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Assessment of a Modified Heat Tolerance Test in Recreational Runners

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Assessment of a Modified Heat Tolerance Test in Recreational Runners

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ABSTRACT

Exercising in hot and humid conditions is a stressful environment that can be taxing on the human body. In certain situations, uncompensable heat stress may occur in which there is an overwhelming of the thermoregulatory system. This may result in exertional heat illnesses, particularly exertional heat stroke, which warrant rapid and appropriate treatment to avoid long term complications, or even death.

Returning to activity, duty, or play after an exertional heat stroke, or for those who exhibit difficulty exercising in the heat, is a complex process. However, heat tolerance tests have been used, particularly in warriors, as an evaluation tool for assessing return to activity. There are no standard guidelines or protocols of when it is safe for these individuals to return to play.

Therefore, we evaluated a modified heat tolerance test in a cohort of recreational runners to compare physiological responses during a laboratory test and a 7.1-mile outdoor road race. We also aimed to assess patterns in the rise of internal body temperature to determine potential temperature criterion for heat tolerance.

We found that when running at 60% VO$_2$max on a treadmill in an environmental chamber set at 27°C and 50% relative humidity, at least 60 minutes of exercise was necessary to see a plateau in internal body temperature. Additionally, the percentage of body mass loss explained the most variance in temperature rise during the lab and the field protocols.
CHAPTER ONE: REVIEW OF LITERATURE

This review of literature will provide an in-depth review of thermoregulation, the heat balance equation, exertional heat illness (EHI), exertional heat stroke (EHS), heat tolerance, return to play (RTP) protocols following an EHS, and modified heat tolerance testing (mHTT). Focus will be placed on mHTT and its role in the population of recreational runners. The need for an accurate, clinically applicable, and objective mHTT to assess heat tolerance will be discussed.

Thermoregulation

Thermoregulation of the body is very complex and involves interactions between the central nervous system (CNS), cardiovascular system, and integumentary system.\(^1\)\(^-\)\(^2\) Body temperature is a result of the balance between heat accumulation and heat dissipation.\(^3\) Heat accumulation is a combination of metabolic heat, heat that is created by physical activity or exertion, and environmental heat, heat which is absorbed by the body from the external environment.\(^1\)\(^,\)\(^3\)\(^-\)\(^6\) The temperature gradient between the environment and body is vital. When environmental temperatures are less than skin temperature (<35°C), there is an increase in cooling as a greater skin to air temperature gradient exists; heat is dissipated from the skin to the environment. If the environmental temperature is about equal to that of skin temperature (35°C) there is no heat exchange. If the environmental temperature is greater than skin temperature (>35°C), heat will be absorbed from the environment.\(^7\) Excessive heat accumulation, a reduced ability to dissipate heat, or a combination of the two, results in heat storage by the body. This is due to overloading of the thermoregulatory system in which temperature continues to rise to a point where the body is unable to compensate.\(^3\)\(^-\)\(^4\)
Thermoregulation is challenged when there is a high metabolic heat production under hot and/or humid conditions; the body heat is not dissipated as effectively compared to cool and/or dry conditions.\(^8\) The rate of the heat production rises at the onset of physical activity.\(^9\) During exercise in the heat, heat production is 15-20 times greater than heat production at rest.\(^6,10\) This can result in a 1°C (1.8°F) increase in body temperature every five minutes if heat is not dissipated from the body.\(^6,10\) As the intensity of the exercise increases, a thermal imbalance may occur when the activity is performed in an uncompensable environment, increasing heat storage and a greater heat strain on the body.\(^9\)

As the core temperature rises, a cascade of events and responses occur to maintain homeostasis of temperature around the set point.\(^4\) This response is meant to aid the body in being able to compensate to the external environment by preventing a rise in core body temperature.\(^11\) Homeostatic changes occur with mechanisms of compensation in the circulatory, thermoregulatory, and endocrine systems. The body systems work together to maintain physiological processes to regulate blood pressure, muscle function, and the balance of fluids in the body.\(^2\)

Exercising in hot conditions evokes a thermoregulatory response of which there are three main phases – the compensatory phase, acute phase, and thermoregulatory failure.\(^11\) The way in which the body dissipates heat is complex. It involves both vasomotor and sudomotor activity (i.e., dilation of the blood vessels and stimulation of the sweat glands) and depends on functioning of the thermoregulatory center, cardiovascular system, and skin.\(^3\) Heat is dissipated through a combination of factors such as an increase in cardiac output, increased sweating, increased heart rate, increased respiratory rate, and vasodilation in the periphery.\(^1-2,4,11\) Blood is redistributed to the periphery from the core to increase heat loss through convection and
evaporation. As a result, there is a lower venous return, stroke volume, central venous pressure, and mean arterial pressure. This all occurs during the compensatory phase of thermoregulation.

The acute phase of thermoregulation involves endothelial and epithelial cells and leukocytes which are responsible for protecting tissue from injury and promoting cellular repair. After heat stress, cellular protection is achieved by the production of stress proteins known as heat shock proteins which regulate tissue reactions that are caused by stresses.

The multi-organ system damage that can result during thermoregulatory failure, or the uncompensable phase of thermoregulation, is related to complex interactions and acute changes that occur in response to the presence of hyperthermic conditions. A state of hyperthermia can cause circulatory failure, hypoxia, and increased cellular metabolic demands. During hyperthermia, there is a direct suppression of cells, cytotoxicity, systemic inflammatory response, and coagulation failure. Because heat stress can initiate the sweating response and subsequent fluid loss that results in a hypohydrated state, blood volume and cardiac output can also be compromised. The central venous pressure is reduced from the overall reduction in blood volume, increased cutaneous blood flow, and peripheral vasodilation. As the central venous pressure is decreased, the body loses its ability to transfer heat to the body’s surface, further increasing accumulation of heat and heat storage within the body resulting in ischemia of the bowel tissues. Blood shifts from mesenteric circulation to that of the exercising muscles and skin, increasing permeability of the gut during exercise in the heat. Damage to cellular membranes allows leakage of endotoxins and lipopolysaccharides from intestinal gram-negative bacteria which are then released into systemic circulation. The endotoxemia increases the production and release of inflammatory cytokines which decrease blood flow to the brain and
through a number of other cellular reactions, can result in edema and cellular injury via the
denaturation of proteins and induction of apoptosis.⁴,¹²

**Heat Balance Equation**

Overall, the internal body temperature is a result of metabolic heat production and the
transfer of heat between the body and external environment.¹ This exchange of heat between the
body and environment is dependent upon a temperature gradient.⁶ The process of heat gain and
heat loss is represented by the heat balance equation seen below where S represents the amount
of heat stored within the body, M represents metabolic heat production during exercise, R
represents heat loss or gain from radiation, K represents heat loss or gain from conduction, C
represents heat loss or gain from convection, and E represents evaporative heat loss.¹,¹²-¹³

\[
S = M \pm R \pm K \pm C - E
\]

Heat gain and heat loss are achieved through four primary mechanisms: evaporation,
radiation, convection, and conduction.¹³ Examples of these mechanisms of heat gain and loss
include sweat being dried off the skin on a windy day (E), sunlight (R), using an ice pack or bag
(K), and air from a fan (C) or cold water immersion (K and C), respectively.¹ Heat can be
dissipated from the body by sensible heat loss through radiation, convection, and conduction or
insensible heat loss through the evaporation of sweat from the skin’s surface. Sweating is
initiated when temperature is unable to be regulated through the sensible mechanisms.⁴

Metabolic heat production is determined by the intensity of physical exertion by an
exercising individual with high intensity exercise resulting in the greatest metabolic heat
production. This will vary from person to person as unfit individuals may have a higher exertion
than fit individuals even when exercising at the same intensity.¹ Cardiovascular fitness increases
cardiac reserve, allowing greater blood flow to the skin and muscles during exercise and in turn
aiding in thermoregulation.\textsuperscript{2} An individual with a higher VO$_{2}\text{max}$, or maximal uptake of oxygen, will have a greater ability to tolerate a given heat stress while those with a lower aerobic power or capacity will have a lower tolerance to heat stress.\textsuperscript{2,6} The relative intensity of exercise will greatly influence the rate at which core body temperature increases.\textsuperscript{1}

Additionally, changes in core body temperature are influenced by the imbalance of heat production, heat storage, body mass, and body composition.\textsuperscript{14} When exercising at a specified \%VO$_{2}\text{max}$, those with a higher VO$_{2}\text{max}$ produce more metabolic heat per unit of body mass. They will also require more evaporative heat to maintain heat balance. In individuals with high VO$_{2}\text{max}$ and low body fat, more heat per unit of body mass will be produced because of a small body size.\textsuperscript{15} In obese individuals, the fat layer acts as an insulator. These individuals have a decreased efficiency of dissipating heat and produce greater metabolic heat during exercise.\textsuperscript{1-2,16} In muscular athletes, lean body mass and lower surface area to mass ratios result in increased production of metabolic heat and a decreased ability to dissipate that heat.\textsuperscript{2}

