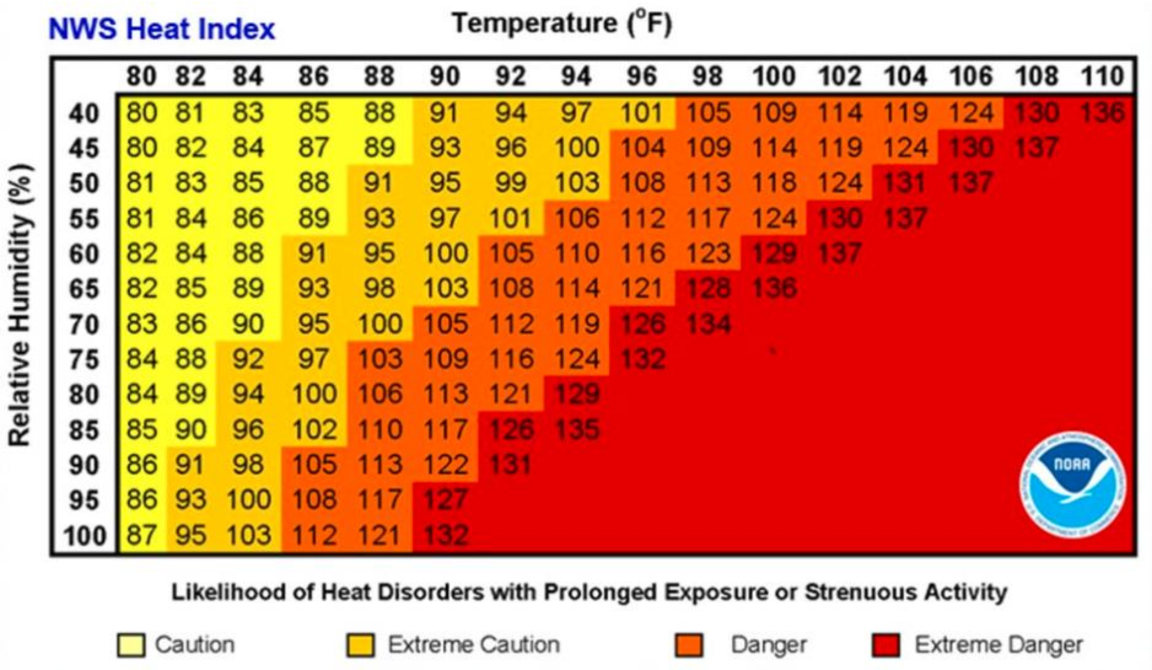
Heat stress is defined as the stress from individual (internal) and/or environmental (external) factors that increase body temperature above normal resting values. Heat strain is the physiological burden imposed by heat stress, relative to the individual’s heat tolerance and thermoregulatory capacity. No consensus exists among thermal physiologists for the definition of heat tolerance (Cheung et al., 2000), but this author describes it as the psychological limit of thermal sensory discomfort, independent of thermoregulatory ability. Thermoregulation refers collectively to the body processes that control internal temperature. Hyperthermia is defined by a core temperature above the hypothalamic set point and can be further classified as either compensable or uncompensable. Compensable hyperthermia (otherwise known as compensable heat stress; CHS) occurs when the body is able to control or otherwise achieve a steady state body temperature. With uncompensable heat stress (UHS), the influx of heat stress exceeds the capacity of the individual to regulate body temperature, and so internal body temperature continues to rise.

The degree of heat strain that one experiences is difficult to measure because it is dependent upon both internal and external heat stressors, the individual's subjective limits of thermal discomfort, and the individual's physiological capacity to control body temperature. On the other hand, heat stress is relatively easier to measure because it is the initial input to the body's complex thermoregulatory system. That difference in measurability between heat stress and heat strain is an important consideration for experimental design in thermophysiology-related research studies. Still, the degree of heat strain can be approximated by the effect of heat stress on performance and fatigue, or its elicitation of signs and symptoms of heat related illness.

Environmental heat stress. Of the two sources of heat stress, environmental heat stress is probably the most straightforward in terms of its quantification. Ambient air temperature, relative humidity, radiation, and wind speed each contribute to the environmental heat stress experienced by the individual (Cheung, 2010). Ambient temperatures contribute to "dry" heat transfer through conduction and convection, and the direction and magnitude of that heat transfer is dependent upon the temperature gradient between the individual and the environment (Cheung et al., 2000). Solar radiation is also a source of dry heat exchange and can be absorbed and/or reflected by objects such as the ground. The relative humidity of the air determines the capacity for “wet” heat exchange through evaporation of sweat, with higher relative humidity corresponding to more limited evaporative heat transfer (Cheung et al., 2000). Wind speed can affect both dry and wet heat transfer, but field measurements are impractical because they require specialized equipment and wind speed is relative to the direction of movement of the individual.

The properties of clothing can also complicate the measurement of environmental heat stress because clothing can create a “microenvironment” at skin level that differs from ambient conditions (Cheung et al., 2000). Additionally, clothing can affect the exchange of heat between the body and the environment (Cheung et al., 2000). In research studies, this confounding effect of clothing can be relatively controlled for by standardizing clothing between research participants or within participants for repeated measures. The latter option might work best for studies involving recreational hikers where there is no standard uniform among individuals.

Notwithstanding the confounding effect of clothing on the individual’s microenvironment, the Wilderness Medical Society (WMS) has identified two indexes that are practical and effective at measuring environmental heat stress. The two indexes are the heat index and the wet bulb globe temperature index (WBGT) (Lipman et al., 2014). The heat index is the simplest index of environmental heat stress because it accounts for only temperature and relative humidity. The American College of Sports Medicine posits that the heat index should be used as a minimum standard for monitoring environmental heat stress (Armstrong et al., 2007). Figure 2 shows the Heat Index, as posted on the National Weather Service (NWS) website (US Department of Commerce, n.d.-a).



NWS Heat Index

Temperature (°F)

Relative Humidity (%)

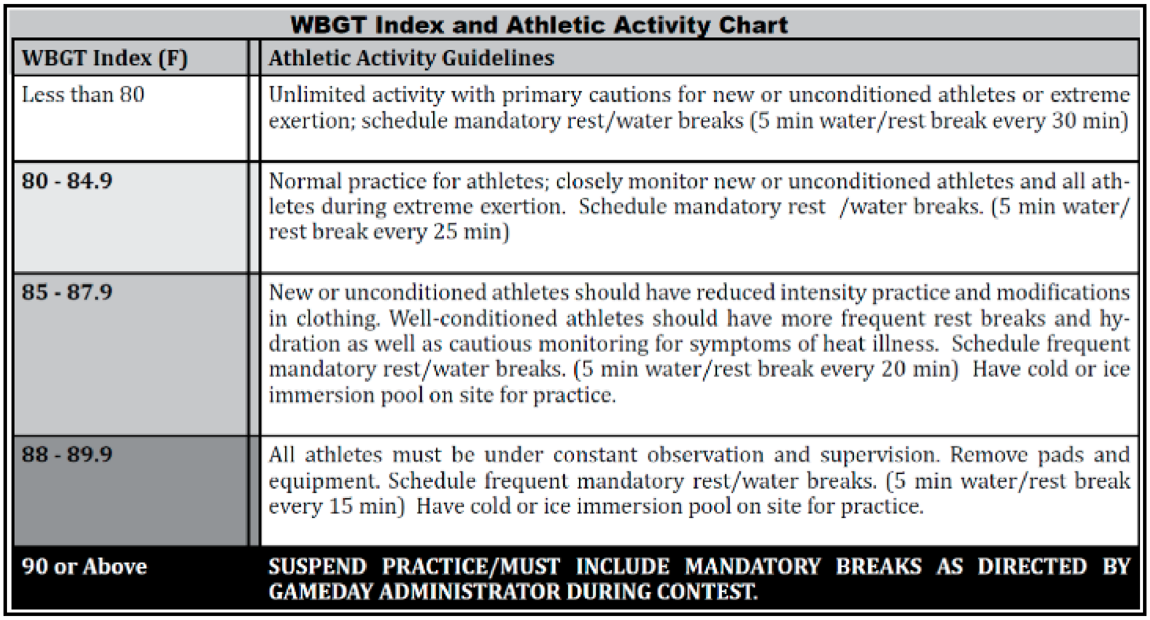
	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Likelihood of Heat Disorders with Prolonged Exposure or Strenuous Activity

🟨 Caution 🟧 Extreme Caution 🟧 Danger 🟥 Extreme Danger

Figure 2. *Heat Index*

Wet bulb globe temperature is preferred by the WMS and ACSM over the heat index because it accounts for radiative heat sources in addition to temperature and humidity (Armstrong et al., 2007; Lipman et al., 2014). Furthermore, the National Athletic Trainer’s Association (NATA) supports the use of the use of the WBGT index for assessing environmental heat stress (Casa et al., 2015). Figure 3 shows the WBGT Index, as posted on the NWS website (US Department of Commerce, n.d.-b).



WBGT Index and Athletic Activity Chart

WBGT Index (F)	Athletic Activity Guidelines
Less than 80	Unlimited activity with primary cautions for new or unconditioned athletes or extreme exertion; schedule mandatory rest/water breaks (5 min water/rest break every 30 min)
80 - 84.9	Normal practice for athletes; closely monitor new or unconditioned athletes and all athletes during extreme exertion. Schedule mandatory rest /water breaks. (5 min water/ rest break every 25 min)
85 - 87.9	New or unconditioned athletes should have reduced intensity practice and modifications in clothing. Well-conditioned athletes should have more frequent rest breaks and hydration as well as cautious monitoring for symptoms of heat illness. Schedule frequent mandatory rest/water breaks. (5 min water/rest break every 20 min) Have cold or ice immersion pool on site for practice.
88 - 89.9	All athletes must be under constant observation and supervision. Remove pads and equipment. Schedule frequent mandatory rest/water breaks. (5 min water/rest break every 15 min) Have cold or ice immersion pool on site for practice.
90 or Above	SUSPEND PRACTICE/MUST INCLUDE MANDATORY BREAKS AS DIRECTED BY GAMEDAY ADMINISTRATOR DURING CONTEST.

Figure 3. *Wet Bulb Globe Temperature Index*

Neither index accounts for wind speed, but the WBGT index is “the standard” for research on heat stress and for setting activity limitations based on environmental conditions in sport and occupational settings (Armstrong et al., 2007; Lipman et al., 2014).

In a classic study, Griefahn demonstrated the consistency of the WBGT index by showing that the course of heat acclimation was similar in three different environments with the same WBGT (33.5 ± 0.1°C) and that the resulting acclimation status bore similar benefits between the three environments (Griefahn, 1997). Subjects (*n* = 8; ages 19 - 32) walked on a treadmill (4 x 25 min at 4km/hr) each day for 15 consecutive days in one of three conditions: warm-humid, hot-dry, and radiant heat. Following the 15-day acclimation, subjects of the warm-humid and radiant conditions were exposed to the hot-dry condition, and those of the hot-dry condition were exposed to the warm-humid condition. No significant differences were found in markers of heat strain when subjects were exposed to the post-acclimation conditions. Griefahn concluded that WBGT-equivalent conditions produce similar effects in heat acclimation, despite large differences in temperature, humidity, and radiation between trials. It follows that exercising in different WBGT conditions may produce significantly different effects despite similarities in temperature, humidity, or radiation.

The risk for exertional heat stroke (EHS) begins to increase at 18.4°C (WBGT) for continuous or competitive activities, and for “high risk” (e.g. unacclimated, unfit, etc.) (Armstrong et al., 2007). Above a WBGT of 32.3°C, the environmental heat stress is considered to be uncompensable for even the lowest-risk individuals (i.e. aerobically fit and heat-acclimatized athletes). But even in the absence of environmental heat stress, as defined by a WBGT below 18.4°C, cases of EHS may still occur due to individual factors (Armstrong et al., 2007). This suggests that the individual factors play an equal if not more important role in the development of exertional heat illness.

Individual factors. An individual factor can be defined as any physiological or behavioral source or modifier of heat stress. In contrast to environmental heat stress factors, individual factors are specific to the person. There is interaction between the individual and the environment, and so the person-specific individual factors produce a person-specific interaction with the environment. Fundamentally, body temperature is the variable that reflects that interaction between the environmental heat stress and the individual’s thermoregulatory capacity (Sawka et al., 2011).

Body temperature. While body temperature reflects the thermal *interaction* between the individual and the environment, ultimately it is the *individual* who bears the burden of that interaction. The numeric value of core body temperature may also be misleading if taken out of that context of interaction. In general, muscle metabolism (exercise) mediates and the environment moderates the rise in core body temperature (Sawka et al., 2011). However, heat acclimation and fitness are associated with a lower core temperature at comparable absolute intensities and a higher core temperature at the time of exhaustion (Cheung, 2010). Despite the nuanced variability in core temperatures between subjects, absolute core temperatures have intrinsic meaning. Regardless of other individual modifiers of core temperature, 40°C is a definitive threshold for the classification of exertional heat stroke (Armstrong et al., 2007; Lipman et al., 2014). The ethical core temperature cutoff limit for research on human subjects is typically between 39 and 40°C (Cheung et al., 2000).

Intensity and duration. The intensity and duration of physical activity are inversely related (Powers & Howley, 2015). The intensity and duration of physical activity are not dictated solely by the environment, but by the behavior and physiological responses of the *individual* in that environment. That behavior has physiological consequences by the metabolic heat stress that physical activity produces. In fact, physical activity can increase metabolic heat production up to 20 times the resting values, depending on the intensity of the activity (Armstrong et al., 2007). Environmental heat stress alone tends to increase heart rate through complex mechanisms (Sawka et al., 2011). Intensity can be measured either relative to the individual's maximum, or it can be measured as an absolute. A common way to measure relative intensity of physical activity is with heart rate. Maximal heart rate can be measured on a graded exercise test at the point of VO_{2max}, or it can be predicted using one of several available equations. One such equation is that of Tanaka, Monahan, and Seals (2001) which has been validated for healthy adults. The equation is as follows: 207 – (0.7·age). Measured heart rate divided by maximal heart rate yields the relative intensity of physical activity expressed as a percent. Absolute intensity is a work rate that can be measured as a metabolic equivalent of tasks (MET), which represents 3.5 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ (Riebe, Ehrman, Liguori, & Magal, 2018).

An increase in the *duration* of physical activity at any set intensity will increase the total energy expenditure because energy expenditure (work) is a product of intensity (work rate) and duration (time) (Riebe et al., 2018).

$$Work\ = work\ rate \cdot time$$

Energy expenditure is directly related to metabolic heat production, which is a source of heat stress within the individual. Human movement is roughly 20% efficient with the other 80% efficiency being lost as metabolic heat (Sawka et al., 2011). In other words, roughly 80% of energy expenditure is bodily heat production. This is a problem for individuals performing physical activity in the heat because the need for heat dissipation may require adjusting the work to rest ratio (W:R) by taking breaks, or by reducing the intensity and/or duration of the activity in order to limit energy expenditure (heat production) (Armstrong et al., 2007; Casa et al., 2015; Lipman et al., 2014).

Acclimatization status. Acclimatization to the heat is the best protective measure for the prevention of exertional heat illness (Armstrong et al., 2007). This assertion should be alarming, considering that the “Take a Hike – Do it Right” campaign makes no mention of acclimatization, and the notion that “many hikers [in the Phoenix area] are also from out of town and unfamiliar with the concept of dry heat” (Cassidy & McGlade, 2015). In approximate progressive order, heat acclimatization decreases heart rate (relative intensity), decreases core temperature, increases production of heat shock proteins (HSPs), increases plasma volume (PV), decreases rating of perceived exertion (RPE), increases sweat rate (SR), and earlier onset of sweating during physical activity in the heat (Garrett, Rehrer, & Patterson, 2011; Powers & Howley, 2015). Altogether, these benefits of heat acclimatization result in a greater heat tolerance, or thermoregulatory capacity for heat stress. The decrease in relative intensity and perceived exertion allows the individual to perform physical activity at a higher absolute intensity, for a longer duration, or both – ultimately resulting in a greater potential for metabolic heat production (energy expenditure). Indeed, acclimatization to heat also increases aerobic exercise capacity in the heat (Sawka et al., 2011). The acclimatization-induced increase in plasma volume serves first as a heat sink to allow greater heat storage, and then as a reservoir for the production of sweat for evaporative heat dissipation (Cheung et al., 2000). Enhanced sweat rate is a later-stage adaptation of heat acclimatization, and appears to be specific to the sweat glands and their microenvironment (warm-humid or hot-dry) during the acclimatization process (Cheung et al., 2000).

Hydration status. Hypohydration is associated with higher core temperatures at rest and during exercise, lower stroke volume, higher heart rate, and higher ratings of perceived exertion while exercising (Sawka et al., 2011). Cheung and colleagues (2000) argue that hydration status is the most important individual factor for protection against hyperthermia. However, this in contrast to the position of Armstrong and colleagues (2007) who assert that acclimatization status is the ultimate protective measure. Indeed, there is intense interaction between hydration and heat acclimatization status. For every 1% loss in body weight from dehydration, there is a 0.1 to 0.2°C penalty in core temperature, which can negate the core temperature lowering effect of heat acclimatization or high aerobic fitness (Sawka et al., 2011). Conversely, heat acclimatization increases plasma volume by 10-12%, adding body water reserves and enhancing the capacity for both heat storage and for heat dissipation through sweat (Powers & Howley, 2015, p. 273). The likelihood of a highly acclimatized person to be more dehydrated at any given point in time than an unacclimatized person seems trivial, and so theoretically, the acclimatized person would have the advantage. Despite heat acclimatization's theoretical absolute advantage, hydration status holds practical significance in that it is more readily modifiable (Lipman et al., 2014). In other words, hydration status is an acute individual variable, whereas heat acclimatization represents a chronic adaptation.

Sweat rate. Sweat rate and hydration status are related in that sweating depends on hydration. Sweating is a primary means for cooling through evaporative heat loss (Powers & Howley, 2015). Sweat rate varies considerably by the individual, environmental condition, exercise intensity, and the microenvironment created by clothing (Sawka et al., 2011). Normative data on a range of adult athletes ($n = 327$) in various sports and environmental conditions shows absolute sweat rates (m ± SD) to be $1.37 \pm 0.71 \text{ L} \cdot \text{h}^{-1}$ (Baker, Barnes, Anderson, Passe, & Stofan, 2016). Similarly, Sawka et al. (2007) reviewed eleven studies involving athletes of various sports and found that sweat rates ranged between 0.5 and $2.0 \text{ L} \cdot \text{h}^{-1}$. While these results are consistent, it should be noted that these sweat rates reflect those of competitive athletes and not necessarily the general population. The high aerobic fitness of an athlete is associated with a high plasma (blood) volume and sweat rate compared to lesser fit individuals

(Cheung, 2010). Acclimatization to heat can result in nearly a threefold increase sweat rate (Powers & Howley, 2015, p. 273).

Cardiorespiratory fitness (CRF). Otherwise known as aerobic fitness, CRF is a chronic marker of physical condition that has direct effects on the core temperature response to exercise. Higher aerobic fitness is associated with both a lower resting core temperature, and a higher endpoint core temperature at the time of fatigue (Cheung & McLellan, 1998). A higher aerobic fitness is also associated with a higher total body water content (higher plasma volume, lower percent body fat, and more muscle glycogen which is stored with water) and sweat rate (Powers & Howley, 2015; Sawka & Montain, 2000). Like in heat acclimatization, however, dehydration can negate these benefits of aerobic fitness (Sawka et al., 2011). Higher levels of fitness, as measured by a higher absolute intensity in METs, is associated with a lower heart rate (relative intensity) at any absolute work rate (Powers & Howley, 2015). As noted above, intensity and duration are inversely related and determined by the behavior of the individual, and so fitness may allow greater intensity, greater duration, or both. It is in this way that fitness level may increase exercise tolerance in the heat. Acutely, environmental heat stress impairs maximal and submaximal aerobic exercise performance (Sawka et al., 2011). It follows that a high CRF level may offset some of this performance decrement. However, environmental heat stress impairs maximal aerobic performance regardless of fitness level, when controlled for acclimatization status (Nybo et al., 2014). The benefit of higher fitness level is thus an absolute benefit, rather than a relative one, in the face of acute exposure to environmental heat stress.

Acute condition. Acute physical conditions can modify the relationship between heat stress and heat strain. Technically, hydration status is an acute physical condition, but because of its core importance in thermoregulation it deserves its own mention (as above). Other acute conditions such as febrile illness or sunburn can contribute to elevated body temperature, or decrease the thermoregulatory capacity of the skin by limiting the sweating response, respectively (Pryor et al., 2015).

Chronic condition. Chronic physical conditions also can modify the relationship between heat stress and thermoregulatory capacity. Just as hydration status is an acute physical condition, heat acclimatization, aerobic fitness, and sweat rates are relatively chronic adaptations. Beyond these chronic adaptations, chronic conditions such as hypertension, diabetes, thyroid disorders, cystic fibrosis, spinal cord injury, eating disorders, and sleeping disorders can affect thermoregulatory response through various mechanisms (Pryor et al., 2015; Sawka & Montain, 2000). Additionally, a history of heat illness can indicate disorder of the thermoregulatory system, and is the primary risk factor for future EHI (Lipman et al., 2014).

Medications. Some medications have their own effects on heat production (including metabolic rate) and thermoregulation (including hydration status), independent of the acute or chronic condition that they are intended to treat. Casa and colleagues (2015) identify stimulants, antihistamines, antipsychotics, and anticholinergics as common medications that affect thermoregulation. These medications can increase the risk for EHI. Lipman et al. (2014) composed a more extensive list of such medications for reference.

Ultimately, the degree of heat strain experienced from continued physical activity-related heat stress can result in exertional heat illness (EHI). Exertional heat illnesses range in severity from the relatively benign heat edema to exertional heat stroke (EHS). Hyperthermia is not necessarily indicative of EHI, unless signs and symptoms develop. Official definitions from the Wilderness Medical Society for heat related illnesses are outlined in Table 1 below (Lipman et al., 2014).

Table 1. *Characteristics of Heat Related Illness*

Condition	Definition
Hyperthermia	A rise in body temperature above the hypothalamic set point when heat-dissipating mechanisms are impaired (by clothing or insulation, drugs, or disease) or overwhelmed by external (environmental) or internal (metabolic) heat production
Heat Edema	Dependent extremity swelling owing to interstitial fluid pooling
Heat Cramps	Exercise-associated painful involuntary muscle contractions during or immediately after exercise
Heat Syncope	Transient loss of consciousness with spontaneous return to normal mentation
Heat Exhaustion	Mild-to-moderate heat-related illness owing to exposure to high environmental heat or strenuous physical exercise; signs and symptoms include intense thirst, weakness, discomfort, anxiety, and dizziness, syncope; core temperature may be normal or slightly elevated >37°C (98.6°F) but <40°C (104°F)
Heat Stroke	Severe heat-related illness characterized by a core temperature >40°C (104°F) and central nervous system abnormalities such as altered mental status (encephalopathy), seizure, or coma resulting from passive exposure to environmental heat (classic heat stroke) or strenuous exercise (exertional heat stroke)

As discussed above, the degree of heat strain is dependent upon individual and environmental sources of heat stress and the body's capacity to dissipate that heat within the environment. The individual will first compensate for the heat stress with lower performance, but if the heat stress becomes uncompensable, the performance will terminate in fatigue or progress to a form of exertional heat illness (Cheung, 2010, p. 29, 36). This process is outlined below in Figure 4.

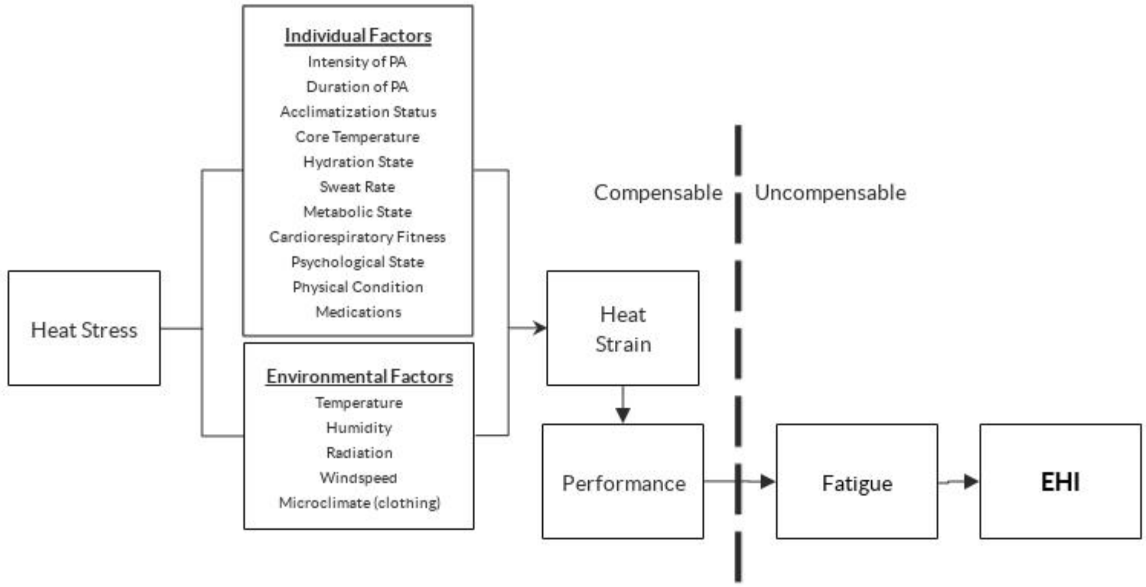


Figure 4. *The Pathway from Heat Stress to EHI*

Environmental Heat Stress: Acute Effects on Aerobic Performance and Fatigue

The previous section focused on the variables affecting heat stress and heat strain. However, heat strain is a broad term that refers to the physiological consequences of heat stress up to and including exertional heat illness and death. Eliciting heat illness in human research subjects is an unethical practice. Because of this, research tends to be either retrospective case studies on EHI, or it focuses on the performances leading up to fatigue or withdrawal (Cheung, 2010; Nybo et al., 2014). This section will review the literature concerning the latter.

Performance, too, is a broad term, but it is more readily measured than “heat strain.” Performances can be categorized as either “anaerobic” or “aerobic” depending on the intensity and duration of the physical activity. Aerobic performances can further be classified into maximal or submaximal performances. Maximal aerobic performance usually refers to the maximal work rate in watts (W) achieved at VO_{2max}, or the VO_{2max} value itself ($L\cdot min^{-1}$). Submaximal aerobic performance is typically measured using self-paced time trials (TT) of a set time or distance, or time to exhaustion (TTE) at a specified work rate. The former (TT) is most applicable to sport in general, and especially recreational hiking where hikers seek to complete a hiking trail of a known distance.

Maximal aerobic performance. A review by Nybo et al. (2014) compared eleven studies that examined the effect of heat stress on maximal aerobic performance, as measured by VO_{2max}. Compared to control conditions (13-25°C), the heat stress conditions (35-49°C) marked an average of an 11% reduction in VO_{2max} in 10 out of 11 of those studies. The mechanism for this reduction was concluded to be related to the inability of the cardiovascular system to meet both the oxygen demands of active muscle and the body's cooling needs through subcutaneous blood flow. While hiking is not typically performed at VO_{2max}, the lower absolute maximal aerobic power associated with heat stress translates into a higher relative intensity at any submaximal work rate.

Researchers Arngrímsson, Stewart, Borrani, Skinner, and Cureton (2003) confirmed that relationship between absolute and relative intensity in the heat, in addition to demonstrating a graded effect of heat stress on maximal aerobic exercise performance. Twenty-two male and female runners walked for 20 minutes at 33% of control VO_{2max} in each of four thermal environments (25, 35, 40, and 45°C dry bulb temperature), immediately followed by a test of VO_{2peak} in the same environment. Steady state heart rates at the end of the 20 minute submaximal period progressively increased with increasing ambient temperatures (107 ± 2, 112 ± 2, 120 ± 2, and 137 ± 2 beats/min). The subsequent measure of VO_{2peak} decreased with increasing temperature (3.77 ± 0.19, 3.61 ± 0.18, 3.44 ± 0.17, and 3.13 ± 0.16 l/min). The authors concluded that graded heat stress elicited a progressively higher relative intensity as measured by both heart rate and oxygen consumption.

Submaximal aerobic performance. In addition to the eleven studies reviewed by Nybo et al. (2014) concerning the effect of heat stress on maximal aerobic performance, fifteen more studies were reviewed for the effect of heat stress on submaximal aerobic performance. The average ambient temperature difference between control (12-23°C) and heat stress (25-40°C) conditions was roughly 10°C. On average, the environmental heat stress condition elicited a 0.4°C rise in core temperature. All studies indicated a reduction in submaximal exercise performance. In the ten TT studies, heat stress impaired performance by an average of 13%. The five TTE studies showed a more than two-fold impairment (-30%) in performance compared to TT. The reviewers noted that TTE performance was often terminated not by exhaustion but by reaching a predetermined duration in the control conditions; in the hot conditions, performances were often terminated by involuntary withdrawal due to reaching ethical cutoff limits in core temperature. These two factors make the true effect of heat stress on TTE performance difficult to discern.

Exhaustion and fatigue. In research on exertional heat stress, exhaustion seems to occur before symptoms of EHI develop (Cheung, 2010, p. 29, 36). As exhaustion or fatigue typically mark the end of aerobic exercise performance, it is important to understand the cause of that limitation in performance. The cause of that fatigue remains a contentious subject among researchers. Some suggest that exercise fatigue in environmental heat stress conditions occurs at a “critical core temperature” (Nielsen et al., 1990). More recent research suggests that exercise fatigue in the heat does not necessarily occur at a critical core temperature per se, but that it may be due to skin temperature’s effect on reducing VO_{2max} (coinciding with the elevation of relative intensity) in environmental heat stress (Cheuvront, Kenefick, Montain, & Sawka, 2010). Nevertheless, studying the effect of heat stress on fatigue can provide useful information about the progression of exertional heat illness, without actually eliciting signs or symptoms of EHI.