Heat loss by radiation and convection is usually not enough to maintain stability in heat balance as the body absorbs heat from the environment when environmental temperatures exceed the temperature of the skin.\textsuperscript{2,7,9,13} Therefore, evaporation through sweating is needed for effective cooling as it is the primary venue of heat dissipation during exercise.\textsuperscript{2,7-8,13} However, heat loss through sweating can only occur if heat is able to evaporate from the skin.\textsuperscript{8} This is dependent upon the environmental humidity and wind speed.\textsuperscript{1} In highly humid conditions, dissipation of heat through sweating is impaired.\textsuperscript{2,8}

The heat balance equation plays an important role in understanding EHS, particularly when there are hot and humid conditions. In these environments, individuals are more predisposed to having an EHS due to uncompensable heat stress. In high humidity, heat loss
through evaporation is diminished and can result in a rapid rise in core body temperature due to the inability to dissipate heat and properly thermoregulate. For these reasons, high heat and high humidity impair the body’s ability to thermoregulate as can be demonstrated by the heat balance equation.¹

**Exertional Heat Illnesses**

EHI are most commonly associated with exercise in the heat under hot and humid conditions. However, they may also occur in normal, less extreme environmental conditions, or even cooler climates, when there is intense, long duration activity.¹,⁶ EHI include exercise-associated muscle cramps, heat syncope, heat exhaustion, exertional heat injury, and exertional heat stroke (EHS). Clinical definitions of EHIs are summarized in Table 1.

**Exertional Heat Stroke**

EHS is the most severe type of EHI and can be fatal.¹,⁸,¹¹,¹⁶ It is a leading preventable cause of nontraumatic exertional sudden death in the athletic and warrior populations.¹¹,¹³,¹⁶-¹⁸ Between 1995 and 2010, there were 46 deaths in American football as a result of EHS among athletes.¹³

EHS is diagnosed by an elevated internal body temperature of at least 40.5°C (105°F) accompanied by dysfunction or disturbance of the CNS.¹,⁴-⁶,⁸,¹¹,¹³,¹⁶-¹⁷,¹⁹-²⁰ A list of EHS signs and symptoms, though not all inconclusive, can be found in Table 2. In addition to those listed, patients with EHS may also be dehydrated, have hot, wet, sweaty skin, be hypotensive, and exhibit hyperventilation, vomiting, and diarrhea.¹,⁵ In contrast, in cases of classic heat stroke, which most commonly affects children and the elderly who are unable to escape heat stresses, the skin is often dry.¹,⁴,¹¹,²¹
EHS occurs because of overwhelming of the thermoregulatory system from a combination of metabolic heat production and environmental heat load as previously described.\textsuperscript{1,4-6} It is brought on by physical exertion and is most common in young, highly motivated individuals.\textsuperscript{11,16,20} Often, it occurs in warm or hot environments when there is strenuous, continuous exercise such as seen in road races.\textsuperscript{2,4-6,9,16,20,22} The highest risk for EHS is during intense exercise greater than 75\% \textit{VO}_2\text{max} for at least an hour in duration when wet bulb globe temperature (WBGT) is greater than 28\degree C (82\degree F).\textsuperscript{6}

No exercising individual is exempt from the potential to experience an EHI.\textsuperscript{2,6} Even physically fit individuals are not immune to increases in core temperature or heart rate under certain conditions in which a combination of inherent qualities and extrinsic risk factors modulate the risk of EHS.\textsuperscript{2,6,19-23} Typically, athletes will cease exercise secondary to fatigue when rectal temperatures reach approximately 40\degree C (104\degree F).\textsuperscript{6} Personality traits such as being overzealous may increase an individual’s risk as they may ignore early warning signs and internal cues to discontinue exercise.\textsuperscript{1-2,6,8} Likewise, a strong determination or internal motivation to win, compete, or succeed may also hinder the perception of cues to cease exercise.\textsuperscript{1,2,6,8,21,24} Numerous risk factors that exist for EHI and EHS are summarized in Table 3.

A delay in the recognition of signs and symptoms and subsequent treatment of EHS can be fatal for the patient or lead to lasting complications.\textsuperscript{1,4-6,13,20} Because EHS may present similarly to other medical ailments, an accurate assessment of body temperature through rectal thermometry is needed.\textsuperscript{1} Treatment of EHS involves lowering the core body temperature to less than 38.9\degree C (102\degree F) within 30 minutes or less following initial collapse.\textsuperscript{1,13,19,21} The amount of impairment, prognosis, and residual effects following an EHS episode is dependent upon the
amount of time the body remains in a hyperthermic state of elevated cellular temperature.\textsuperscript{1,4-6,13,17,19-21}

If not treated appropriately, EHS may result in damage to the organs or body’s systems leading to impairments for performing physical activity.\textsuperscript{5,19} Following the episode, it is necessary to ensure an individual can safely participate in exercise in the heat.\textsuperscript{2} It is imperative to determine the cause(s) of the EHS to make attempts to correct the issue and prevent a subsequent episode.\textsuperscript{2,5,19} Methods of EHI prevention are summarized in Table 4.

All cases of EHS are different leading to highly variable recovery times.\textsuperscript{13} Because of this, there is no universal guideline or standard protocol for return to activity (RTA) after an EHS.\textsuperscript{5,13} RTP decisions may not be easy, and should therefore involve a gradual, progressive, controlled, and closely supervised reintroduction to the heat and exercise.\textsuperscript{2,5,13,19,24}

In general, RTA depends on the severity of the EHS and any residual effects that remain.\textsuperscript{5,13,19} Some may be able to return to modified activity within one month after receiving clearance from a physician for a gradual return.\textsuperscript{1} On the other hand, cases with sequela may require months or even years to fully recover and return to “normal” exercise and training.\textsuperscript{13} Most guidelines recommend patients be asymptomatic and have normal blood-work before the initiation of a gradual return.\textsuperscript{1,5,19} Additionally, a HTT should be used for athletes and warriors when making difficult RTP or RTD decisions.\textsuperscript{5,13,16,19,23,24}

**Heat Tolerance**

Individuals vary in their ability to tolerate a given load or heat stress.\textsuperscript{3,9} This is in part due to both congenital and predisposing factors.\textsuperscript{3} The term compensable is used to describe the body’s ability to tolerate, or compensate to, a given heat load by maintaining an appropriate core body temperature. However, uncompensable means the body is not able to tolerate a given heat
load. The heat stress overwhelms the thermoregulatory system and continued exposure to the heat may ultimately result in an EHI such as EHS.\textsuperscript{11}

Individuals who are heat intolerant are incapable of adequately adapting to workloads or exercise in the presence of heat or a hot environment.\textsuperscript{3,21-23,25} Heat intolerance is an inability to dissipate heat and properly acclimatize to the heat as compared to normal individuals under similar conditions.\textsuperscript{5,26} The body temperature of those who are heat intolerant will rise more quickly and at a faster rate compared to those who are heat tolerant.\textsuperscript{3,22,26} Common characteristics among heat intolerant individuals usually include an earlier rise in core body temperature, a greater rise in core body temperature, increased storage of metabolic heat, a higher physiological strain during exercise of moderate intensity in the heat, and a decreased sensitivity to sweating.\textsuperscript{9} Underlying factors for heat intolerance may include a low level of physical fitness, age, lack of heat acclimatization, being overweight, sweat gland dysfunction, drug abuse, medications, dehydration, lack of sleep, and infectious diseases or illness.\textsuperscript{3,22,26} Several associations with other factors have been shown in heat intolerant individuals. Those who exhibit heat intolerance have been shown to have compromised function of the cardiovascular system, low VO\textsubscript{2}max, poor heat transfer between the core and the skin, low working efficiency, low body surface area-to-mass ratio, and low sweat sensitivity.\textsuperscript{25} Heat intolerance may in turn predispose an individual to an EHI or EHS.\textsuperscript{21,23}

Much variability exists among heat intolerant individuals as there is not one single cause nor is it consistent from one person to the next.\textsuperscript{3} There are no clear, concrete definitions of what characterizes someone as heat tolerant or intolerant.\textsuperscript{19} Heat intolerance may be temporary or permanent and inherent or acquired.\textsuperscript{3,9,22,26,27} Cases of temporary heat intolerance may be due to acquired factors that do not affect heat dissipation mechanisms such as acute thermoregulatory
injury, inadequate acclimatization to heat, dehydration, infectious disease, or illness. A temporary heat intolerance may occur following a case of EHS. These individuals may lag behind in their heat tolerance compared to their peers and teammates upon return to activity. Following an EHS, some individuals may establish heat tolerance three weeks after the episode, but in other cases it may take up to five years to achieve heat tolerance. Reasons for these varied results may be related to inconsistencies of HTT protocols where variations are seen among the duration, environmental conditions, exercise intensity, and acclimation periods of the testing procedures. Patients who are evaluated on HTT longer after an EHS episode, may display more heat tolerance due to a longer recovery period. Longer periods of recovery allow for complete recovery of all body systems and the potential to rid any predisposing factors that may have had an influence. Cases of permanent heat intolerance are often due to congenital factors that affect the body’s ability to effectively thermoregulate by impairing mechanisms of heat dissipation, but can be acquired as well. Congenital abnormalities such as cystic fibrosis, linear skin dystrophy, ectodermal dysplasia, scleroderma, differences in gene expression due to disturbances among heat shock proteins, and chronic idiopathic and concurrent disease such as CNS lesions, sweat gland dysfunction or impairment, cardiovascular disease, hyperthyroidism, pheochromocytoma, infectious disease, diabetes mellitus, psychiatric illness, parkinsonism, and anhydrosis can all lead to a more permanent heat intolerance. Additionally, aside from congenital factors and disorders, a permanent heat intolerance may result from severe burns over a large portion of the body. 