Preventing Exertional Heat Illness

Due to the severe consequences of exertional heat illness, and its prevalence in the mountains of the Phoenix metropolitan area, preventing EHI should be a high priority. Prevention strategies range from chronic to acute in terms of their implementation. Ultimately, the goal of EHI rescue prevention in hikers should be to influence the behavior of the hiker so that they make the appropriate decision to hike out *before* a rescue situation becomes inevitable. This involves knowing one’s physical limitations, and the realization of when those limitations are exceeded. Unfortunately, by the time hydration behavior becomes critical, the cognitive decision-making ability may be too impaired to make sound decisions regarding one’s safety. Therefore, longer-term strategies should be considered.

Aerobic fitness. According to the Wilderness Medical Society, enhancing fitness through aerobic physical activity is an effective measure for the prevention of EHI

(Lipman et al., 2014). It is beyond the scope of this review to detail a health promotion intervention for increasing the fitness of recreational hikers, but instead this section will provide rationale for such a campaign. As outlined previously, higher aerobic fitness levels are associated with (a) lower resting core temperatures, (b) higher tolerable exercising core temperatures, (c) increased total body water, (d) increased sweat rate, and (e) an increased exercise tolerance in the heat. Additionally, fitness may attenuate the negative effects of hypohydration due to the reduced stress on the cardiovascular system during exercise heat stress (Cadarette, Sawka, Toner, & Pandolf, 1984). Some research shows that the increased risk of exercise hyperthermia in persons with higher body fatness is not apparent when controlled for fitness level (Limbaugh, Wimer, Long, & Baird, 2013). Garrett and colleagues (2011) admit that from a physiological perspective, endurance athletes appear to be already acclimatized to heat stress. Endurance athletes acclimatize faster than those of lower fitness levels (Garrett et al., 2011). Altogether, these benefits of aerobic fitness make it an attractive target for the prevention of EHI in recreational hikers. However, significantly increasing one’s aerobic fitness level safely may take weeks to months to accomplish (Riebe et al., 2018). Therefore, the promotion of aerobic physical activity for the purposes of increasing fitness should be a long-term strategy in a multifaceted effort to prevent EHI in recreational hikers.

Acclimatization. “Heat acclimatization is the best known protection against both EHS [exertional heat stroke] and heat exhaustion” (Armstrong et al., 2007, p. 565). In review, the benefits of heat acclimatization include the following: (a) reduced heart rate (relative intensity) at a given work rate in the heat, (b) reduced core temperature at rest and during exercise, (c) elevated levels of heat shock proteins (HSPs), (d) increased plasma (blood) volume, (e) reduced perceived exertion for exercise in the heat, (f) earlier onset of sweating, and (g) increased sweating capacity and sweat rate. Heat acclimatization also has been shown to increase maximal aerobic capacity (VO_{2max}) in the heat by 8% in as little as 10 days (Lorenzo, Halliwill, Sawka, & Minson, 2010). Without question, heat acclimatization must be addressed as an important aspect of any effort to prevent EHI. Most heat acclimatization protocols entail gradually increasing heat exposure and exercise intensity and/or duration over the course of 8 to 14 days (Armstrong et al., 2007; Garrett et al., 2011; Lipman et al., 2014), making it a medium-term EHI-preventative measure. Sustained elevated core temperature by 1-2°C during physical activity lasting 60-90 minutes on consecutive days appears to be the primary stimulus for acclimatizing to environmental heat stress (Pandolf, Burse, & Goldman, 1977). However, emphasis should be placed on the “gradual” nature of acclimatizing heat stress, rather than adhering to specified intensity or duration of exposure. To heat-unacclimatized hikers, the first hiking experience marks the first exposure to environmental heat stress, and so that exposure should be conservative to start.

Hydration. The maintenance of body water is critical for thermoregulation in exertional and environmental heat stress (Cheung et al., 2000). Relative to hypohydration, euhydration has the following benefits, as discussed previously: (a) increases stroke volume and lowers heart rate (relative intensity) at a given exercise work rate in the heat, (b) reduces ratings of perceived exertion in the heat, (c) reduces resting and exercise core temperature, (d) increases heat storage capacity, and (e) increases sweating (heat dissipation) capacity. While the thermoregulatory benefits of hydration are straightforward, maintaining euhydration during exercise in the heat is much more complicated. A “one-size-fits-all” approach to rehydration is inappropriate due to the immense variation in individual physiology, physical activities, and environmental conditions. Rehydration recommendations have shifted from a general to more individually-tailored approach because of that variability within and between individuals, physical activities, and environments (Armstrong et al., 2007; Burke & Deakin, 2015; McDermott et al., 2017).

Despite the complicated nature of rehydration recommendations, hydration status remains the “most readily modifiable” factor for the prevention of EHI (Lipman et al., 2014). Modifying hydration behavior is therefore a last resort effort to prevent EHI. The Wilderness Medical Society advocates a “drink to thirst” approach (Lipman et al., 2014), but others have concluded that thirst is an unreliable indicator of hydration status and that such a strategy is insufficient to prevent dehydration while exercising in the heat (Sawka & Montain, 2000). The “Take a Hike – Do it Right” infographic says to “Bring Water: Hydrate before you go. Have plenty of water, more than you think you need. Turn around and head back to the trailhead before you drink half of your water.” (“Take a Hike - Do it Right,” 2015). While this seems slightly better than simply “drinking to thirst,” it essentially attempts to control hiking duration by the highly variable behavior of drinking water. Evidence for the utility of this strategy is needed.

Hypohydration: Effects on Aerobic Performance in the Heat

While hydration and thermoregulation are intimately related, each has its own effect on physiology and performance. Indeed it seems impossible to completely separate the two as even slight hypohydration (1%, as measured by euhydrated body mass) has been shown to elevate core temperature (Ekblom, Greenleaf, Greenleaf, & Hermansen, 1970), and heat stress creates a relative body water deficit due to the added strain of shunting blood to the skin (Sawka et al., 2011). Although slight, there is a noteworthy difference between heat stress and hydration and the mechanisms by which they affect one another. That difference is between the absolute and relative body water deficit. Hypohydration is typically compared to resting euhydration in terms of body mass or absolute volume of blood (plasma). Under conditions of exercise heat stress, the absolute volume of the cardiovascular system “grows” to accommodate skin blood flow while the absolute volume of body water remains the same, thus creating relative hypohydration. It is in this way that heat stress and hypohydration can have such similar effects on physiology and subsequent performance.

Whereas 1% hypohydration was shown to affect thermoregulation, hypohydration of ≥2% has consistently been shown to impair aerobic exercise performance, especially when accompanied by environmental heat stress (Cheuvront et al., 2010; Sawka & Noakes, 2007). Even in the absence of environmental heat stress, Webster, Rutt, and Weltman (1990) demonstrated significant reductions peak treadmill speed (-6.5%), VO_{2max} (-6.7%), and time to exhaustion (-12.4%) at 5% hypohydration compared to euhydration.

While hypohydration can decrease maximal aerobic performance without environmental heat stress, much of the research focuses on hypohydration’s effect on prolonged (submaximal) aerobic performance. This may be due to a complex interaction between hydration status and body weight where the ergolytic effect of hypohydration is balanced with the benefit of a lighter-weight body. Additionally, the increased core temperature associated with hypohydration may actually enhance certain muscular functions in cooler environments, similar to a warmup. A review by Nybo and colleagues (2014) suggests that despite the interacting effects of hypohydration and hyperthermia on performance, hypohydration consistently exacerbates many of the same physiological effects as heat stress does when environmental heat stress is present. Reviews by Sawka et al. (2011) and Cheuvront and Kenefick (2014) support this idea from a performance perspective such that hypohydration shows little effect on aerobic performances (VO_{2max}, TT, and TTE) of <1hr in cool conditions, but has progressively more detrimental effect with increasing time in heat stress.

In 2001, Nybo, Jensen, Nielsen, and González-Alonso demonstrated that dehydration of 4% body mass resulted in a 6% reduction in VO_{2max} under normal thermal strain conditions (skin temperature of 31°C). When skin temperature was elevated by six degrees (37°C), the penalty of dehydration increased another 10% for a combined effect of a 16% reduction in VO_{2max}. Again, while hiking is not typically performed at VO_{2max}, except maybe intermittent maximal efforts, the lower absolute maximal aerobic power associated with hypohydration translates into a higher relative intensity at any submaximal work rate. Submaximal aerobic performance has also been shown to be impaired by hypohydration. A study by Kenefick, Cheuvront, Palombo, Ely, and Sawka (2010) found that dehydration of 4% body mass impaired 15-minute TT cycling performance (as measured by total work) by -3% at 10°C, -5% at 20°C, -12% at 30°C, and -23% at 40°C, compared to the euhydration trials at the same temperatures.

Beyond its effects on aerobic performance, hypohydration is known to negatively affect measures of cognitive performance (ratings of mental fatigue, mood-state, taskperformance, attention, and short-term memory) (Baker & Jeukendrup, 2014; McDermott et al., 2017). Given that hiking requires the ability to navigate in potentially adverse conditions (e.g. environmental heat stress and heat strain) and the ability to make sound behavioral modifications in response to those conditions (Ainslie, Campbell, Lambert, MacLaren, & Reilly, 2005), the detrimental effect of hypohydration on cognitive performance should be of concern to both the hiker and those involved in rescue prevention.

Hydration for Physical Activity in the Heat

The shift from general to more individualized recommendations (Sawka et al., 2007) necessitates a tailored rehydration strategy for recreational hikers. While it is impractical to account for all of the individual variability, hydration recommendations can at least be tailored to the physical activity and the environment. Physical activities can be categorized by type, intensity, and duration – each having a specific effect on hydration needs (Baker & Jeukendrup, 2014). Further, the properties of the environment (temperature, humidity, wind speed, and radiation) will affect individual thermoregulation and subsequent hydration requirements (Sawka et al., 2007). The recommended composition of fluids consumed varies by these factors (physical activity and environment), but the three main constituents include water, electrolytes, and carbohydrate (Baker & Jeukendrup, 2014). Below is a brief discussion concerning these common fluid properties:

Water. In general, people should drink enough water to prevent a >2% loss in body mass (Baker & Jeukendrup, 2014). Kenefick and Cheuvront (2012) predict that dehydration of more than 2% body weight rarely occurs in recreational runners in temperate environments. However, high-intensity (≥6 METs), longer-duration (>1 h) physical activities, or those occurring in environmental heat stress conditions, are likely to elicit a >2% loss in body mass due to sweating, if water losses are insufficiently replenished (Baker & Jeukendrup, 2014). Therefore, recreational hiking in the heat necessitates rehydration with water. The amount of water required will depend on the individual's sweat rate and the duration of physical activity. As previously discussed, the sweat rates of adult athletes vary dramatically (1.37 ± 0.71 L/h), and the average sweat rate of hikers has not been investigated (Baker et al., 2016). Therefore, no specific water recommendation can be made without the risk of the individual under- or over-hydrating. Alternative approaches to increasing body water reserves (at least before exercise in the heat) without the risk of under- or over-hydrating could be to increase one's fitness or to acclimatize to heat – both of which are associated with increased plasma (blood) volume (Powers & Howley, 2015).

Electrolytes. "The addition of sodium to sports beverages can replace sodium losses associated with sweating, prevent hyponatremia, promote the maintenance of plasma volume and enhance intestinal absorption of glucose and fluid." (Burke & Deakin, 2015). Additionally, sodium increases palatability and stimulates thirst when added to fluid replacement beverages in sufficient quantity (Baker & Jeukendrup, 2014). But electrolytes need not come exclusively from fluid replacement beverages – salty foods can provide a similar effect for hikers (Backer & Shlim, 2013). Sodium supplementation, from either fluid replacement beverages or salty foods, becomes less necessary as a person acclimatizes to heat because heat acclimatization improves sodium chloride reabsorption and reduces sodium losses in sweat (Allan & Wilson, 1971). However, for those unacclimatized to heat, added electrolytes may be of benefit in the first few days of the acclimatization process (Sawka & Montain, 2000). Burke and Deakin (2015) recommend adding 20-30 meq/L sodium to exercise fluid replacement beverages. More exact amounts can be estimated by measuring the electrolyte content of sweat, which varies drastically by individual acclimatization status, hydration status, sweat rate, and diet (Baker et al., 2016; Sawka & Montain, 2000).

Carbohydrate. Carbohydrate as an additive to fluid replacement beverages serves multiple functions as a palatability-enhancer, a chemical messenger to the brain, a synergistic nutrient with sodium to enhance water absorption in the gut, and as an energy substrate, to name a few (Baker & Jeukendrup, 2014). While carbohydrate supplementation is not metabolically necessary unless glycogen depletion is to be expected, its non-metabolic ergogenic effect (Burke & Maughan, 2015) may warrant its inclusion in fluid replacement beverages in low (< ~10%) doses for exercise in the heat (Burke & Deakin, 2015).

Environmental Heat Stress and Carbohydrate

Environmental heat stress has been shown to increase glycogenolysis and glycogen utilization during exhaustive submaximal aerobic exercise (Parkin et al., 1999). The prevailing explanation for this phenomenon is that environmental heat stress elicits a heightened sympatho-adrenal response (adrenaline) along with elevated muscle temperature – both of which accelerate glycogenolysis (Febbraio, 2001). But while glycogen depletion is often a cause of fatigue in prolonged aerobic exercise in thermoneutral (~20°C) climates (Coyle, Coggan, Hemmert, & Ivy, 1986), glycogen depletion is not associated with fatigue in hot (40°C) environments (Parkin et al., 1999).

Despite the fact that glycogen is not performance-limiting in the heat, carbohydrate supplementation was found to improve moderate and high-intensity aerobic exercise performance in the heat (Carter et al., 2003). Carter and colleagues (2003) admitted that the ergogenic effect of carbohydrate supplementation could not be explained metabolically, but suggested that the effect could involve the central nervous system tolerating more exertional heat stress after sensing nutrient availability. A later meta-analysis solidified this hypothesis concerning the non-metabolic ergogenic effect of carbohydrate in 2013 when nine out of eleven included studies showed an ergogenic effect of carbohydrate mouth rinsing on moderate to high-intensity aerobic exercise (de Ataide e Silva et al., 2013). However, the meta-analysis did not account for environmental temperature, and so it remains unclear if the ergogenic effect of carbohydrate varies by environmental condition. As such, current during-exercise carbohydrate recommendations do not reflect changes based on environmental conditions (Burke & Deakin, 2015, p. 781).

Summary

The more than 200 (and growing) mountain rescues annually in the Phoenix metropolitan area has gained the attention of local public officials. In response to this alarming statistic, local authorities have collaborated to create the “Take a Hike – Do it Right” educational campaign which attempts to inform the public about preventative safety measures for hiking in the heat of Phoenix. As many of the mountain rescues are presumed to be exertional heat illness-related, it is important to understand the physiological underpinnings of heat stress and heat strain. Beyond the effect of heat stress on physiology, heat stress has measurable effects on aerobic performance, which has yet to be studied in recreational hikers. There is a need to re-evaluate EHI prevention strategies from a hiking performance perspective. Further, the usual focus on hydration as a prevention strategy must be reconsidered in the context of the performance leading up to exhaustion in the heat. The severity of the problem (rescues and deaths on the mountains) warrants an in-depth look at the best practices for preventing EHI which include acclimatization, aerobic fitness, and hydration (including fluid additives). Evidence is needed to support the support the many safety recommendations set forth for recreational hikers.