Though some individuals may be able to tolerate a greater amount of heat stress than others, there is still a limit to human thermoregulation. Even those who are healthy, fit, and acclimatized will inevitably reach a point of heat storage and a rise of core body temperature.
under extreme instances of heat stress if exercise is not ceased before the uncompassable heat stress.³

When determining heat tolerance versus intolerance by means of a HTT, heart rate and internal body temperature have been used to distinguish between the two groups. A steady state of thermoregulation is defined by a plateau in body temperature and heart rate response.¹¹ With strenuous exercise in moderate environmental conditions, internal temperature will tend to rise for about 20 minutes before plateauing.⁷,¹¹

**Return to Play Protocols following an Exertional Heat Stroke**

Currently, evidence based guidelines for a structured, safe RTP, RTD, or RTA protocol for individuals who have suffered an EHS, or who have difficulty exercising in the heat, do not exist and remain controversial; there is no consensus on how to create a standardized protocol or how to interpret the results.¹,⁵,⁶,¹¹ Most HTTs involve walking or jogging on a treadmill at a fixed rate between 7.2 and 9.7 km/h (4.5 and 6.0 mph) at an incline of 2-6% in an environmental chamber set at 27 to 40°C (81 to 104°F).⁵ Continuous monitoring of physiological measures is used to help provide a practical, clinical marker for heat tolerance.⁵,¹¹

A popular protocol, the Israel Defense Force (IDF) HTT is administered to warriors only after all laboratory values are normal and after having received medical clearance for full activity by a physician. It involves walking on a treadmill for two hours at 5 km/h (3.1 mph) with a 2% incline in an environmental chamber set at 40°C (104°F) with 40% relative humidity. Individuals are classified as heat intolerant if their temperature exceeds 38.5°C and/or their heart rate exceeds over 150 bpm. While the IDF HTT places a challenge on the thermoregulatory system, it can be completed as many warriors have successfully completed the test before their RTD. In about 10% of cases, individuals do not pass the first time, but less than 2% fail when
repeating the test. Passing the test allows the individual to RTD, or RTP when used in the athletic setting. An inability to pass the test elicits the need for a repeat HTT approximately three months later.²⁹

Questions and skepticism have been raised regarding the IDF HTT’s diagnostic and prognostic validity and the cut-off points used in the protocol.¹¹,¹⁶ There also remains a controversy in its ability to establish a relationship between heat intolerance and cases of EHS.¹¹ This protocol is designed for the average fit, young male and may be more applicable in settings, such as the military, where there is a long duration and low to moderate intensity of exercise such as that which is done throughout the testing.²,⁹,²¹ The nature of the test may not be applicable in other settings or populations such as in runners, cyclists, sprinters, or elite triathletes where there is a higher intensity of exercise.²,⁹,¹⁶,²⁴ Female subjects may also respond differently than male subjects on the IDF HTT due to gender differences.¹¹,¹⁶,²⁴ Therefore, it may be necessary to create a separate diagnostic criteria when female subjects are being tested for heat tolerance using the HTT.¹¹,²¹ If the test is not designed to meet the characteristics of the tested cohort, HTT also has a risk of misdiagnosing individuals for heat intolerance.⁹ Other limitations with the IDF HTT that have been discussed include its ability to predict future cases of EHS, its ability to accurately determine thermoregulatory deficits, its ability to aid in the RTD or RTP process, and the length of the protocol not being feasible in some settings.¹¹,¹⁶

A description of previously published HTTs are summarized in Table 5. The relationship between normal test results and return to play still needs to be evaluated; further research is needed to establish and validate an effective and standard HTT.¹,¹⁶ Additional research evaluating HTT and changes in temperature is summarized in Table 6.

**Modified Heat Tolerance Testing**
Determining RTP or RTD for someone who has suffered an EHS is a complex, clinical challenge that has the potential for detrimental consequences if someone is cleared before they are able to physiologically tolerate heat stress. Additionally, it is important for the test to be able to identify individuals who have difficulties with exercising in the heat. Because of this, there is a need for a HTT designed to detect heat intolerance among the general population, recreational runners, and EHS patients who wish to safely RTA, RTP, or RTD. HTT can provide an initial evaluation of an athlete’s exercise capabilities in the heat. In past cases, individuals who have returned too soon after suffering an EHS without being evaluated on a HTT or those who have ignored HTT results, have often experienced another episode of EHI or EHS. Using a HTT can also help to identify those who may be at risk before an episode of EHI or EHS occurs. Specifically, in military cases, not only is it important to consider the individual, but others the individual may have contact with while on duty who may be affected if the person were to suffer an EHI or EHS.

A single HTT does not have the ability to assess one’s adaptations to exercise in the heat – it is necessary for a person to undergo more than one HTT to see the exhibition of any changes and adaptations that have occurred. Therefore, individuals who have suffered an EHS or experience difficulty exercising in the heat should be evaluated over time.

It has been suggested that HTT protocols involve exposure to the heat and testing for 90 minutes or more. Research in 2004 concluded that a HTT less than 120 minutes could not distinguish between heat tolerance and heat intolerance. However, later work in 2007, found that the rate of increase in rectal temperature and heart rate during the initial 20-30 minutes of exercise could differentiate between heat tolerance and heat intolerance. This suggested a HTT of 30 minutes may be an efficient way to assess response to heat stress.
Research by Hosokawa in 2016 evaluated associations in physiological measurements between a laboratory modified heat tolerance test (mHTT) and outdoor road race among 34 recreational runners. The mHTT utilized a 30-minute running protocol at 60% VO$_2$max and a 2% incline on a treadmill in an environmental chamber set at 40°C and 40% relative humidity. The study found that body mass, body surface area, and VO$_2$max explained 48% of the variance in rectal temperature gain. Differences in environmental conditions and exercise intensity limited the ability of the mHTT to identify temperature and heart rate response associations at a road race.$^{30}$

Running specific tests are important for use in evaluating a runner’s ability to tolerate and resist heat stresses placed upon the body; however a standardized running HTT currently lacks in the literature.$^9$ Although many studies have used treadmill running, running economy can differ between participants by up to 30% when the treadmill speed is fixed.$^{31}$ Commonly, VO$_2$max has been used in studies to establish relative exercise intensity due to the belief that aerobic fitness can alter the thermoregulatory response.$^{31}$ However, highly fit individuals may display a benefit to a HTT if VO$_2$max and workload are not normalized to the individual person. If not normalized, a person who is highly fit may appear to be heat tolerant, when they are actually heat intolerant, secondary to too low of an intensity of the HTT.$^{27}$ With that said, the exercise intensity for a given heat tolerance test is extremely important as differences between individuals may relate to their personal characteristics such as body mass, body fat percentage, and surface area.$^{31}$ Some have suggested the optimal way to compare groups or individuals of the same physical characteristics is using an exercise that results in the same heat production regardless of VO$_2$max and running speed.$^{31-32}$ However, in some circumstances, using an absolute fixed workload may be a limitation as the use of metabolic heat production and
evaporative heat loss for exercise prescription requires extensive equipment to monitor heat production.\textsuperscript{9,33} Additionally, while it is appropriate for evaluating heat tolerance in a repeated measure scenario, such as to evaluate an individual over time, it may not be applicable for comparing groups in which individuals differ in their characteristics.\textsuperscript{9} Specifically, in reference to an athlete who has suffered an EHS, it is impossible to control for their heat production in a real-life setting.\textsuperscript{31,33} Their heat production may vary based upon environmental conditions, practice requirements and intensity, and padding or other equipment.\textsuperscript{31} VO\textsubscript{2}max, which is a component of exercise heat production, allows for a standardized protocol that can be utilized across populations and athletes that can be repeated over time with the same individual.\textsuperscript{7,33}