Chapter 3

METHODS

Subjects

Twelve healthy individuals (7 male, 5 female) between the ages of 18 and 40 were recruited to participate in this study from Arizona State University's Downtown Phoenix and Tempe campuses via flyers and word of mouth. Inclusion criteria included (a) residential status in a hot-arid desert area (e.g. Phoenix or Tempe, AZ) and (b) mountain hiking experience. Exclusion criteria included (a) pregnant status, (b) the use of tobacco, (c) the use of medications that influence hydration status, (d) consumption of more than 21 standard alcoholic beverage servings per week, and (e) any contraindications to ingesting a telemetric intestinal temperature (CorTemp) capsule. The inclusion and exclusion criteria were assessed through an online screening questionnaire. Participants who met the criteria were then invited to an informational meeting about the study.

Study Design and Description of Activities

This study utilized a within-groups repeated measures study design using environmental condition as the independent variable. Participants attempted to complete a ~4mi hike on 'A' Mountain in Tempe, Arizona on a hot summer day (HOT), and again on a moderate day (MOD) in the fall season. Participants served as their own controls, and were instructed to maintain consistent lifestyle behaviors between trials, therefore making environmental condition the primary source of any observed differences in dependent variables between the two hikes. Measured dependent variables included time (duration of the hike), core temperature (T_c), heart rate, respiratory rate, accelerometry (activity), rated perceived exertion (RPE), immediate post-exercise respiratory exchange ratio (RER), and measures of hydration (urine specific gravity [USG], sweat rate, and percent body mass loss).

Procedures

Screening questionnaire and initial visit. Participants were screened for eligibility using an online questionnaire. Eligible participants willing to participate were then invited to an information session about the study where they could then read and sign the IRB-approved informed consent document and the contraindications form for the telemetric intestinal temperature capsule (CorTemp, HQ Inc., Florida, USA). During this meeting and after informed consent was signed, participants' height and weight were measured using a portable stadiometer and scale (SECA, Hamburg, Germany), and then a practice measurement was taken on a handheld metabolic analyzer (Breezing Co., Tempe, Arizona) after walking on a 10° inclined treadmill for two minutes to simulate hiking conditions. Participants were sent home with a CorTemp capsule to ingest 12 to 4 (rationale to follow) hours prior to the hike, a standardized breakfast of cereal and low fat milk (~330 kcal; ~65g carbohydrate; ~8g protein; ~4g fat) to consume two hours prior to the hike, and instructions regarding how to prepare for the hike. These instructions advised participants to prepare as they normally would (including bringing water and food) for a ~4 mile hike (e.g. Camelback Mountain). The preparation instructions were purposely open to interpretation so that we could observe the participants' natural behavior and preparedness.

First study day hike. The twelve participants chose one of two days (Friday or Saturday) to complete each hiking trial. Text reminders were sent to participants for telemetric capsule ingestion at least 4 hours prior to the hike and for the consumption of the standard breakfast at 2 hours prior to the hike. Participants were instructed to abstain from caffeine and to consume only water between the breakfast and the start of the hike (12:00 PM ± 1:00) to ensure that all participants were roughly in the same metabolic state upon arrival.

Participants arrived at the laboratory approximately 1 hour prior to the start of the hike. Food and drinks brought by the participants were measured for weight (with 1 gram precision, Sartorius ENTRIS623-IS) and nutritional composition, and then this information was recorded. Two resting RER measurements were then taken with the handheld metabolic analyzer to serve as a baseline for comparison to the immediate post-exercise measurements during the hike. An "all-out" urine sample was then collected to void the bladder and to assess hydration status (USG), and then participants were immediately weighed on a scale in an extra set of minimal dry clothing not to be worn on the hike. Following weigh-ins, participants were equipped with an activity monitor chest strap (Bioharness-3, Zephyr Technology, Anapolis, USA), dawned their hiking clothing, and gathered their pre-measured food and drink. Finally, a pre-hike briefing was given, instructing participants on the trail to be hiked, and informing them of the safety protocol if they should need to withdraw from the hike. Participants were instructed to hike a "brisk pace" without stopping for the view or for pictures, and without running.

Following the in-lab briefing, participants walked a very short distance to the base station at the bottom of 'A' Mountain. Baseline core temperatures were taken and then participants were sent off on the hike at 1-minute intervals for staggering. Participants hiked at their self-selected pace to the top of ‘A’ Mountain (Figure 5) and back down to the base station four times for a total of roughly 4 miles, until voluntary withdrawal, or until withdrawal by the research team for safety (see “Protection of Subjects from Injury or Harm” section below for details).

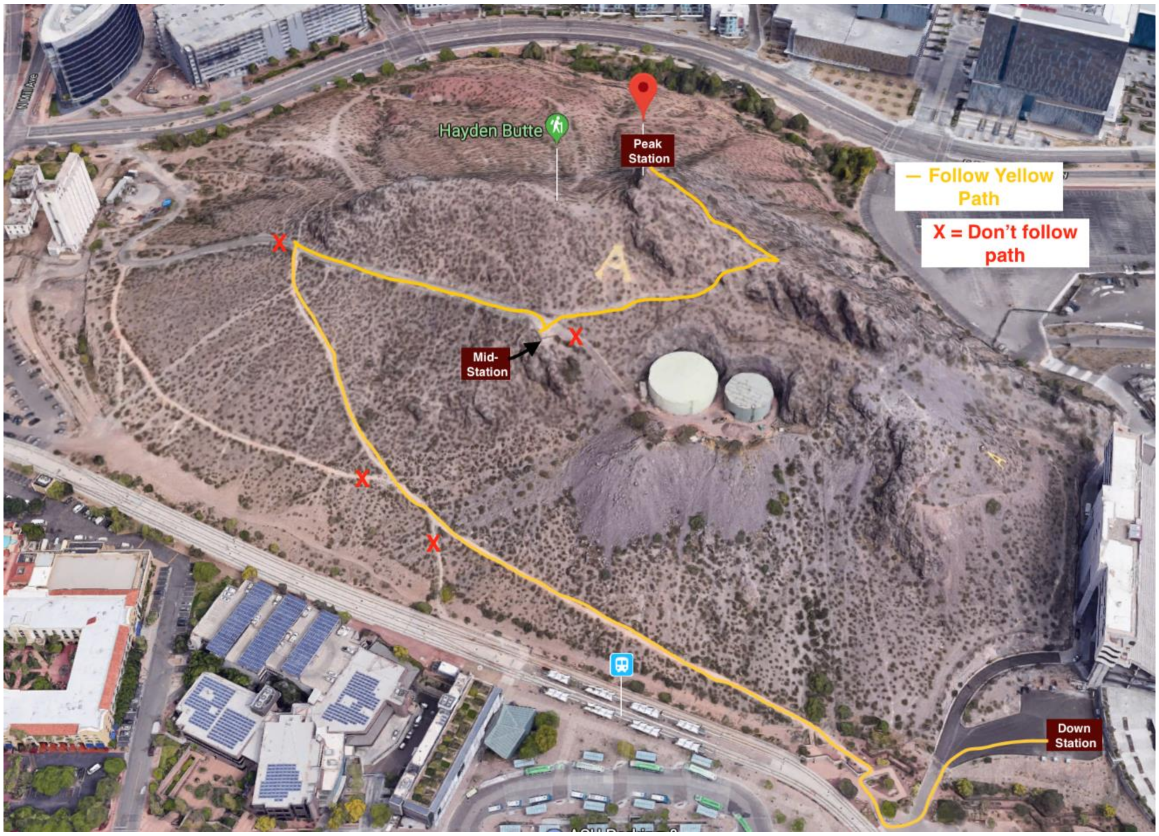


Figure 5. *‘A’ Mountain Trail Route*

Core temperatures, split times, and RPE were recorded at each base and peak station passing. An immediate post-exercise metabolic measurement was taken on the first descent, second ascent, third descent, and fourth ascent on a sitting bench approximately two-thirds of the way up the mountain. During the hike, participants had ad libitum access to their own food and drink.

Following the cessation of the hiking activity, participants were escorted back to the laboratory for food and fluids to be re-weighed. Another “all-out” urine sample was collected to void the bladder, ensuring the measurement of actual body weight (following), and to assess hydration status (USG). Activity monitors were removed, and then participants were weighed in their extra set of minimal dry clothing. Participants were given a urine collection container to provide a morning-after mid-stream urine sample, and then released from the laboratory. First morning-after urine samples were collected on the following day to be tested for color and urine specific gravity.

Measurements

Environmental factors.

Environmental Heat Stress. Environmental conditions including dry bulb temperature, relative humidity, and wet bulb globe temperature (WBGT) were measured using two handheld weather monitors (Kestrel 5400 Heat Stress Tracker, Nielsen-Kellerman, Boothwyn, Pennsylvania). One device was placed in the shade near the base of the mountain, and the other was placed in direct sunlight next to the trail at the mid-mountain resting area. The WBGT is the recommended measure of environmental heat stress (Lipman et al., 2014), and it is automatically calculated by the Kestrel device using the following formula: [$\text{WBGT} = 0.1(T_{\text{dry}}) + 0.7(T_{\text{wet}}) + 0.2(T_{\text{globe}})$] (Armstrong et al., 2007). The Kestrel devices recorded measurements at 10-minute intervals from the start of the first hiker until the last hiker was finished. Outcomes were calculated as averages ± SD for HOT and MOD conditions.

Individual factors.

Exercise duration. Because the hike was a set distance, exercise duration was dependent upon the hiker's pacing strategy. Hikers were advised not to run, but to hike at a "brisk" pace without stopping unnecessarily. Therefore the hike resembled a "time trial" (TT) performance, rather than a "time to exhaustion" (TTE) performance, unless hikers withdrew before completion. Hike start and finish times were measured with common wrist watches that were synced to Arizona Mountain Standard Time on the morning of the hike. Split times were recorded at both base and peak mountain stations. Times were recorded in hh:mm:ss format and then converted to decimal format for data analysis.

Core body temperature. Intestinal temperature (T_{int}) was measured using a capsular telemetric system (CorTemp, HQinc., Palmetto, Florida). This system has been shown to be safe and effective at measuring T_{int} at rest as well as during exercise (Gant, Atkinson, & Williams, 2006). Additionally, T_{int} is an accurate and practical measure of "core" body temperature (T_c) for the purposes of research in exercise physiology, and so T_{int} may be interchanged with T_c in this discussion (Gant et al., 2006). Participants ingested the telemetric capsule at least 4 hours prior to the start of the hike to ensure complete passage through the stomach where ingested fluids may alter temperature (Wilkinson, Carter, Richmond, Blacker, & Rayson, 2008), and at most 12 hours prior to the start of the hike in order to avoid excretion. The telemetric reader, worn in a pouch around the waist, measured and recorded T_c at 10-second intervals from approximately 30 minutes prior to the hike until the end of the hike.

Exercise intensity. Heart rate (HR), respiration rate (RR), and activity were measured using a wearable chest strap activity monitor (Bioharness-3, Zephyr Technology, Anapolis, USA) from approximately 30 minutes prior to the hike until the end of the hike at 1-second intervals. The device utilizes a 3-axis accelerometer to produce an activity score (A) that can be used to estimate metabolic equivalents (METs) using the following formula: $\text{MET} = -1.1644 + (0.02947 * \text{HR}) + (5.8985 * \text{A}) + (0.03583 * \text{RR})$ (Rosenberger, Haskell, Albinali, & Intille, 2011). The metabolic equivalent is a widely accepted measure of absolute intensity of exercise (Riebe et al., 2018). Relative intensity of exercise can be measured as a percent of predicted maximum heart rate ($\%\text{HR}_{\text{max}}$) with the following equation: heart rate / (208 – (0.7 x age) (Riebe et al., 2018). Estimated MET values were used to calculate energy expenditure (MET-h) and predicted cardiorespiratory fitness (CRF-p). Energy expenditure (MET-h) was calculated as the product of METs and hiking time in hours (i.e., METs x hours). Predicted cardiorespiratory fitness (CRF-p) was calculated as the average absolute intensity (METs) divided by average relative intensity ($\%\text{HR}_{\text{max}}$).

Rating of perceived exertion (RPE). The Borg RPE scale is an adjunct method of monitoring perceived exertion and relative intensity that is recommended by the ACSM (Riebe et al., 2018). The participants were briefed on the Borg RPE scale of 6 to 20 before beginning the hike. In this scale, 6 represents “no exertion at all” and 20 represents “maximal exertion.” At every base and peak station pass, participants were asked to report their RPE on the Borg scale. Participants pointed to the number that corresponded to their perceived exertion immediately leading up to that moment and the scores were recorded.

Metabolic analysis. A handheld metabolic analyzer (Breezing Co., Tempe, Arizona) was used to measure oxygen consumption, carbon dioxide production, and the respiratory exchange ratio (RER; VCO_2/VO_2) of participants before and during the hike. Unlike most indirect calorimeters which provide continuous gas analysis, this portable device utilizes a disposable chemical sensor to take a roughly 30-second "snapshot" of whole-body metabolic gas exchange. The system consists of a sensor body with an integrated flow meter and Bluetooth receiver, a non-rebreathing Hans-Rudolph valve, a mouthpiece, and requires a sensor cartridge and a mobile device with a camera (e.g. a smart phone or tablet) capable of running the mobile application over Bluetooth. The O_2 and CO_2 sensor was developed and patented at Arizona State University and has been tested and validated for the measurement of resting and sedentary activity energy expenditure (Zhao et al., 2014). Energy expenditure is calculated from VO_2 and VCO_2 using the Weir equation (Weir, 1949). Because the device is not yet capable of measuring energy expenditure during non-sedentary activities, we elected to take the non-resting "momentary" measurements immediately following exercise with the participant in the seated or standing position. These measurements were taken on the first descent, second ascent, third descent, and fourth ascent of 'A' Mountain at a resting location approximately two thirds of the distance up the mountain.

Food and fluid intake during exercise. All food and fluids brought by participants to be consumed after the initial bodyweight measurement (and during the hike) were weighed on a scale (g. Sartorius ENTRIS623-IS) and then labelled. Immediately following the hike, all remaining food and fluids were weighed in their original containers (including wrappers) and then recorded. Nutritional information labels and a food consumption table were used to estimate energy (kcal) and nutrients (g) consumed during the hike.

Fluid balance and hydration status. Sweat rate was calculated using the difference in pre- and post-hike body mass and accounting for consumption and excretion. The following formula adapted from McDermott et al. (2017) was used: sweat rate (mL/h) = (pre-exercise body mass – post-exercise body mass + fluid intake + food intake – urine output) / exercise duration. The change in percent of pre-hike body mass (PBML) was monitored at every base station visit (4 times total), and the end total value was recorded for data analysis. Official pre- and post-hike body mass measurements were taken in the same set of minimal dry clothes not used during the hike. Post-hike urine was collected within 15 minutes of exercise termination and then weighed (PT 1400, Sartorius AG, Gottingen, Germany) and recorded.

Each participant provided an “all-out” urine sample immediately before and immediately after the hike. Between these pre- and post-hike measurements, participants were instructed to urinate only in the laboratory facilities or in the portable lavatory at the ‘A’ Mountain base station. No participants needed to urinate during the hike. Participants completely voided their bladders into urine collection cups to be weighed and tested for color and USG. Urine specific gravity was tested using a 30mL sample at the standard sample temperature of 20°C (PEN-refractometer, ATAGO, Tokyo, Japan). A USG value ≥1.020 g/mL is considered to be hypohydrated (McDermott et al., 2017). The urine samples were also tested for hydration status using a color test (Armstrong et al., 1994). Hikers were asked to score the color of their own urine samples using that index.

Protection of Subjects from Injury or Harm

Participants were briefed on the safety protocol (similar to the Take a Hike – Do it Right infographic) immediately prior to the start of the hike. The briefing included aerial map directions for staying on the trail, and a recommendation to hike individually and at their own “brisk” pace without running or stopping unnecessarily. Participants were encouraged to bring drinks and snacks and to consume them at their convenience (ad libitum). While participants were encouraged to complete as much of the hike as possible, clear procedures were presented for voluntarily terminating the hiking performance. Terminating prior to the halfway point was deemed an “informed decision” to simulate hiking back out to the trailhead. Termination after this point represented a “rescue” situation in which in which the participant had hiked past their ability to “hike out.” In addition to these voluntary termination situations, mandatory termination could be initiated by the research team if participants lost more than 2% body mass (measured at each base station pass) (Sawka et al., 2007), or if their core temperatures exceeded our ethical cutoff limit of 39.5°C (measured at both peak and base stations) (Cheung et al., 2000). If performances were terminated on the mountain, the hiker was instructed to walk back down to the base station. In any case of performance termination, cold “rescue water” was made available at the base of the mountain, as well as ice packs. A wheelchair was kept at the base station to transport participants to the laboratory in case any symptoms of EHI were to develop. A cold water immersion tub was made available for emergency treatment of hyperthermia, as recommended by Lipman et al. (2014).

Data Analysis

Statistical analysis was performed using the International Business Machines Statistical Package for Social Sciences (IBM SPSS Statistics, version 25). Normality of the data was justified using a combination of scores of skewness, kurtosis, and histogram inspection. Descriptive statistics were presented as mean ± standard deviation. Environmental condition ("hot" or "moderate" WBGT) served as the independent variable in this study. Differences in measured dependent variable means (time, T_c, intensity, RPE, METs, MET-h, RER, CRF-p, SR, and PBML) between the hot and moderate hikes were analyzed using paired-samples t-tests. Differences in repeatedly measured variables within each environmental condition were analyzed using one-way repeated measures ANOVA. Difference scores were computed (hot – moderate) in order to compare between-groups effects with the one-way repeated measures ANOVA. Statistical significance was set at $p \leq 0.05$ for all tests.

Activity data were checked for anomalies. In rare cases of anomalous activity data, the data were either re-synced to estimated performance times, or imputed with mean values. In cases where the sphericity assumption was not met in the repeated measures data, the Greenhouse-Geisser corrected degrees of freedom were used to interpret F-statistics.

Chapter 4

RESULTS

The purpose of the study was to measure environmental heat stress and its effect on individual physiology and recreational hiking performance. Measured individual variables included: hiking times, core temperature (T_c), rating of perceived exertion (RPE), relative intensity (%HR_{max}), estimated absolute intensity (METs), estimated energy expenditure (MET-h), respiratory exchange ratio (RER), hydration status (USG), percent body mass loss (PBML), sweat rate (SR), and predicted cardiorespiratory fitness (CRFp).

Subject and Environmental Descriptives

Twelve participants (5 female, 7 male; mean age 21.6 ± 2.47) were included in the study. After inclusion, participants hiked 'A' Mountain on a "hot" (HOT; wet bulb globe temperature [WBGT] = 31.6°C) summer day and then again on a "moderate" (MOD; WBGT = 19.0°C) day in Tempe, Arizona. Four participants did not finish the entire hike (4 climbs; ~4mi) on the hot day. Three of those four participants dropped the study between the hot and moderate hiking trials. Nine participants (2 female, 7 male) returned in the fall to complete the entire hike in the "moderate" condition. Participant and environmental descriptive statistics are shown in Table 2.

Table 2. *Participant and Environmental Descriptives During HOT and MOD Days*

	HOT	**MOD**
Subjects (M/F)	7 / 5	7 / 2
Subject Age (y)	21.6 ± 2.47	22.1 ± 2.62
WBGT (°C)	31.6 ± 2.10	19.0 ± 0.74
T_{dry} (°C)	40.4 ± 2.50	22.9 ± 1.60
Relative Humidity (%)	21.4 ± 2.92	18.2 ± 1.38

Values are expressed as means ± SD. Environmental measurements were taken from the start of the first hiker until the last hiker finished. T_{dry} is dry bulb (ambient) temperature.

Mean Differences Between HOT and MOD

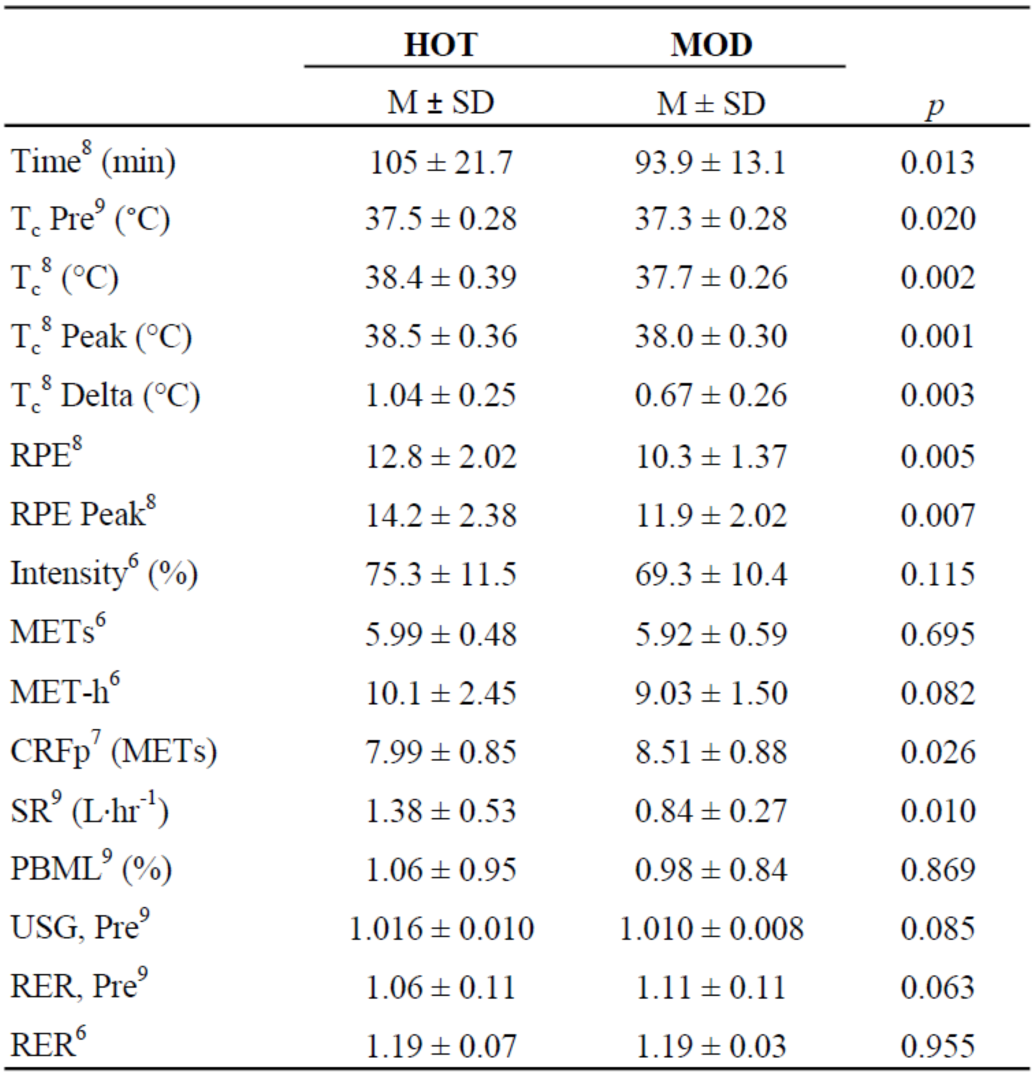
Measured Variables.

Between HOT and MOD trials, baseline hydration status (USG, Pre) (1.013 ± 0.009) and respiratory exchange ratio (RER, Pre) (1.09 ± 0.11) were not significantly different ($p > 0.05$). Baseline core temperature (T_c Pre) was significantly different between HOT (37.5 ± 0.28°C) and MOD (37.3 ± 0.28°C) trials ($p = .020$). This result was unexpected, but could be due to influence from seasonal circadian rhythm differences or the 12:00 PM ± 1:00 hiking start times between days. Time trial performance (time) was significantly impaired by -11% (11.1 minute difference) in the HOT trial (105 ± 21.7 min), compared to MOD (93.9 ± 13.1 min) ($p = .013$). Core temperatures (T_c) and ratings of perceived exertion (RPE) were measured at base and peak stations (4 climbs = 8 measurements) and both T_c and RPE were significantly higher in the HOT trial (38.4 ± 0.39°C and 12.8 ± 2.02, respectively) than in MOD (37.7 ± 0.26°C and 10.3 ± 1.37, respectively) ($p = .002$ and $p = .005$, respectively). Peak core temperatures (T_c Peak) and RPE Peak were measured only at the peak station (4 measurements) and both were significantly higher in HOT (38.5 ± 0.36°C and 14.2 ± 2.38, respectively) versus MOD (38.0 ± 0.30°C and 11.9 ± 2.02, respectively) (*p* = .001 and *p* = .007, respectively). Within-subjects core temperature intervals (T_c Delta) represents the difference between the baseline and the absolute peak core temperature achieved during the trial, and this was significantly greater in the HOT trial (1.04 ± 0.25°C) compared to MOD (0.67 ± 0.26°C) (*p* = .003). Sweat rates were higher in the HOT trial (1.38 ± 0.53 L/h) versus MOD (0.84 ± 0.27 L/h) (*p* = .010). Percent body mass loss (PBML) was measured at the end of the trial hikes relative to pre-hike body mass, and no significant differences were found between HOT and MOD (1.20 ± 0.90, *p* = .869), indicating that ad libitum fluid consumption was sufficient to prevent dehydration during the hike. The respiratory exchange ratio represents an average of four measurements taken during each hike, and no significant differences were found between HOT and MOD trials. Table 3 summarizes these results.

Estimated Variables.

Estimated relative intensity (Intensity) and absolute intensity (METs) were measured a 1-second intervals throughout each trial. Energy expenditure (MET-h) was computed by multiplying average METs by total hike time in hours. The following values were higher in HOT versus MOD, but no significant differences were found between relative intensity (75.3 ± 11.5 vs. 69.3 ± 10.4%, *p* = .115), absolute intensity (5.99 ± 0.48 vs. 5.92 ± 0.59 METs, *p* = .695), or energy expenditure (10.1 ± 2.45 vs. 9.03 ± 1.50 MET-h, *p* = .082). Predicted cardiorespiratory fitness (CRFp) was reduced by 6% in the HOT trial (*p* = 0.26).

Table 3. *Performance and Physiological Variables During HOT and MOD Days*



	HOT	**MOD**	
	M ± SD	M ± SD	*p*
Time^{8} (min)	105 ± 21.7	93.9 ± 13.1	0.013
T_c Pre^{9} (°C)	37.5 ± 0.28	37.3 ± 0.28	0.020
T_c^{8} (°C)	38.4 ± 0.39	37.7 ± 0.26	0.002
T_c^{8} Peak (°C)	38.5 ± 0.36	38.0 ± 0.30	0.001
T_c^{8} Delta (°C)	1.04 ± 0.25	0.67 ± 0.26	0.003
RPE^{8}	12.8 ± 2.02	10.3 ± 1.37	0.005
RPE Peak^{8}	14.2 ± 2.38	11.9 ± 2.02	0.007
Intensity^{6} (%)	75.3 ± 11.5	69.3 ± 10.4	0.115
METs^{6}	5.99 ± 0.48	5.92 ± 0.59	0.695
MET-h^{6}	10.1 ± 2.45	9.03 ± 1.50	0.082
CRFp^{7} (METs)	7.99 ± 0.85	8.51 ± 0.88	0.026
SR^{9} ($L \cdot hr^{-1}$)	1.38 ± 0.53	0.84 ± 0.27	0.010
PBML^{9} (%)	1.06 ± 0.95	0.98 ± 0.84	0.869
USG, Pre^{9}	1.016 ± 0.010	1.010 ± 0.008	0.085
RER, Pre^{9}	1.06 ± 0.11	1.11 ± 0.11	0.063
RER^{6}	1.19 ± 0.07	1.19 ± 0.03	0.955

Superscript numbers represent sample size (*n*). Values are expressed as means ± SD.

Mean Differences Within HOT, MOD, and Difference Scores

Measured Variables.

Individual pacing was consistent within hikers both during HOT and MOD conditions as hiking times did not vary significantly within (climbs 1-4; $p = .105$, and $p = .172$, respectively) or between each trial (Diff; $p = .211$). However, there were significant between-subjects differences in climbing times on the HOT ($p < .001$) and MOD ($p <$

.001) conditions, as well as between-subjects difference scores between trials (Diff) (p = .013). Peak (summit) station core temperatures were significantly different within and between subjects on the HOT ($p < .001$) and MOD ($p = .001$ and $p = .013$) conditions, and between trials (Diff; $p < .001$ and $p = .001$, respectively). Within and between-subjects peak (summit) ratings of perceived exertion were significantly different over the course of both HOT ($p = .023$ and $p < .001$, respectively) and MOD ($p = .037$ and $p < .001$, respectively). Additionally, both within- and between-subjects RPE differences achieved statistical significance between trials (Diff) ($p = .021$ and $p = .009$, respectively).

Estimated Variables.

There were significant differences in relative intensity (Intensity; %HR_{max}) between subjects in HOT ($p < .001$). Relative intensity showed significant within- and between-subjects differences in MOD ($p = .022$ and $p < .001$), but no significant differences were seen between trials (Diff). Estimated absolute intensity (METs) differed only between subjects on the HOT ($p < .001$) and MOD ($p < .001$) days. Similarly, estimated energy expenditure (MET-h) differed between subjects on the HOT ($p < .001$) and MOD ($p < .001$) days, but also within-subjects in MOD ($p = .031$). Table 4 summarizes these results below.