The desire to compete may push an athlete to return sooner than they are ready or exercise in conditions beyond their physical limits. This necessitates the need for an objective measure, such as a mHTT to determine when return is safe and what conditions are tolerable.\textsuperscript{2,5} It is important to use RTP protocols that are specific to the future exercise and environmental conditions that the individual will be participating in.\textsuperscript{24} The use of a mHTT allows heat tolerance to be quantified while being doable, effective, easy to use, time efficient, practical, and clinically applicable.\textsuperscript{1,27} Because decisions for RTP and exercise in the heat often need to be made on a case by case basis, a mHTT is needed to aid clinicians in objectively determining a safe RTP, but is also why the creation of such a protocol is difficult to standardize.\textsuperscript{5}
CHAPTER TWO: INTRODUCTION TO THE PROBLEM

The New Balance Falmouth Road Race is a 7.1-mile (11.4 km) race that is scheduled annually in August in Falmouth, MA. The distance of the race requires runners to maintain a high exercise intensity throughout the duration while the environmental condition is often warm, which adds further physiological challenge to runners. Historical ambient temperatures for the race are $23.3 \pm 2.5^\circ C$ ($17.2-27.7^\circ C$) with a relative humidity of $70 \pm 16\%$ (47-98%) and heat index of $24 \pm 3.5^\circ C$ (17-33°C).\(^8,13,17\)

The Falmouth Road Race has the highest published incidence rate of EHS cases with 1-2 EHS per every 1000 participants, but with 100% survival due to immediate treatment using cold water immersion at the race medical tents.\(^17\) Over the course of 18 years, there was an average of 15.2 $\pm$ 13.0 cases of EHS at the Falmouth Road Race.\(^8,13,17\) In 2003, 53 cases of EHS had occurred; the environmental conditions were more extreme and higher than average with an ambient temperature of 27.7°C, relative humidity of 87%, and heat index of 33°C, leading to a higher incidence rate.\(^8,17\)

Statement of the Problem

An accurate, effective, and valid modified heat tolerance test (mHTT) does not currently exist as a tool for investigating heat tolerance and thermoregulatory ability among the athletic and recreationally active populations.

Significance of the Study

The risk of EHI including EHS is a concern for physically active individuals, particularly while exercising in the heat. One study which examined the prevalence of heat related fatalities in physical activities found nine fatalities in distance running events from 2004-2015.\(^34\) These
deaths were reported in newspaper sources; there are likely more that have not been reported in
the public media as well as many additional cases that did not result in death. 34

EHS is characterized by an elevated internal body temperature of greater than 40.5°C (104.9°F) with CNS dysfunction; this state of thermoregulatory dysfunction is called uncompensable heat stress. Diagnosis of EHS can be confirmed by the assessment of internal temperature via rectal thermometry and the recognition of neurological changes such as disorientation, irritability, aggressiveness, loss of consciousness, and irrational behavior. A delay in treatment of rapid, whole-body cooling can lead to long-term complications or death. 1

Individuals vary in their ability to tolerate heat stress. A number of factors may affect a person’s ability to thermoregulate in the heat, including a previous history of EHS. Those unable to thermoregulate in the heat are said to be heat intolerant. Physiologic measures can be assessed and monitored during HTT to help determine one’s heat tolerance status. 3,11 However, there is currently no standard HTT protocol for athletes or recreationally exercising individuals to evaluate a person’s response to the heat. 11

The IDF have developed a HTT protocol required to be completed by all warriors who have sustained an EHS before returning to duty. The protocol consists of the following: walking for 2 hours at 5 km/h (3.1 mph) with a 2% incline while in an environmental chamber with set conditions of a temperature at 40°C (104°F) and relative humidity of 40%. Individuals who are heat intolerant will exhibit an internal body temperature of >38.5°C, which continues to rise without reaching a plateau, and a heart rate >150 beats per minute (bpm) during the two-hour protocol. 11

The IDF HTT protocol may not accurately assess the heat tolerance of athletes or recreationally active individuals as it was not developed for these specific populations.
Additionally, due to the length of time of the test, it may not be practical for these populations. Thus, there is a need to develop a mHTT that can accurately assess the heat tolerance and risk of EHS in active individuals who wish to exercise in the heat as well as establish normative values of heat tolerance criteria.

**Purpose and Aim**

The purpose of this study was to identify factors that have been used as physiological measures of heat tolerance (e.g. internal temperature, heart rate) that present with strong associations between the laboratory and field settings. As part of this analysis, we also investigated differences among males and females in their response to a mHTT, investigated the association between the body’s response to exercise in the heat in a laboratory setting and on the day of a 7.1-mile outdoor road race, and determined factors with the greatest influence on the change in rectal temperature (T<sub>R</sub>) and gastrointestinal temperature (T<sub>GI</sub>).
CHAPTER THREE: METHODS

Participants

A recruitment email was sent by the New Balance Falmouth Road Race, which included pre-screening questions. Interested participants were asked to submit their contact information via an online form that allowed researchers to obtain consent after a briefing session over a phone call. Participant inclusion criteria included the following: ages between 18 and 65 years old, registered for the 2017 Falmouth Road Race, no history of chronic health problems, cardiovascular, metabolic, or respiratory disease, no fever or other current illness at the time of the Falmouth Road Race, no gastrointestinal tract motility disorders, no experience of syncope during exercise, no family history of malignant hyperthermia, no problems with anesthesia, and prediction to finish the race in under 60 minutes. Exclusion criteria included the following: current musculoskeletal injury that would limit physical activity, magnetic resonance imaging scheduled in the near future, and positive pregnancy test for females.

Data Collection

Participants were asked to make one visit to the Human Performance Laboratory at the University of Connecticut for a VO₂max and mHTT approximately two to five weeks prior to the New Balance Falmouth Road Race (Figure 1). Participants were asked to log their training four weeks prior to the day of the race as well as dietary intake three days prior to the race (Figure 2). All field data collection occurred at the 2017 New Balance Falmouth Road Race (Figure 3).

Laboratory Testing

Participants were instructed to arrive well hydrated prior to the scheduled testing and wear typical running gear such as sneakers, shorts, and a tee-shirt. All participants started the test euhydrated (urine specific gravity ≤1.020) (light refractometer, Atago, Inc., Model A300CL,
Spartan, Tokyo, Japan). Urine samples were also assessed for urine color\textsuperscript{35} and a pregnancy test was conducted for all female participants before exercise testing (Fisher HealthCare\textsuperscript{TM} Sure-Vue\textsuperscript{TM} Serum/Urine hCG Test Kit).

Participants were fitted with a heart rate (HR) monitor (TICKR X Workout Tracker with Memory, Wahoo Fitnessm Atlanta, GA) and completed a five-minute warmup on the treadmill (NordicTrack, Logan, UT) at their own pace prior to the VO\textsubscript{2}max test. The first stage of the VO\textsubscript{2}max test was set at a speed that was equivalent to 80\% of their best 5-kilometer running time. The treadmill incline was set at 2.0\% grade and each testing stage was set at three minutes. HR and perceived rating of exertion (RPE)\textsuperscript{36} were collected at the end of each stage. Based on performance on the VO\textsubscript{2}max test, participants were ranked into a category\textsuperscript{37} corresponding to their age and sex.

Participants rested for at least 30 minutes before starting a mHTT performed on a treadmill set at 2.0\% grade incline in an environmental chamber (ambient temperature, 27\degree C; relative humidity, 50\%). Participants were asked to run up to 7.1 miles (i.e., distance of the New Balance Falmouth Road Race) at 60\% of the velocity at VO\textsubscript{2}max. Nude body mass was measured before and after the mHTT to calculate sweat rate and a rectal thermometer (Temperature Sensory – Model 402, Measurement Specialties, Hampton, VA) was inserted at least 10cm beyond the anal sphincter to monitor rectal temperature (T\textsubscript{R}). Before beginning the mHTT, participants sat in the chamber for 10 minutes.

Participants also completed a Modified Environmental Symptoms Questionnaire (ESQ)\textsuperscript{36(38)} and Sport Motivation Scale (SMS-28).\textsuperscript{39} Additionally, they reported RPE and thermal sensation\textsuperscript{40} during laboratory testing. Stopping criteria for the mHTT included the following: completing 7.1 miles, volitional fatigue, T\textsubscript{R} \geq 39.99\degree C, and signs and symptoms such
as angina, shortness of breath, wheezing, lightheadedness, nausea, confusion, ataxia, pallor, and cyanosis.

Field Testing

Field testing was conducted on August 20, 2017 at the 2017 New Balance Falmouth Road Race. Study participants reported to the pre-race research tent prior to the start of the race. Participants iPhones were synced with a HR monitor, Wahoo Fitness iPhone application (Wahoo Fitness, Atlanta, GA, Version 5.9.10), and gastrointestinal (GI) thermistor pill and corresponding unit (CorTemp ELITE HQ Inc. Palmetto, FL). The GI temperature pill was ingested the night prior to the race to monitor GI temperature (T\(_{GI}\)) during the race. Following the race, participants reported to the post-race research tent. Participants exhibiting signs and symptoms of an EHS were immediately taken to the medical tent for proper treatment.

Data Analysis Procedures

Statistical analyses were completed using SPSS (version 25; IBM Corporation, Armonk, NY). Anthropometric and physiological data for the population is reported using mean ± standard deviation (SD). Independent t-tests were used for group mean comparisons between males and females. Paired-samples t-tests were also used for comparing laboratory and field data. Two-tailed Pearson correlations were used to assess for bivariate correlations. Linear regressions were used to explain the variance in both laboratory and field temperature change. For all statistical analyses, significance was set at p<0.05 with 95% confidence intervals (CI).

Because of signaling errors on the day of the race, we did not have complete T\(_{GI}\) data for our participants. Therefore, we investigated the rise in internal temperature for both laboratory and field testing in four participants (A, B, C, and D). For these four participants, we investigated causes for temperature change to present a case series. The slope of temperature
rise was calculated at the following inflection points: the first inflection point was determined by a time point where we observed the greatest rate of rise. The second inflection point was defined when internal temperature ($T_R$ or $T_{GI}$) reached 39.5°C. 

For those participants who continued to exercise above 39.5°C, a third segment was calculated. We examined the slope for each segment and also focused on the rise in temperature during the last 20 minutes of exercise. We defined a plateau in internal temperature during the last 20 minutes of exercise as a rise in temperature, or slope, less than 0.01.
CHAPTER FOUR: RESULTS

In total, 32 participants completed both field and laboratory study procedures. The study population consisted of 13 females and 19 males ranging in age from 21-65 who were recreational runners. Participant characteristics, physiological findings from laboratory testing, and physiological findings from field testing are summarized in Tables 7, 8, and 9, respectively. Independent t-tests, paired t-tests, correlations, and linear regression are also summarized in Tables 10, 11, 12, and 13, respectively. For further analysis, we were able to obtain continuous internal body temperature data from four participants. All data that follows is reported as mean ± standard deviation.

Males and females displayed significant differences in height, body mass, body surface area, body mass index, and sweat rate; there were no significant differences in their age or VO2max as reported in the tables. Males (14.1 km/h ± 1.7 km/h) ran faster than females (12.8 km/h ± 1.2 km/h) during the VO2max test (t(29) = 2.355, p = 0.026). Therefore, males (8.5 km/h ± 1.0 km/h) were also running faster than females (7.1 km/h ± 2.2 km/h) during the mHTT (t(30) = 2.361, p = 0.025). There were no significant differences between males and females for the speed which they ran during the race (t(29) = 2.033, p = 0.052).

Males and females were analyzed for differences in change of internal body temperature (ΔT). There was a significantly greater ΔTR for males (1.54°C ± 0.42°C) than females (1.11°C ± 0.50°C) during the mHTT (t(30) = 2.665, p = 0.012). Prior to the start of the mHTT, males (37.60°C ± 0.40°C) and females (37.53°C ± 0.30°C) displayed similar rectal temperatures (t(30) = 0.480, p = 0.634). On the other hand, there were no significant differences found between males (2.34°C ± 1.13°C) and females (2.25°C ± 0.91°C) for ΔTGI during the race (t(29) = 0.260, p = 0.797). Prior to the start of the race, males (37.01°C ± 0.57°C) and females (37.30°C ±
0.45°C) also displayed similar gastrointestinal temperatures (t(30) = -1.550, p = 0.132). Overall, starting (pre-) laboratory TR (37.57°C ± 0.35°C) and pre-field TG (37.13°C ± 0.53°C) amongst the cohort were significantly correlated (t(31) = 5.050, p < 0.001).

As for the perceptual scales that were utilized, there were no significant differences between males and females for Δ thermal sensation (t(30) = -0.828, p = 0.414), Δ RPE (t(30) = -0.299, p = 0.767), or Δ ESQ (t(30) = 1.188, p = 0.244) during laboratory testing. Significant differences were also not seen during field testing with Δ thermal sensation (t(29) = 0.778, p = 0.443) or Δ RPE (t(30) = 1.379, p = 0.178). Significant differences were seen between males (12 ± 7) and females (8 ± 4) with Δ ESQ during the field testing (t(30) = 2.043, p = 0.05) as males experienced a greater change in ESQ score.

The independent t-tests used to analyze urine characteristics revealed significant differences (t(30) = -2.633, p = 0.013) between males (0.006 ± 0.006) and females (0.012 ± 0.005) for Δ urine specific gravity (USG) in the laboratory setting. However, there were no significant differences in Δ USG in the field setting (t(28) = 0.607, p = 0.549). As for Δ in urine color, there were no differences in the laboratory (t(30) = -0.840, p = 0.408) or field (t(28) = -0.336, p = 0.739) between males and females.

Correlations were not seen when body surface area (BSA) (r = 0.128, p = 0.484), BM (r = 0.047, p = 0.800), body fat percentage (%BF) (r = -0.356, p = 0.069), and Δ USG (r = -0.220, p = 0.226) were compared with laboratory Δ TR. There were also no correlations with field Δ TG and BSA (r = 0.074, p = 0.693), BM (r = 0.201, p = 0.296), %BF (r = -0.096, p = 0.655), or Δ USG (r = 0.288, p = 0.129). There was no correlation between field Δ TG and VO2max (r = 0.128, p = 0.516) or field Δ TG and race finish time (minutes) (r = -0.296, p = 0.112).
As for participant training for the four weeks leading up to the race, no correlations were seen between finish time and the number of bouts of running \((r = -0.139, p = 0.456)\), total duration of training (in hours) \((r = -0.237, p = 0.200)\), and total distance of training (in kilometers) \((r = -0.298, p = 0.104)\).

Linear regression analysis was performed to explain the variance in laboratory \(\Delta T_R\) and field \(\Delta T_{GI}\). %BML and peak HR explained 47.6% of the variance of \(\Delta T_R\). %BML accounted for 25.5% and peak HR accounted for 22.2%. %BML was the only variable retained in the regression for \(\Delta T_{GI}\); it accounted for 25.4% of the variance. Other co-variates that were inputted into the regression included: BM, BSA, BM/BSA, %BF, %vVO\(_{2\text{max}}\), and speed. These variables were indifferent in affecting the \(\Delta T_R\) or \(\Delta T_{GI}\).

**Case Comparisons**

We performed an in-depth analysis of four participants of our cohort to further examine their response to exercise in the lab and field. These participants will be referred to as Subject A (Female, 46 years old), Subject B (Female, 53 years old), Subject C (Female, 22 years old), and Subject D (Male, 41 years old). Comparisons of lab and field HR and temperature as well as segmented slopes for temperature for these four subjects can be seen in Figures A-D. In an attempt to explain the responses observed, we investigated numerous anthropometric and physiological factors. A comparison of our four runners can be seen in Table 14.

**Subject A:** Subject A displayed a higher HR and temperature in the field as compared to the lab (Figure A1). Her temperature did not reach 39.5°C in the lab, so we did not have a third segment to analyze rise in temperature (Figure A3). During her last 20 minutes of exercise in the lab, she did not reach a plateau as defined by our parameters (Figure A4). However, she did reach a plateau during the last 20 minutes in the field (Figure A4).
Subject B: Subject B displayed a higher HR and temperature in the field as compared to the lab (Figure B1). Her temperature did not reach 39.5°C in the lab nor the field, therefore we did not have a third segment for rise in temperature during either situation (Figures B2-B3). During their last 20 minutes of exercise in the lab, she did not reach a plateau and exhibited a rise in temperature (Figure B4). Subject B did reach a plateau during the last 20 minutes of exercise in the field (Figure B4).

Subject C: Subject C displayed a higher HR and temperature in the field as compared to the lab (Figure C1). Her starting temperature in the field was also higher than that of in the lab (Figure C1). Near the end of the mHTT, a signaling error with the heart rate monitor was responsible for the deflection point in HR that is seen (Figure C1). Signaling in the field was also likely interrupted, leading to the disbursement and disarray of the temperature points that are displayed graphically (Figure C2). The participant did not reach 39.5°C in the lab, though she did display a plateau during the final 20 minutes of exercise during the mHTT (Figure C4). She did not show a plateau during the last 20 minutes in the field according to the slope of the segment (Figure C4).