Table 4. *Mean ± SD and Difference Scores in Performance and Physiological Variables Between MOD and HOT Days During Four Hiking Climbs of ‘A’ Mountain*

Climb	Trial	1	2	3	4	Within	Between
Time (min)	$\mathrm{HOT}^{8,S}$	24.3 ± 3.89	25.0 ± 4.24	28.1 ± 7.76	28.1 ± 7.47	$p = .105$	$p < .001$
	MOD^{9}	23.1 ± 3.18	22.7 ± 2.95	24.2 ± 4.20	23.6 ± 2.70	$p = .172$	$p < .001$
	Diff^{8}	1.13 ± 2.85	2.18 ± 1.74	3.77 ± 4.64	4.49 ± 5.10	$p = .211$	$p = .013$
T_c (°C)	$\mathrm{HOT}^{8,S}$	$37.8 \pm 0.29^{0,2,3,4}$	$38.5 \pm 0.39^{0,1}$	$38.9 \pm 0.47^{0,1}$	$38.8 \pm 0.50^{0,1}$	$p < .001$	$p < .001$
	$\mathrm{MOD}^{9,S}$	$37.7 \pm 0.30^{0,2}$	$38.1 \pm 0.26^{0,1}$	38.0 ± 0.65^{0}	38.0 ± 0.29^{0}	$p = .001$	$p = .013$
	Diff^{8}	$0.12 \pm 0.16^{3,4}$	0.44 ± 0.29	0.69 ± 0.41^{1}	$0.83 \pm 0.47^{0,1}$	$p < .001$	$p = .001$
RPE Peak	$\mathrm{HOT}^{8,S}$	11.9 ± 2.80	13.8 ± 2.60	15.1 ± 2.90	15.3 ± 3.11	$p = .023$	$p < .001$
	$\mathrm{MOD}^{9,S}$	11.2 ± 1.79	11.7 ± 2.06	12.1 ± 2.26	12.7 ± 2.40	$p = .037$	$p < .001$
	$\mathrm{Diff}^{8,S}$	1.00 ± 2.83^{2}	2.38 ± 2.20^{1}	3.38 ± 1.69	2.88 ± 1.64	$p = .021$	$p = .009$
Intensity (%)	HOT^{6}	71.1 ± 11.0	77.1 ± 12.4	76.9 ± 11.6	76.1 ± 12.7	$p = .124$	$p < .001$
	MOD^{9}	69.1 ± 8.94^{2}	72.5 ± 10.4^{1}	72.3 ± 10.7	71.8 ± 9.12	$p = .022$	$p < .001$
	Diff^{6}	3.21 ± 6.39	7.11 ± 9.56	6.87 ± 8.80	6.58 ± 8.85	$p = .324$	$p = .119$
METs	$\mathrm{HOT}^{6,S}$	5.92 ± 0.52	6.13 ± 0.47	5.96 ± 0.55	6.03 ± 0.72	$p = .639$	$p < .001$
	MOD^{9}	5.93 ± 0.55	6.18 ± 0.64	6.05 ± 0.75	6.06 ± 0.52	$p = .244$	$p < .001$
	Diff^{6}	0.11 ± 0.45	0.17 ± 0.57	0.04 ± 0.53	0.05 ± 0.63	$p = .932$	$p = .656$
MET-h	$\mathrm{HOT}^{6,S}$	2.34 ± 0.44	2.53 ± 0.53	2.60 ± 0.82	2.63 ± 0.77	$p = .319$	$p < .001$
	MOD^{9}	2.28 ± 0.35	2.33 ± 0.33	2.41 ± 0.36	2.38 ± 0.31	$p = .031$	$p < .001$
	$\mathrm{Diff}^{6,S}$	0.11 ± 0.34	0.29 ± 0.23	0.32 ± 0.49	0.34 ± 0.49	$p = .443$	$p = .081$

Note. Baseline (Climb-0) T_c values are not shown. Superscript numbers in ‘Trial’ column represent sample size (*n*). Superscript ‘S’ indicates that the sphericity assumption was not met, and that the associated *p*-values represent the Greenhouse-Geisser correction. Superscript numbers in columns 1-4 indicate the pairwise comparison differences.

Figure 6 shows graphically the sample mean time course data (by climb) for core temperature and estimated energy expenditure (MET-h), showing that both were higher on the HOT day. While core temperature was significantly different within subjects between trials ($p < .001$), estimated energy expenditure was not ($p = 0.443$).

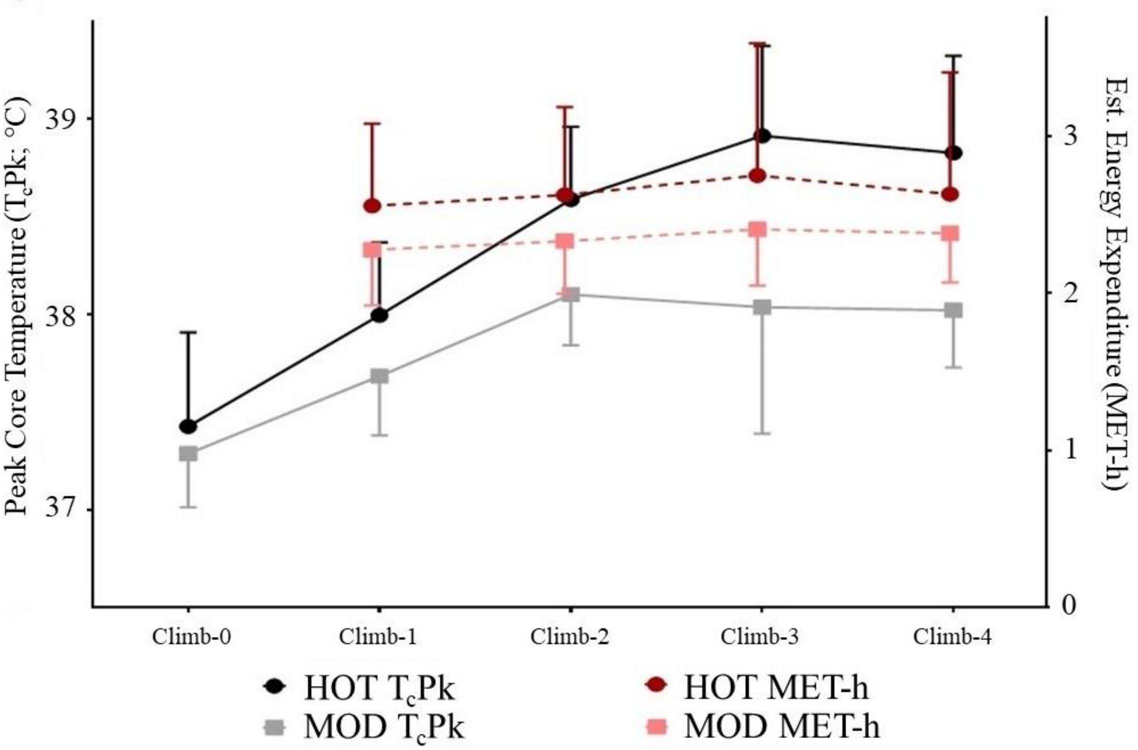


Figure 6. *Baseline (Climb-0) and Peak Station Core Temperatures and Estimated Energy Expenditure (MET-h) on MOD and HOT Days During Four Hiking Climbs of 'A' Mountain*

Chapter 5

DISCUSSION

Our data confirms the general consensus that environmental heat stress degrades submaximal aerobic exercise performance, but in a previously unstudied group (recreational mountain hikers). Additionally, this study provided a physiological evidence-based framework on which to build future EHI prevention recommendations for hikers in the desert southwest.

Aerobic Performance (Time)

Heat stress is known to degrade maximal aerobic capacity (VO_{2max}) and submaximal aerobic time trial (TT) performance by an average of 11% and 13%, respectively (Nybo et al., 2014). Our study corroborated these findings as environmental heat stress (T_{dry} = 40.4°C; WBGT = 31.6°C) impaired ~4 mile mountain hiking TT performance by 11% (time increased 11.1 minutes from 93.9 ± 13.1 minutes in MOD to 105 ± 21.7 minutes in HOT). The HOT condition also reduced predicted maximal aerobic capacity (VO_{2max}; CRFp) by 6% from 8.46 ± 0.80 to 7.99 ± 0.85 METs. Environmental heat stress was shown to slow self-selected hiking pace and decrease predicted maximal aerobic capacity in recreational mountain hikers, the results of which adds hiking to the list of aerobic-type physical performances that are impaired by heat.

Core Temperature

The review by Nybo et al. (2014) indicated a 0.4°C mean rise in core temperature during submaximal aerobic performances in environmental heat stress (25-40°C) compared to control environments (12-23°C). In our study, environmental heat stress elicited an even greater 0.7°C mean rise in core body temperature compared to the moderate control environment. This above average rise in core temperature may be due to our study's specific environmental conditions, which were at the upper dry-bulb temperature ranges of those reviewed by Nybo and colleagues. The difference in observed core temperatures between trials grew steadily from 0.12°C on the first climb to 0.83°C on the fourth and last climb as MOD core temperatures leveled off after the second climb and HOT core temperatures continued to rise. In the HOT trial, two participants self-initiated withdrawal from the trial after the first climb (of four). Interestingly, these participants (*n* = 2) hiked at the slowest pace (33.6 ± 1.80 min), and had the two highest core temperatures (38.8 ± 0.27°C) relative to the other participants (*n* = 10) during the first climb (24.1 ± 3.49 min and 38.1 ± 0.33°C, respectively). The withdrawal of those two participants coincided with a "critical" core temperature over 38.5°C, which is consistent with the findings of Cheung (2010) as the upper limit core temperature of subjects of lesser aerobic fitness. Two more female participants dropped out after the third climb with final core temperature readings of 39.66°C (found after self-withdrawal) and 38.50°C. The difference in endpoint core temperatures at the same hiking distance could be explained by the participants leveraging pacing with tolerable upper limit core temperature – the faster hiker tolerating higher temperatures and achieving them more quickly. Finally, the slowest participant to finish all four climbs (137 minutes) in the HOT trial also attained the absolute highest core temperature of all participants (39.69°C) coincident with completion of the hike and the onset of minor heat cramps. Environmental heat stress was found to increase core temperatures in recreational hikers relative to moderate conditions, and voluntary cessation of hiking performance (fatigue) coincided with commonly observed tolerable upper-limit core temperatures.

Ratings of Perceived Exertion and Intensity

Environmental heat stress is known to increase ratings of perceived exertion and relative intensity (Cheuvront et al., 2010). In our study, the average of four RPE scores reported immediately following summiting the mountain was 19% higher in HOT (14.2 ± 2.38) versus MOD (11.9 ± 2.02). Compared to the 11% performance impairment seen in hikers, perception of exertion is even more affected by heat stress. The oppressive nature of heat stress on the individual psyche bears grave practical consequences. Hiking safely requires vigilance (Ainslie et al., 2005), and when decisions regarding one's health and safety must be made, a hiker may already feel helpless. Perhaps reducing RPE while hiking in the heat should be the subject of future research.

The reduction of absolute maximal aerobic capacity (VO_{2max}) due to environmental heat stress results in an increased relative intensity at any absolute submaximal intensity. In our study, average relative intensity, as a percentage of age-predicted maximal heart rate (HR), was higher in the HOT trial (75.3 ± 11.5%) than in the MOD trial (69.3 ± 10.4%), but did not achieve statistical significance. Despite the high variability between subjects, the result was still in line with the vast literature that has found relative intensity to be increased in the heat (Sawka et al., 2011).

Estimated Absolute Intensity and Energy Expenditure

Similar to the increase in relative intensity, estimated absolute intensity (METs) was slightly higher in the HOT trial (5.99 ± 0.48 METs) versus the MOD trial (5.92 ± 0.59 METs). The detrimental effect of heat stress on maximal aerobic capacity (VO_{2max}) was expected to result in a lower absolute work rate at a given relative intensity ($\%HR_{max}$) (Nybo et al., 2014). Given that relative intensity was also affected by heat stress, and the fact that participants were able to self-select their own work rate, it is difficult to draw any conclusions from our data about how heat stress affects absolute intensity. Although our observed differences in absolute intensity were small and not statistically significant, they suggest that heat stress may reduce exercise efficiency by increasing physiological work rate (METs) for a given work load (distance hiked). Despite the variability masking any significant differences between HOT and MOD trials, the average absolute intensity for both trials was 6.0 METs, where $\geq$6.0 METs is classified as "vigorous intensity" according to the American College of Sports Medicine (Riebe et al., 2018). This holds practical significance because hiking is often thought of as a leisurely pursuit, but our data shows that continuous self-paced mountain hiking can be highly intense. The combination of increased metabolic heat (from both decreased efficiency and higher work rate [absolute intensity]) and the longer durations (11%) spent at that work rate can have dire physiological consequences in an already thermally-stressful environment.

Due to the fact that energy expenditure is the product of absolute intensity (work rate) and duration (time), and that participants were able to self-select their own pace, it was unclear how environmental heat stress would affect energy expenditure in hikers.

Our data suggest that environmental heat stress increases both intensity and duration, resulting in greater estimated energy expenditure when hiking. Again, even though no statistical significance was found, this result holds practical significance because increased time in the heat was associated with ever-rising core temperatures (as mentioned above). It stands to reason that if exercise duration went unchecked in an unsupervised setting, the uncompensable heat stress (UHS) situation could have resulted in actual exertional heat illness in subjects.

Hydration and Sweat Rate

Generally, athletes are said to be well-hydrated prior to exercise performance (Cheuvront & Kenefick, 2014). This was also true for our study participants, who began both HOT and MOD trials in a euhydrated state (USG = 1.016 ± 0.010 and 1.010 ± 0.008, respectively), with no significant difference in hydration state between trials. The utility of using USG as a marker of hydration status, however, can be misleading. As previously discussed in chapter 2, heat stress elicits a relative hypohydrated state based on the volume of blood needed to perfuse active skeletal muscle and the skin, whereas USG cannot account for changes in volume (blood or vasculature) directly. Further, USG cannot account for the individual differences in absolute plasma (blood) volume between subjects. Fitness level and acclimatization status both increase plasma volume (Powers & Howley, 2015), and when compared to similar but lesser fit/acclimatized subjects having the same USG values, the fitter, more heat-acclimatized individuals may have greater total body water and thus greater potential cooling capacity.

Measures of during-performance hydration status showed similarly equivocal results. No participant exceeded the 2% body mass loss safety criteria for performance termination during the HOT or MOD trials. Mean post-performance percentages of initial body mass loss (PBML) were less than 2% in the HOT (1.06 ± 0.95%) and MOD (0.98 ± 0.84%) conditions, and no significant difference was found between the two. This, and the measures of pre-performance hydration status (USG), indicate that environmental heat stress degrades performance *despite* "adequate" pre- and during-performance hydration.

Sweat rate is a better indicator of during-performance hydration status because it is not subject to the moment-to-moment variability like in body mass. However, sweat rate is impractical for lay-persons to measure or calculate, and it varies dramatically between individuals, even in sub-populations such as adult athletes (1.37 ± 0.71 L/h) (Baker et al., 2016). Our study found sweat rates to be significantly higher in the HOT (1.38 ± 0.53 L/h) trial compared to MOD (0.84 ± 0.27 L/h). Although these data are interesting, caution should be taken in making generalized rehydration recommendations based on the mean sweat rates due to the risk of individuals under- or over-hydrating relative to their specific sweat rate. Even knowing one's own individual sweat rate may not offer any advantage, given our results showing that participants maintained euhydration out of their own volition. In summary, pre- and during-performance euhydration status did not differ by environmental condition, and this suggests that individual hydration behavior is sufficient to counteract dehydration due to sweat loss.