Subject D: Subject D displayed a higher HR and temperature in the field as compared to the lab (Figure D1). During both the lab and field, he reached a $T_R$ and $T_{GI}$ respectively of 39.5°C (Figure D2-D3). Subject D had a plateau during the final 20 minutes of exercise in the field, but he continued to have an increase in $T_R$ during the mHTT (Figure D4).
CHAPTER FIVE: DISCUSSION

The purpose of our study was to identify factors that have been used as physiological measures of heat tolerance that present with strong associations between the laboratory and field settings. We investigated differences among males and females in their response to a mHTT, investigated the associations between the body’s response to exercise in the heat in a laboratory setting and during an outdoor road race, and determined factors with the greatest influence on change in $T_R$ and $T_{GI}$.

Our sample of recreational runners exhibited no significant differences in age and VO$_2$max between male and female participants, allowing us to pool our data and examine a variety of recreational runners representing a range of age and fitness levels.

While investigating differences among males and females, the body size difference observed is expected as males tend to be larger than females. The greater $\Delta T_R$ and sweat rate among males in the laboratory setting is likely due to their larger body size and higher intensity of exercise based on 60% vVO$_2$max. Consequently, the similar exercise intensities between males and females in the field led to similar $\Delta T_{GI}$ data. These results support previous research on the role of the relative intensity of exercise, body mass, and body composition on changes in body temperature that have been discussed in the literature.$^{1-2,14-15}$ Therefore, it is important to take these characteristics into consideration when using a mHTT to evaluate responses to heat stress. Particularly, the relative intensity of exercise will greatly affect physiological measurements. For example, an individual may be able to tolerate walking in a stressful environment but may exhibit faster and more prominent rises in internal temperature and HR in the same environment while running.
Investigation into the body’s response to exercise in the heat in a laboratory setting and field setting identified the absolute rise in body temperature was greater in the field than in the lab; post-lab $T_R$ was an average of 1.4°C higher than pre-lab $T_R$ while post-field $T_{GI}$ was an average of 2.4°C higher than pre-field $T_{GI}$. The % difference in $\Delta T_R$ in the lab was 3.61% while the % difference in $\Delta T_{GI}$ in the field was 6.0%. Because starting temperatures for the mHTT and race were similar, these comparisons can be made. The greater absolute rise in body temperature and % difference of $\Delta T_{GI}$ in the field compared to $\Delta T_R$ in the lab can be explained by the higher intensity of exercise during the race. This was expected by study design as intensity during the laboratory testing was limited to 60% of $vVO_{2\text{max}}$. It was expected that runners would exercise more intensely during the race as was illustrated by differences in speed. As previously mentioned, the intensity of exercise plays a large role in physiological response.$^{1,9,31}$ Likewise, environmental conditions are impactful as well.$^{1,3-4,6,9}$ The environmental conditions in the laboratory were ambient temperature 27.2 ± 0.6°C (81.0 ± 1.0°F), humidity 51.6 ± 3.8%, and WBGT 22.6 ± 0.7°C (72.7 ± 1.2°F). For the day of the Falmouth Road Race, conditions were 25°C (77°F) and 61% relative humidity with a heat index of 25°C (77°F). In both settings, participants were able to dissipate heat to the environment, due to environmental temperatures being less than skin temperature; these participants were not gaining heat from the environment.$^7$ Although these conditions were quite similar, environmental differences still exist in terms of radiation from the sun, wind and air movement, and surface temperature from running on pavement. Therefore, increases in temperature in the field may also have been related to the environment in addition to the higher exercise intensity.

A negative correlation was present between $VO_{2\text{max}}$ and race finish time. This shows that as a participant’s $VO_{2\text{max}}$ increased, his or her race finish time decreased. Clinically, this
supports the idea of VO₂max serving as an indicator of aerobic fitness level.¹²,⁶,³¹ A higher level of cardiovascular fitness can help an individual effectively thermoregulate.²,⁶ If individuals are struggling to exercise in the heat under stressful environmental conditions, increasing his or her own fitness level may assist in improving outcomes.

Even though there was a 6.0% difference in temperature change on the day of the race, as compared to a 3.61% difference in the lab, %BML remained similar between the two situations. There was no difference in %BML in the lab and the field as shown by paired t-tests; the means for %BML were actually the same. All participants started the race and mHTT hydrated. However, hydration status was better during the lab which is likely due to the directions given to arrive for testing well hydrated. Although there was a chance to drink ad libitum on the day of the race, participants still had %BML similar to that of the lab even though they knew and were informed of their sweat rate. Despite this education, most individuals were unable to correct their %BML on race day. Due to the higher intensity of the race, participants may have not have realized it was necessary to increase their fluid intake. As previously published, dehydration leads to a rise in core temperature and can put one at risk for developing a heat-related illness.³,²²,²⁶ This concept is relevant to the current study; as seen by correlation analyses, as %BML loss increased, there was also an increase in internal body temperature in both the laboratory and field settings. This is important from the standpoint of hydration in that something simple such as staying hydrated can help regulate body temperature during intense exercise. If an individual knows their sweat rate, adequately adapts for it, and utilizes it, they may be able to limit the unsafe rise of their core body temperature.

%BML explained the most variance in Tᵲ and Tₓi despite some differences between the laboratory and field testing. Other characteristics such as BSA, BM, and VO₂max were
indifferent in relation to $\Delta T_R$ or $\Delta T_{GI}$. Based on this information, sweat losses on the day of the race trumped every other variable when assessing $\Delta T_{GI}$. Regardless of body size, intensity, pace, and other anthropometric and physiological measures, body mass loss was the main factor determining the change in temperature in both laboratory and field settings. This differs from the results of similar previous research in which body mass, body surface area, and VO$_2$max explained nearly half of the variance in temperature gain.$^{30}$ The difference in results may be due to the different environmental conditions and protocol between the two studies; the current study employed less stressful environmental conditions and a longer protocol.

Because of a person’s uniqueness and individuality, it is very difficult, if not impossible, to determine one factor that has the same predictive level for evaluating risk for increase in body temperature for all persons. It is likely that a summation of factors is responsible for temperature increase rather than the presence of certain factors alone. While this study did find $\%BML$ as explaining the most variance in $T_R$ and $T_{GI}$, a large portion of the variance still exists and is likely represented by a number of other compounding factors. It is possible that individual factors not measured or identified, such as genetic predispositions, were also responsible for physiologic response.

Case Comparison

Because Subject A only completed 40 minutes of exercise in the lab, it was likely not long enough to see a plateau in $T_R$. When comparing the last 20 minutes of exercise during the mHTT with the corresponding time during the race (20-40 minutes), there was not a plateau in $T_{GI}$. The slope of $T_{GI}$ in the field was greater than that of the slope of $T_R$ in the lab during this time point. The plateau in $T_{GI}$ was seen later with 20 minutes left in the race. This further
suggests that the duration of exercise during the mHTT was not long enough to see a plateau in temperature.

While Subject B did not reach a plateau during the lab, her temperature did look as if it were starting to plateau. Likely, a plateau in $T_R$ would have been seen if she continued to exercise. She stopped exercising at 60 minutes in the lab and completed the race in 75 minutes where a plateau was seen. Unique for this subject is though she had a higher initial temperature in the lab as compared to the field, her temperature ended at similar points. Because she exercised for 15 minutes longer in the field, lab temperature would likely have been higher had the duration of exercise been more similar. This subject never reached the 39.5°C threshold as mentioned in the literature which may suggest this person is very well adapted to exercise and is able to adequately thermoregulate.

Although Subject C did not display a plateau during the last 20 minutes of exercise with $T_{GI}$, this may have been skewed secondary to signaling errors that resulted in multiple outliers within the data. This participant exercise for the same duration in the lab as the field at 60 minutes. We can then compare the last 20 minutes of both bouts of exercise. Even though the time was the same, the distance covered was different due to the difference in speeds. In the lab, Subject C completed 7.7 kilometers (4.81 miles) during the mHTT while running at 7.7 km/h (4.81 mph). In the race, she completed 11.4 kilometers (7.1 miles) while running at an average speed of 11.5 km/h (7.12 mph). When comparing the slope and overall average rate of rise in temperature during the mHTT and race, Subject C had a gain in $T_R$ of 1.63°C, equaling an average 0.027°C per minute rise in temperature. As for $T_{GI}$, her overall gain was 2.09°C with an average rise of 0.035°C per minute. This may be explained by the increased intensity of exercise during the race.
Subject D had similar durations of exercise in the lab and field with 60 minutes during the mHTT and a race finish time of 64 minutes. However, his rise in $T_R$ during the mHTT was greater than the rise in $T_{GI}$ during the race in the last 20 minutes of exercise although end temperature was similar. When examining reasons for this difference, Subject D started out a higher temperature in the lab than the field. This participant likely benefitted from exercise outside where air movement was present. Additionally, while he did run for similar durations, the distance covered in the lab was 8.7 kilometers (5.42 miles), while in the field was 11.4 kilometers (7.1 miles). With this difference in duration, the participant may have needed more time running in the mHTT at the lower intensity to achieve a steady state. During the field testing, the first inflection point, the point of the greatest rate of rise, for $T_{GI}$ was earlier than that of $T_R$ in the lab.

Even though each of the four subjects in the case comparison had a greater increase in temperature and greater average rate of rise of temperature during the race, three out of four exhibited a plateau during the race in the last 20 minutes of exercise; only one subject, the one who did not plateau in the race, had a plateau in the lab.

Based on the case comparisons, different HTT guidelines may be needed for males versus females and individuals of different body sizes. Because some subjects never reached the 39.5°C cut-off for heat tolerance versus intolerance, this number may not be appropriate, specifically when HTT consists of higher intensity exercise. Prior studies have used 38.5°C$^{13,20,23,41}$ and 39.5°C$^{17}$ as a cutoff for rectal temperature during a HTT as a measure of heat intolerance. Others have also used a 0.45°C$^{3,23}$ rise in temperature as an indicator for heat intolerant individuals. However, since these protocols involved walking, the results need to be carefully considered when applying them to a running-based exercise situation such as this. While
running, individuals will inevitably experience a faster and greater rise in temperature than exercise, such as walking, that is at a much lower intensity, even when the same environmental conditions are present. For this reason, it is necessary to define additional criteria when evaluating patients who are exercising at a higher intensity. In addition, slope increases and dangerous rates of rise for internal temperature may need to be further defined as well.

As for duration of HTT, the investigation into these four case comparison subjects suggest that a HTT of at least 60 minutes is most likely necessary. In subjects who completed a shorter duration of the mHTT, plateauing of rectal temperature was not seen. Additionally, the difference in intensities between the laboratory and field likely led to the absence and presence of plateau in the two settings. During the mHTT, participants stopped due to fatigue, but they did not stop during the race. This is related to the presence of EHS in highly motivated individuals; individuals cease to discontinue exercise when under other, normal circumstances the person would likely stop.1,2,6,8,21,24

It may be useful to employ a series of HTTs, as suggested in the literature, in individuals who have experienced exertional heat illnesses or generalized heat intolerance and difficulty exercising in the heat.1,11,24 Following an initial mHTT, at a lower intensity such as used in this protocol, a second mHTT of a higher intensity may help to further define heat tolerance status. In addition to intensity, duration of the protocol may also be increased as intensity/velocity and time seem to be important factors in observing a plateau in rectal temperatures. The results also suggest that it is difficult to create a standardized mHTT that is applicable to every individual. It may be necessary to develop a standardized protocol that can then be manipulated depending on specific factors.

Limitations
There are limitations to our study. Our specific population was of recreational runners who may tend to be more similar in size with not as much variance as compared to other types of athletes. Because of our specific cohort, these results may not be applicable to other populations of athletes or warriors. Additionally, these individuals were healthy; our cohort did not include diseased people or grossly positive situations of heat intolerance. The individuals in our study are people who may not have issues or will never have issues in the heat.

We recorded the average speed of our participants during the race. We do not have changes in pace throughout the race that would allow us to correlate spikes in temperature with changes in the race terrain and increased intensity such as may be seen in individuals who increase their speed as they are nearing the finish line.

We also experienced signaling errors on the day of the race which gave us incomplete data for $T_{GI}$ and HR. Though our case series is unique in that we can see differences among individual persons by comparing laboratory and field data, we were only able to investigate the responses of four individuals. The signaling errors decreased our ability to make inferences on the applicability of our laboratory testing as we did not have a robust data set for the secondary comparison. Similarly, there are inherent differences in the environments when comparing a controlled, laboratory setting and a real world, field setting. This needs to be taken into consideration when discussing differences in data between the two environments.

Lastly, we asked our participants to self-report data such as their training information, dietary intake, and fluid intake during the race. Our participants may not have been accurate in reporting all of this information and some information may have been accidentally omitted.

Conclusions
In conclusion, when using a mHTT, attention needs to be given to the intensity and duration of the test. An accurate mHTT needs to account for the intensity of exercise and the amount of time needed to see a plateau in temperature and heart rate at the specified velocity. In this study, at least 60 minutes of exercise at 60% of VO2max was likely needed to assess heat tolerance. While 39.5°C was use during the case series evaluation, some individuals did not reach this temperature mark. Others who did reach this mark did not experience any signs or symptoms of exertional heat illnesses. Because past HTT protocols have frequently been developed as walking protocols, criteria need to be changed to reflect the increased intensity of exercise while running. %BML was found to explain the most variance in rectal temperature increase. Therefore, it is important to know individual sweat rates to help prevent large increases in internal temperature. Proper hydration is an easy and effective strategy that may help those who struggle with exercise in the heat by preventing the onset on exertional heat illnesses.

Future research should focus on determining the length of time needed for a mHTT as well as establishing a cutoff point for TR during testing and normative values for heat tolerance. Future studies are needed to compare mHTT and field results in large subject pools, focusing on higher exercise intensities that are more applicable to a realistic setting. Research in these areas will help to establish a mHTT for athletic populations by establishing criteria to reflect the increased intensity of running during a mHTT as compared to a walking HTT.
**LEGENDS**

*Figure 1.* Overview of laboratory data collection. \( \text{VO}_2\text{max} = \) Maximal Oxygen Consumption, \( \text{mHTT} = \) Modified Heat Tolerance Testing, \( T_R = \) Rectal Temperature, \( \text{HR} = \) Heart Rate, \( \text{WBGT} = \) Wet Bulb Globe Temperature.

*Figure 2.* Overview of data collection up to the day of the race.

*Figure 3.* Overview of field data collection. \( \text{GI} = \) Gastrointestinal. * If GI temperature could not be assessed, rectal temperature assessment was used.

*Figure A1.* Subject A comparison of laboratory heart rate and rectal temperature and field heart rate and gastrointestinal temperature.

*Figure A2.* Subject A segmented slopes of field gastrointestinal temperature.

*Figure A3.* Subject A segmented slopes of laboratory rectal temperature.

*Figure A4.* Subject A laboratory rectal temperature and field gastrointestinal temperature during the final 20 minutes of exercise.

*Figure B1.* Subject B comparison of laboratory heart rate and rectal temperature and field heart rate and gastrointestinal temperature.
Figure B2. Subject B segmented slopes of field gastrointestinal temperature.

Figure B3. Subject B segmented slopes of laboratory rectal temperature.

Figure B4. Subject B laboratory rectal temperature and field gastrointestinal temperature during the final 20 minutes of exercise.

Figure C1. Subject C comparison of laboratory heart rate and rectal temperature and field heart rate and gastrointestinal temperature.

Figure C2. Subject C segmented slopes of field gastrointestinal temperature.

Figure C3. Subject C segmented slopes of laboratory rectal temperature.

Figure C4. Subject C laboratory rectal temperature and field gastrointestinal temperature during the final 20 minutes of exercise.

Figure D1. Subject D comparison of laboratory heart rate and rectal temperature and field heart rate and gastrointestinal temperature.

Figure D2. Subject D segmented slopes of field gastrointestinal temperature.

Figure D3. Subject D segmented slopes of laboratory rectal temperature.
Figure D4. Subject D laboratory rectal temperature and field gastrointestinal temperature during the final 20 minutes of exercise.
<table>
<thead>
<tr>
<th>Illness</th>
<th>Definition</th>
<th>Presentation</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exercise Associated Muscle Cramps</td>
<td>Cramps occurring in skeletal muscle during or following exercise.</td>
<td>Painful, involuntary contractions; Possible inability to ambulate</td>
<td>May progressively worsen and be visually noticeable</td>
</tr>
<tr>
<td>Heat Syncope (Orthostatic Dizziness)</td>
<td>Fainting or passing out as result of maximal vasodilation within the skin.</td>
<td>Fainting after long periods of exercise, standing, or changes in posture in the heat</td>
<td>Common in individuals who are unfit or unacclimatized to the heat</td>
</tr>
<tr>
<td>Heat Exhaustion</td>
<td>An inability to exercise in the heat due to an elevated core body temperature that does not result in end-organ damage.</td>
<td>Cessation of exercise with intense physical activity in hot and humid conditions; Rectal temperature below 40.5°C, no central nervous system dysfunction</td>
<td>Most common among individuals who are unacclimatized to the heat and/or dehydrated</td>
</tr>
<tr>
<td>Exertional Heat Injury</td>
<td>Organ and tissue injury such as damage to the liver, kidneys, gut, or muscles.</td>
<td>Indications of systemic, internal injury such as dark urine, severe muscle pain, and abnormal blood chemistry</td>
<td>Absence of CNS dysfunction; High sustained body temperature usually greater than 40.5°C (105°F)</td>
</tr>
</tbody>
</table>
Table 2. Signs and Symptoms of Exertional Heat Stroke\textsuperscript{1-4,9-10,21}