Interactions

As evidenced outlined in the literature review, and in the results of our study, thermoregulation is a complex process involving interaction between the individual and the environment. Interaction exists even within an individual as a person attempts to reconcile their conscious behavior (acute and chronic) with their subconscious physiological adaptations or lack thereof. Our data illustrates this complex interaction and points to *gradual* exposure to heat stress as a critical component of not only EHI prevention campaigns, but of any successful attempt to adapt to a stressor such as heat. Still, regardless of heat acclimatization status, the intensity and duration of physical activity lies in precarious balance within the control of the individual. Both of these individual factors are positively impacted by others such as fitness (a chronic adaptation) and hydration status (an acute condition). Our data show the potentially dangerous effect of prolonged (timewise) exposure to heat stress on core temperature, somewhat independently from exercise intensity and hydration status. Therefore, future hiking safety and EHI prevention recommendations should consider duration (time) as a primary variable of interest where less heat-adapted, less aerobically fit individuals require shorter doses at first. Attempting to hike a difficult trail of a set distance by balancing lower exercise intensity with longer duration (slower pace) is a losing strategy in uncompensably hot environments where core temperatures continue to rise as a function of time. In these cases, the reduced work rate (absolute intensity) or complete cessation of activity in an effort to cool down may not counterbalance the extended duration of environmental heat exposure and its tendency to increase internal temperature. After stopping for rest, hikers may then be faced with the choice of hiking out (and further increasing metabolic heat production), calling for a rescue, or succumbing to the unrelenting heat.

Limitations

After reviewing the raw heart rate (HR) data, it appears that approximately 5% the data included instrumentation errors. The errors seemed to be either an incorrect time-sync, or overestimated HR values during periods of low “HR confidence” (such as when positioning or repositioning the HR monitor chest strap). The data were adjusted before analysis in accordance with the methods previously described in chapter 3. These adjustments in the HR data probably affected our relative intensity results most because of their primary dependence on HR. Estimated absolute intensity (METs) was probably less affected because the formula included other variables (breathing rate and activity score) in addition to HR. Estimated energy expenditure was a product of METs and time, further lessening the effect of HR.

Another limitation to the study was the sensitivity of the handheld metabolic analyzer. The instrument seemed to have a ceiling effect, preventing it from measuring oxygen uptakes of more than 1.5 METs. As the respiratory exchange ratio (RER) is a ratio of VCO_2 to VO_2, and VO_2 was unreliably measured, non-resting RER therefore was unreliable as well. Furthermore, the increased postprandial carbohydrate oxidation following the high-carbohydrate standardized breakfasts eaten by participants two hours prior to the hike may have obscured any effect of heat stress on RER. However, the VO_2 ceiling effect would have nullified the during-hike measurements anyways, making it a moot point. The high-carbohydrate breakfast can actually be viewed in a positive light in that it may have ensured that carbohydrate availability was not a limiting factor in the hiking performances. This could potentially allow other performance limiters to manifest without confounding effects from carbohydrate availability.

While not a primary outcome of our study, our safety protocol to monitor during-hike body mass (removing participants exceeding 2% of baseline body mass) may have been affected by sweat-laden clothes. We did not require participants to change clothing for each check of body mass during the hikes, and so the un-evaporated sweat mass was included in these checks. Official pre- and post-hike body mass measurements were not affected because participants were weighed in the same dry set of clothing not worn during the hike. Therefore, the results for during-performance hydration status (PBML) remain unaffected.

Finally, there may have been a learning effect of the hiking route within our sample of participants. All participants performed the HOT trial before MOD, and so a regression to the mean may slightly affect the internal validity of this study. Due to the repetitious nature of the hike (four climbs in each trial), we suspect that the total effect is small and probably applies more to the first climb in the HOT condition than any climb thereafter.

Conclusions

The severity of the problem (EHI) and its prevalence in the mountains of the Phoenix metropolitan area demands an in-depth, multi-disciplinary, evidence-based approach to solving it. Our study found that environmental heat stress impaired ~4 mile self-paced hiking performance by 11%. However, significant variability exists between individual physiological and performance responses to environmental heat stress. Heat stress (both individual and environmental sources), heat strain, and performance impairment seem to contribute to a sort of positive feedback loop whereby the best defense – the thing that affects all parts of that feedback loop – is acclimatization to heat, which is itself an individual factor moderated by fitness level. While hydration status is important and is readily modifiable up to and including physical activity, hikers tend to be well-hydrated before and during activity, if able to drink ad libitum. Due to the immense variation between individuals (save hydration status and rehydration behavior), a more generalizable safety recommendation is needed. That recommendation should include progressive (in terms of duration) exercise-heat exposure where hikers can "test drive" their individual response to heat stress, adapt (acclimatize and learn about their hydration and fitness preparedness), and then come back prepared for more adventure.

REFERENCES

Ainslie, P. N., Campbell, I. T., Lambert, J. P., MacLaren, D. P., & Reilly, T. (2005). Physiological and metabolic aspects of very prolonged exercise with particular reference to hill walking. *Sports Medicine*, *35*(7), 619–647.

Allan, J. R., & Wilson, C. G. (1971). Influence of acclimatization on sweat sodium concentration. *Journal of Applied Physiology*, *30*(5), 708–712.

Armstrong, L. E., Casa, D. J., Millard-Stafford, M., Moran, D. S., Pyne, S. W., & Roberts, W. O. (2007). Exertional heat illness during training and competition. *Medicine & Science in Sports & Exercise*, *39*(3), 556–572.

Armstrong, L. E., Maresh, C. M., Castellani, J. W., Bergeron, M. F., Kenefick, R. W., LaGasse, K. E., & Riebe, D. (1994). Urinary indices of hydration status. *International Journal of Sport Nutrition*, *4*(3), 265–279.

Arngrímsson, S. Á., Stewart, D. J., Borrani, F., Skinner, K. A., & Cureton, K. J. (2003). Relation of heart rate to percent VO2peak during submaximal exercise in the heat. *Journal of Applied Physiology*, *94*(3), 1162–1168. https://doi.org/10.1152/japplphysiol.00508.2002

Athena, K. (2017, December 10). Rescue crews are close by when South Mountain hikers are injured [Local Newspaper]. Retrieved January 26, 2019, from http://www.ahwatukee.com/community_focus/article_9b03e51c-dad2-11e7-8885-7fb63907d0d3.html

Backer, H. D., & Shlim, D. R. (2013). Problems with Heat & Cold. *CDC Health Information for International Travel 2014: The Yellow Book*, *16*(2), 101.

Baker, L. B., Barnes, K. A., Anderson, M. L., Passe, D. H., & Stofan, J. R. (2016). Normative data for regional sweat sodium concentration and whole-body sweating rate in athletes. *Journal of Sports Sciences*, *34*(4), 358–368. https://doi.org/10.1080/02640414.2015.1055291

Baker, L. B., & Jeukendrup, A. E. (2014). Optimal Composition of Fluid-Replacement Beverages. In R. Terjung (Ed.), *Comprehensive Physiology* (pp. 575–620). Hoboken, NJ, USA: John Wiley & Sons, Inc. https://doi.org/10.1002/cphy.c130014

Burke, L., & Deakin, V. (2015). *Clinical sports nutrition* (Fifth Edition). North Ryde, NSW: McGraw Hill Education.

Burke, L. M., & Maughan, R. J. (2015). The Governor has a sweet tooth–mouth sensing of nutrients to enhance sports performance. *European Journal of Sport Science*, *15*(1), 29–40.

Cadarette, B. S., Sawka, M. N., Toner, M. M., & Pandolf, K. B. (1984). Aerobic fitness and the hypohydration response to exercise-heat stress. *Aviation, Space, and Environmental Medicine*, *55*(6), 507–512.

Carter, J., Jeukendrup, A. E., Mundel, T., & Jones, D. A. (2003). Carbohydrate supplementation improves moderate and high-intensity exercise in the heat. *Pflügers Archiv*, *446*(2), 211–219.

Casa, D. J., DeMartini, J. K., Bergeron, M. F., Csillan, D., Eichner, E. R., Lopez, R. M., … Sawka, M. N. (2015). National Athletic Trainers' Association position statement: exertional heat illnesses. *Journal of Athletic Training*, *50*(9), 986–1000.

Cassidy, M., & McGlade, C. (2015, June 15). Phoenix mountain rescues increase to even out in 2015. Retrieved January 26, 2019, from https://www.azcentral.com/story/news/local/phoenix/2015/06/13/phoenix-mountain-rescues-spike-increase-even-out/71132004/

Cheung, S. S. (2010). *Advanced environmental exercise physiology*. Champaign, IL: Human Kinetics.

Cheung, S. S., & McLellan, T. M. (1998). Heat acclimation, aerobic fitness, and hydration effects on tolerance during uncompensable heat stress. *Journal of Applied Physiology*, *84*(5), 1731–1739.

Cheung, S. S., McLellan, T. M., & Tenaglia, S. (2000). The thermophysiology of uncompensable heat stress. *Sports Medicine*, *29*(5), 329–359.

Cheuvront, S. N., & Kenefick, R. W. (2014). Dehydration: Physiology, Assessment, and Performance Effects. In R. Terjung (Ed.), *Comprehensive Physiology* (pp. 257–285). Hoboken, NJ, USA: John Wiley & Sons, Inc. https://doi.org/10.1002/cphy.c130017

Cheuvront, S. N., Kenefick, R. W., Montain, S. J., & Sawka, M. N. (2010). Mechanisms of aerobic performance impairment with heat stress and dehydration. *Journal of Applied Physiology*, *109*(6), 1989–1995. https://doi.org/10.1152/japplphysiol.00367.2010

Coyle, E. F., Coggan, A. R., Hemmert, M. K., & Ivy, J. L. (1986). Muscle glycogen utilization during prolonged strenuous exercise when fed carbohydrate. *Journal of Applied Physiology*, *61*(1), 165–172.

de Ataide e Silva, T., Di Cavalcanti Alves de Souza, M., de Amorim, J., Stathis, C., Leandro, C., & Lima-Silva, A. (2013). Can Carbohydrate Mouth Rinse Improve Performance during Exercise? A Systematic Review. *Nutrients*, *6*(1), 1–10. https://doi.org/10.3390/nu6010001

Ekblom, B., Greenleaf, C. J., Greenleaf, J. E., & Hermansen, L. (1970). Temperature regulation during exercise dehydration in man. *Acta Physiologica Scandinavica*, *79*(4), 475–483.

Febbraio, M. A. (2001). Alterations in energy metabolism during exercise and heat stress. *Sports Medicine*, *31*(1), 47–59.

Gant, N., Atkinson, G., & Williams, C. (2006). The validity and reliability of intestinal temperature during intermittent running. *Medicine and Science in Sports and Exercise*, *38*(11), 1926–1931.

Garrett, A. T., Rehrer, N. J., & Patterson, M. J. (2011). Induction and decay of short-term heat acclimation in moderately and highly trained athletes. *Sports Medicine*, *41*(9), 757–771.

Griefahn, B. (1997). Acclimation to three different hot climates with equivalent wet bulb globe temperatures. *Ergonomics*, *40*(2), 223–234. https://doi.org/10.1080/001401397188314

Hargreaves, M., Angus, D., Howlett, K., Conus, N. M., & Febbraio, M. (1996). Effect of heat stress on glucose kinetics during exercise. *Journal of Applied Physiology*, *81*(4), 1594–1597. https://doi.org/10.1152/jappl.1996.81.4.1594

Hiking Safety Campaign - Take a Hike. Do it Right. (2015). Retrieved from https://www.youtube.com/watch?v=Ua_TF1J0eZA

Jeukendrup, A. E., & Chambers, E. S. (2010). Oral carbohydrate sensing and exercise performance. *Current Opinion in Clinical Nutrition & Metabolic Care*, *13*(4), 447–451.

Kenefick, R. W., & Cheuvront, S. N. (2012). Hydration for recreational sport and physical activity. *Nutrition Reviews*, *70*, S137–S142. https://doi.org/10.1111/j.1753-4887.2012.00523.x

Kenefick, R. W., Cheuvront, S. N., Palombo, L. J., Ely, B. R., & Sawka, M. N. (2010). Skin temperature modifies the impact of hypohydration on aerobic performance. *Journal of Applied Physiology*, *109*(1), 79–86.

Leemon, D., & Schimelpfenig, T. (2003). Wilderness injury, illness, and evacuation: National Outdoor Leadership School's incident profiles, 1999–2002. *Wilderness & Environmental Medicine*, *14*(3), 174–182.

Limbaugh, J. D., Wimer, G. S., Long, L. H., & Baird, W. H. (2013). Body Fatness, Body Core Temperature, and Heat Loss During Moderate-Intensity Exercise. *Aviation, Space, and Environmental Medicine*, *84*(11), 1153–1158. https://doi.org/10.3357/ASEM.3627.2013

Lipman, G. S., Eifling, K. P., Ellis, M. A., Gaudio, F. G., Otten, E. M., & Grissom, C. K. (2014). Wilderness Medical Society Practice Guidelines for the Prevention and Treatment of Heat-Related Illness: 2014 Update. *Wilderness & Environmental Medicine*, *25*(4), S55–S65. https://doi.org/10.1016/j.wem.2014.07.017

Lorenzo, S., Halliwill, J. R., Sawka, M. N., & Minson, C. T. (2010). Heat acclimation improves exercise performance. *Journal of Applied Physiology*, *109*(4), 1140–1147. https://doi.org/10.1152/japplphysiol.00495.2010

McDermott, B. P., Anderson, S. A., Armstrong, L. E., Casa, D. J., Cheuvront, S. N., Cooper, L., … Roberts, W. O. (2017). National Athletic Trainers' Association Position Statement: Fluid Replacement for the Physically Active. *Journal of Athletic Training*, *52*(9), 877–895.

Nielsen, B., Savard, G., Richter, E. A., Hargreaves, M., & Saltin, B. (1990). Muscle blood flow and muscle metabolism during exercise and heat stress. *Journal of Applied Physiology*, *69*(3), 1040–1046. https://doi.org/10.1152/jappl.1990.69.3.1040

Nybo, L., Jensen, T., Nielsen, B., & González-Alonso, J. (2001). Effects of marked hyperthermia with and without dehydration onV o 2 kinetics during intense exercise. *Journal of Applied Physiology*, *90*(3), 1057–1064.

Nybo, L., Rasmussen, P., & Sawka, M. N. (2014). Performance in the heat-physiological factors of importance for hyperthermia-induced fatigue. *Compr Physiol*, *4*(2), 657–689.

Pandolf, K. B., Burse, R. L., & Goldman, R. F. (1977). Role of physical fitness in heat acclimatisation, decay and reinduction. *Ergonomics*, *20*(4), 399–408.

Parkin, J. M., Carey, M. F., Zhao, S., & Febbraio, M. A. (1999). Effect of ambient temperature on human skeletal muscle metabolism during fatiguing submaximal exercise. *Journal of Applied Physiology*, *86*(3), 902–908. https://doi.org/10.1152/jappl.1999.86.3.902

Powers, S. K., & Howley, E. T. (2015). *Exercise physiology: theory and application to fitness and performance* (Ninth edition). New York, NY: McGraw-Hill Education.

Pryor, R. R., Bennett, B. L., O'Connor, F. G., Young, J. M. J., & Asplund, C. A. (2015). Medical Evaluation for Exposure Extremes: Heat. *Wilderness & Environmental Medicine, 26*(4), 69–75. https://doi.org/10.1016/j.wem.2015.09.009

Riebe, D., Ehrman, J. K., Liguori, G., & Magal, M. (Eds.). (2018). *ACSM's guidelines for exercise testing and prescription* (Tenth edition). Philadelphia: Wolters Kluwer.

Rosenberger, M. E., Haskell, W. L., Albinali, F., & Intille, S. (2011). Device Measuring Heart Rate, Respiration Rate, and Motion Accurately Estimates Activity Level and Energy Expenditure: 727. *Medicine & Science in Sports & Exercise*, *43*(5), 63.

Sawka, M. N., Burke, L. M., Eichner, R. E., Maughan, R. J., Montain, S. J., & Stachenfeld, N. S. (2007). Exercise and fluid replacement. *Medicine & Science in Sports & Exercise*, *39*(2), 377–390.

Sawka, M. N., Leon, L. R., Montain, S. J., & Sonna, L. A. (2011). Integrated Physiological Mechanisms of Exercise Performance, Adaptation, and Maladaptation to Heat Stress. In R. Terjung (Ed.), *Comprehensive Physiology* (pp. 1883–1928). Hoboken, NJ, USA: John Wiley & Sons, Inc. https://doi.org/10.1002/cphy.c100082

Sawka, M. N., & Montain, S. J. (2000). Fluid and electrolyte supplementation for exercise heat stress–. *The American Journal of Clinical Nutrition, 72*(2), 564S-572S.

Sawka, M. N. & Noakes, T. D. (2007). Does Dehydration Impair Exercise Performance?: *Medicine & Science in Sports & Exercise*, *39*(8), 1209–1217. https://doi.org/10.1249/mss.0b013e318124a664

Take a Hike - Do it Right. (2015). City of Phoenix Parks & Recreation Department. Retrieved from https://www.phoenix.gov/parkssite/Documents/PKS_NRD/Take%20a%20Hike%20-%20Do%20it%20Right.pdf

Tanaka, H., Monahan, K. D., & Seals, D. R. (2001). Age-predicted maximal heart rate revisited. *Journal of the American College of Cardiology*, *37*(1), 153–156.

US Department of Commerce, N. (n.d.-a). Heat Index. Retrieved February 16, 2019, from https://www.weather.gov/safety/heat-index

US Department of Commerce, N. (n.d.-b). Wet Bulb Globe Temperature, Latest + Forecasts. Retrieved February 16, 2019, from https://www.weather.gov/rah/WBGT

Webster, S., Rutt, R., & Weltman, A. (1990). Physiological effects of a weight loss regimen practiced by college wrestlers. *Medicine and Science in Sports and Exercise*, *22*(2), 229–234.

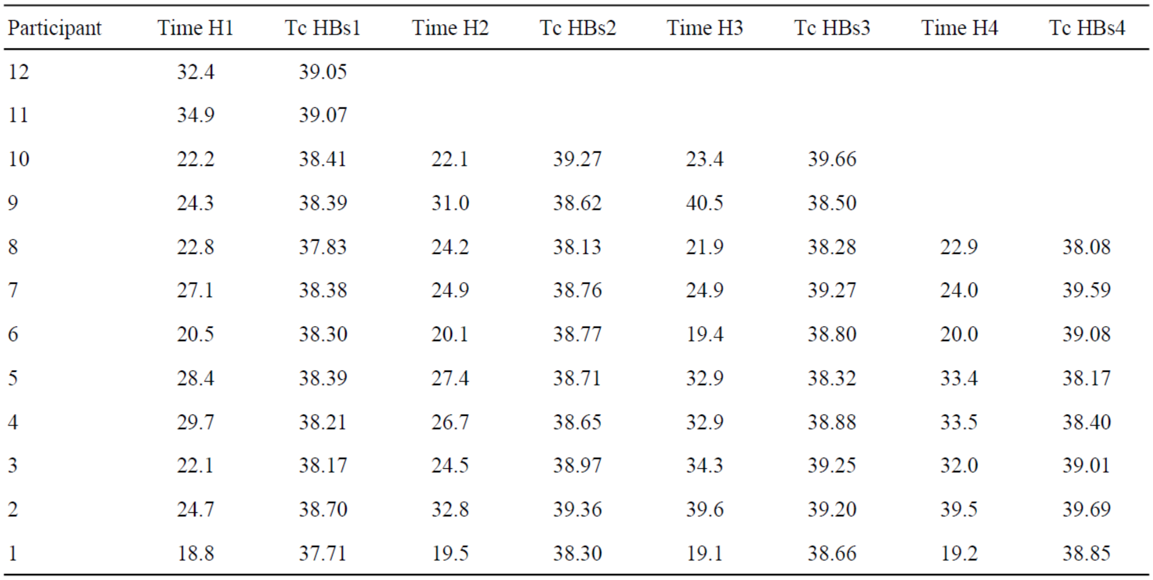
Weir, J. de V. (1949). New methods for calculating metabolic rate with special reference to protein metabolism. *The Journal of Physiology*, *109*(1–2), 1–9.

Wilkinson, D. M., Carter, J. M., Richmond, V. L., Blacker, S. D., & Rayson, M. P. (2008). The effect of cool water ingestion on gastrointestinal pill temperature. *Medicine and Science in Sports and Exercise*, *40*(3), 523–528.

Zhao, D., Xian, X., Terrera, M., Krishnan, R., Miller, D., Bridgeman, D., … Tao, N. (2014). A pocket-sized metabolic analyzer for assessment of resting energy expenditure. *Clinical Nutrition*, *33*(2), 341–347. https://doi.org/10.1016/j.clnu.2013.06.001

APPENDIX A

SELECTED PARTICIPANT DATA

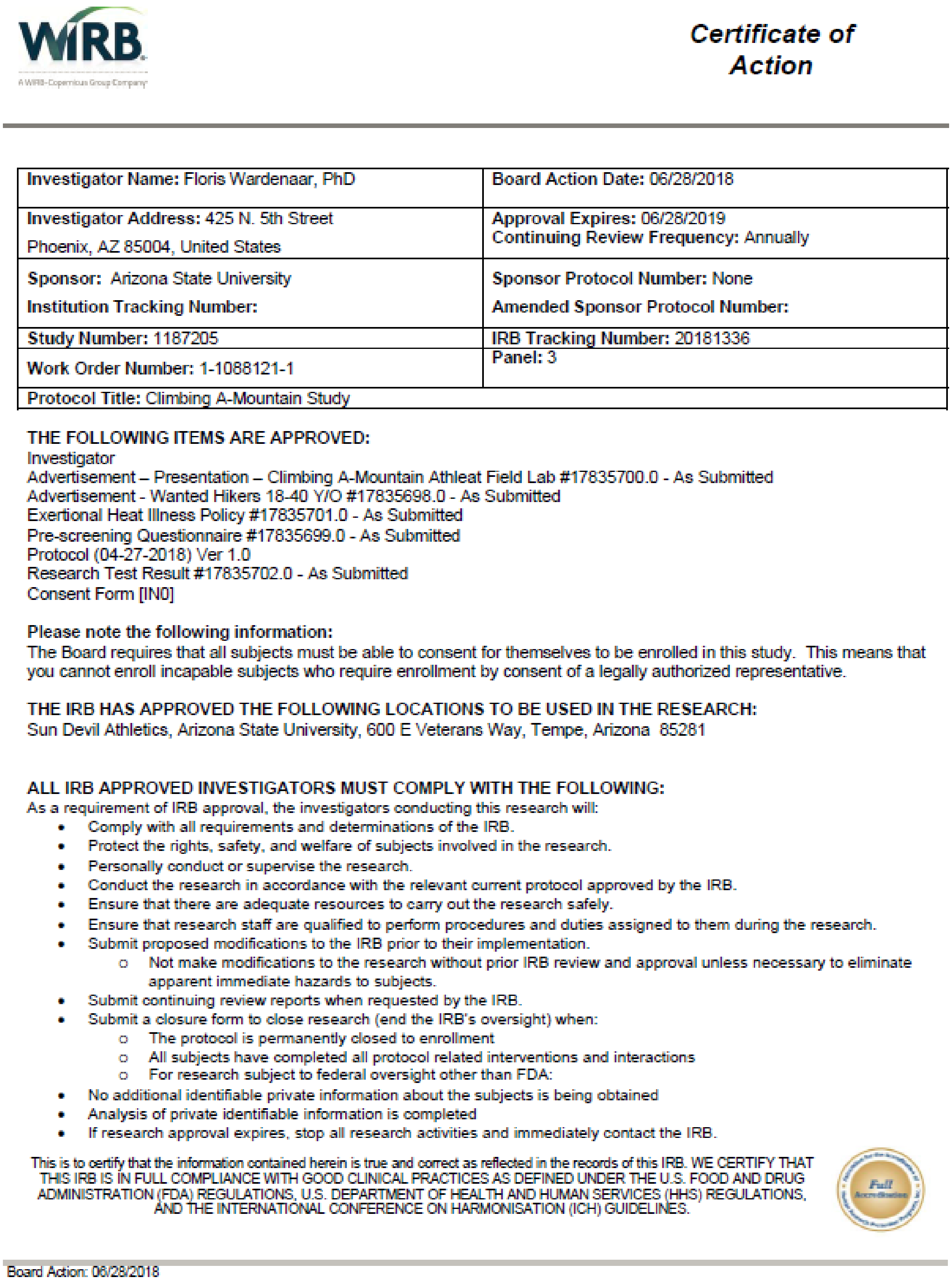


Participant	Time H1	Tc HBs1	Time H2	Tc HBs2	Time H3	Tc HBs3	Time H4	Tc HBs4
12	32.4	39.05						
11	34.9	39.07						
10	22.2	38.41	22.1	39.27	23.4	39.66		
9	24.3	38.39	31.0	38.62	40.5	38.50		
8	22.8	37.83	24.2	38.13	21.9	38.28	22.9	38.08
7	27.1	38.38	24.9	38.76	24.9	39.27	24.0	39.59
6	20.5	38.30	20.1	38.77	19.4	38.80	20.0	39.08
5	28.4	38.39	27.4	38.71	32.9	38.32	33.4	38.17
4	29.7	38.21	26.7	38.65	32.9	38.88	33.5	38.40
3	22.1	38.17	24.5	38.97	34.3	39.25	32.0	39.01
2	24.7	38.70	32.8	39.36	39.6	39.20	39.5	39.69
1	18.8	37.71	19.5	38.30	19.1	38.66	19.2	38.85

Note. Split times (min) for each climb and base-station core temperatures (°C) immediately following climbs 1-4 in HOT, respectively.

APPENDIX B

HUMAN SUBJECTS RESEARCH APPROVAL



WIRB
A WIRB-Copernicus Group Company

Certificate of Action

Investigator Name: Floris Wardenaar, PhD	**Board Action Date:** 06/28/2018
Investigator Address: 425 N. 5th Street Phoenix, AZ 85004, United States	**Approval Expires:** 06/28/2019 **Continuing Review Frequency:** Annually
Sponsor: Arizona State University **Institution Tracking Number:**	**Sponsor Protocol Number:** None **Amended Sponsor Protocol Number:**
Study Number: 1187205	**IRB Tracking Number:** 20181336
Work Order Number: 1-1088121-1	**Panel:** 3
Protocol Title: Climbing A-Mountain Study	

THE FOLLOWING ITEMS ARE APPROVED:
Investigator
Advertisement – Presentation – Climbing A-Mountain Athleat Field Lab #17835700.0 - As Submitted
Advertisement - Wanted Hikers 18-40 Y/O #17835698.0 - As Submitted
Exertional Heat Illness Policy #17835701.0 - As Submitted
Pre-screening Questionnaire #17835699.0 - As Submitted
Protocol (04-27-2018) Ver 1.0
Research Test Result #17835702.0 - As Submitted
Consent Form [IN0]

Please note the following information:
The Board requires that all subjects must be able to consent for themselves to be enrolled in this study. This means that you cannot enroll incapable subjects who require enrollment by consent of a legally authorized representative.

THE IRB HAS APPROVED THE FOLLOWING LOCATIONS TO BE USED IN THE RESEARCH:
Sun Devil Athletics, Arizona State University, 600 E Veterans Way, Tempe, Arizona 85281

ALL IRB APPROVED INVESTIGATORS MUST COMPLY WITH THE FOLLOWING:
As a requirement of IRB approval, the investigators conducting this research will:

- Comply with all requirements and determinations of the IRB.
- Protect the rights, safety, and welfare of subjects involved in the research.
- Personally conduct or supervise the research.
- Conduct the research in accordance with the relevant current protocol approved by the IRB.
- Ensure that there are adequate resources to carry out the research safely.
- Ensure that research staff are qualified to perform procedures and duties assigned to them during the research.
- Submit proposed modifications to the IRB prior to their implementation.
    - Not make modifications to the research without prior IRB review and approval unless necessary to eliminate apparent immediate hazards to subjects.
- Submit continuing review reports when requested by the IRB.
- Submit a closure form to close research (end the IRB's oversight) when:
    - The protocol is permanently closed to enrollment
    - All subjects have completed all protocol related interventions and interactions
    - For research subject to federal oversight other than FDA:
- No additional identifiable private information about the subjects is being obtained
- Analysis of private identifiable information is completed
- If research approval expires, stop all research activities and immediately contact the IRB.

This is to certify that the information contained herein is true and correct as reflected in the records of this IRB. WE CERTIFY THAT THIS IRB IS IN FULL COMPLIANCE WITH GOOD CLINICAL PRACTICES AS DEFINED UNDER THE U.S. FOOD AND DRUG ADMINISTRATION (FDA) REGULATIONS, U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES (HHS) REGULATIONS, AND THE INTERNATIONAL CONFERENCE ON HARMONISATION (ICH) GUIDELINES.

Board Action: 06/28/2018

- Promptly report to the IRB the information items listed in the IRB's "Prompt Reporting Requirements" available on the IRB's Web site.
- Not accept or provide payments to professionals in exchange for referrals of potential subjects ("finder's fees.")
- Not accept payments designed to accelerate recruitment that are tied to the rate or timing of enrollment ("bonus payments") without prior IRB approval.
- When required by the IRB ensure that consent, permission, and assent are obtained and documented in accordance with the relevant current protocol as approved by the IRB.
- Promptly notify the IRB of any change to information provided on your initial submission form.

Consistent with AAHRPP's requirements in connection with its accreditation of IRBs, the individual and/or organization shall promptly communicate or provide, the following information relevant to the protection of human subjects to the IRB in a timely manner:

- Upon request of the IRB, a copy of the written plan between sponsor or CRO and site that addresses whether expenses for medical care incurred by human subject research subjects who experience research related injury will be reimbursed, and if so, who is responsible in order to determine consistency with the language in the consent document.
- Any site monitoring report that directly and materially affects subject safety or their willingness to continue participation. Such reports will be provided to the IRB within 5 days.
- Reports from any data monitoring committee, data and safety monitoring board, or data and safety monitoring committee in accordance with the time frame specified in the research protocol.
- Any findings from a closed research when those findings materially affect the safety and medical care of past subjects. Findings will be reported for 2 years after the closure of the research.

If your research site is a HIPAA covered entity, the HIPAA Privacy Rule requires you to obtain written authorization from each research subject for any use or disclosure of protected health information for research. If your IRB-approved consent form does not include such HIPAA authorization language, the HIPAA Privacy Rule requires you to have each research subject sign a separate authorization agreement. "

Federal regulations require that the IRB conduct continuing review of approved research. You will receive Continuing Review Report forms from this IRB when the expiration date is approaching.

Thank you for using this WCG IRB to provide oversight for your research project.

DISTRIBUTION OF COPIES:
<u>Contact, Company</u>
Floris Wardenaar, PhD, Arizona State University