<table>
<thead>
<tr>
<th>Signs and Symptoms</th>
<th>Signs and Symptoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggressiveness</td>
<td>Agitation</td>
</tr>
<tr>
<td>Altered level of consciousness</td>
<td>Apathy</td>
</tr>
<tr>
<td>Clumsiness</td>
<td>Coma</td>
</tr>
<tr>
<td>Confusion</td>
<td>Dehydration*</td>
</tr>
<tr>
<td>Delirium</td>
<td>Diarrhea</td>
</tr>
<tr>
<td>Disorientation</td>
<td>Dizziness*</td>
</tr>
<tr>
<td>Drowsiness</td>
<td>Extreme fatigue</td>
</tr>
<tr>
<td>Headache*</td>
<td>Hyperventilation</td>
</tr>
<tr>
<td>Hysteria</td>
<td>Inability to ambulate</td>
</tr>
<tr>
<td>Inability to lucidly answer questions</td>
<td>Inappropriate comments</td>
</tr>
<tr>
<td>Irrational or unusual behavior</td>
<td>Irritability</td>
</tr>
<tr>
<td>Light headedness*</td>
<td>Loss of balance</td>
</tr>
<tr>
<td>Loss of balance and muscle function</td>
<td>Loss of consciousness</td>
</tr>
<tr>
<td>Nausea*</td>
<td>Seizure</td>
</tr>
<tr>
<td>Staggering</td>
<td>Stumbling</td>
</tr>
<tr>
<td>Stupor</td>
<td>Sudden collapse</td>
</tr>
<tr>
<td>Syncope*</td>
<td>Vomiting</td>
</tr>
</tbody>
</table>

\textsuperscript{*} Early signs and symptoms of an exertional heat stroke.
Table 3. Risk Factors and Predisposing Factors for Exertional Heat Stroke

<table>
<thead>
<tr>
<th>Risk Factor</th>
<th>Predisposing Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acute illness</td>
<td>Age (&gt;40 years old)</td>
</tr>
<tr>
<td>Alcohol use</td>
<td>Body composition</td>
</tr>
<tr>
<td>Clothing, equipment, or gear</td>
<td>Cumulative fatigue</td>
</tr>
<tr>
<td>Dehydration</td>
<td>Dietary supplements</td>
</tr>
<tr>
<td>Disregard for safety regulations</td>
<td>Drug use</td>
</tr>
<tr>
<td>Electrolyte imbalances</td>
<td>Exercise duration</td>
</tr>
<tr>
<td>Exercise intensity</td>
<td>Exercise unmatched for fitness</td>
</tr>
<tr>
<td>Exposure to repeated days of strenuous exercise</td>
<td>Fever</td>
</tr>
<tr>
<td>Genetics</td>
<td>High ambient temperature</td>
</tr>
<tr>
<td>High relative humidity</td>
<td>High WBGT</td>
</tr>
<tr>
<td>History of EHI or EHS</td>
<td>Ignoring early signs and symptoms of EHI</td>
</tr>
<tr>
<td>Inadequate accessibility to fluids</td>
<td>Inappropriate work to rest ratios</td>
</tr>
<tr>
<td>Increased BMI</td>
<td>Ineffective of absent medical triage</td>
</tr>
<tr>
<td>Infectious disease</td>
<td>Intense solar radiation</td>
</tr>
<tr>
<td>Internal motivation</td>
<td>Lack of access to shade</td>
</tr>
<tr>
<td>Lack of compensatory changes</td>
<td>Lack of heat acclimatization</td>
</tr>
<tr>
<td>Lack of knowledge and education</td>
<td>Long initial heat exposure</td>
</tr>
<tr>
<td>Low air movement/wind speed</td>
<td>Malignant hyperthermia</td>
</tr>
<tr>
<td>Medication use</td>
<td>Mental stress</td>
</tr>
<tr>
<td>Metabolic heat production</td>
<td>Obesity</td>
</tr>
<tr>
<td>Physical stress</td>
<td>Poor aerobic conditioning</td>
</tr>
<tr>
<td>Poor nutrition</td>
<td>Poor physical fitness</td>
</tr>
<tr>
<td>Predisposing medical conditions</td>
<td>Skin disease</td>
</tr>
<tr>
<td>Sleep deprivation</td>
<td>Sleep quality</td>
</tr>
<tr>
<td>Stimulant use</td>
<td>Sudden increase in training</td>
</tr>
<tr>
<td>Sunburn</td>
<td>Sweat gland dysfunction</td>
</tr>
<tr>
<td>Time of day</td>
<td>Time of year</td>
</tr>
<tr>
<td>Warrior mentality</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: WBGT = wet bulb globe temperature, EHI = exertional heat illness, EHS = exertional heat stroke, BMI = body mass index.
Table 4. Methods of Preventing Exertional Heat Illnesses<sup>3-4,6-8,10,19</sup>

<table>
<thead>
<tr>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ability to assess rectal temperature</td>
</tr>
<tr>
<td>Adequate sleep and rest in cool environments</td>
</tr>
<tr>
<td>Adequate and appropriate trained medical personnel, such as athletic trainers, available on site</td>
</tr>
<tr>
<td>Annual review and rehearsal of the emergency action plan for dealing with EHI</td>
</tr>
<tr>
<td>Athletes with a viral infection, fever, illness, or serious skin rash should be withheld from participation</td>
</tr>
<tr>
<td>Avoiding training and exercising during the hottest hours of the day</td>
</tr>
<tr>
<td>Balanced and nutritious diet</td>
</tr>
<tr>
<td>Close monitoring of those more susceptible to EHI of with a history of EHI</td>
</tr>
<tr>
<td>Cold-water immersion tubs and ice towels readily available</td>
</tr>
<tr>
<td>Conduction of thorough preparticipation medical exams to identify athletes at risk</td>
</tr>
<tr>
<td>Discouraged use of dietary supplements</td>
</tr>
<tr>
<td>Early recognition and removal from activity of any persons displaying symptoms of EHI</td>
</tr>
<tr>
<td>Educating athletes on how to protect their own health and safety</td>
</tr>
<tr>
<td>Education of relevant personnel regarding the recognition of EHI</td>
</tr>
<tr>
<td>Gradual introduction of activity</td>
</tr>
<tr>
<td>Implementing activity restrictions and environmental guidelines for hot/humid conditions based on WBGT</td>
</tr>
<tr>
<td>Maintenance of proper hydration before, during, and after activity with available fluids during activity</td>
</tr>
<tr>
<td>Matching physical efforts to fitness levels</td>
</tr>
<tr>
<td>Monitoring athletes for behavior and performance changes</td>
</tr>
<tr>
<td>Not allowing coaches to oversee the medical care for their athletes</td>
</tr>
<tr>
<td>Proper heat acclimatization occurring gradually over 7-14 days</td>
</tr>
<tr>
<td>Proper work-to-rest ratios and adequate rest breaks</td>
</tr>
<tr>
<td>Removal of excessive clothing and equipment</td>
</tr>
</tbody>
</table>

Abbreviations: EHI = exertional heat illness, WBGT = wet bulb globe temperature.
Table 5. Previously Published Heat Tolerance Testing Guidelines

<table>
<thead>
<tr>
<th>Author</th>
<th>Purpose</th>
<th>Environment</th>
<th>Protocol</th>
<th>Results/Application</th>
</tr>
</thead>
</table>
| Wyndham | Evaluate heat tolerance among individuals applying for a job in the gold mines | • 34°C  
• Nearly 100% relative humidity | • 4 hours  
• Stepping up and down on a bench | Heat intolerance if $T_R > 38.6 \degree C$ and HR $> 160$ bpm, or participant was exhausted |
| Shapiro | HTT used to evaluate response of exposure to heat between men who had an EHS 2-5 years prior and healthy men who served as a control | • 23°C and 40°C  
• 40% relative humidity | • Stepping 60 min., 12 steps/min. on a 30cm bench & 20 min., 24 steps/min. (23°C)  
• Stepping 3 hrs., work load of 40W, 12 steps/min. (40°C) | Heat intolerance if $T_R > 38.5 \degree C$ and HR $> 145$ bpm with no plateau  
Severity determined by amount of deviation |
| Epstein | Modification of Shapiro HTT from 1979 in 1983 | • 40°C  
• 40% relative humidity | • 2 hours  
• Walking on a treadmill (5km/h, 2% incline) | Heat intolerance if $T_R > 38.5 \degree C$ and/or HR $> 150$ bpm  
Rise of $<0.45 \degree C$ acceptable plateau |
| Moran | Mandatory testing on all warriors who sustain an EHS as part of the RTD process required by the IDF | • 40°C  
• 40% relative humidity | • 2 hours  
• Walking on a treadmill (5 km/h, 2% incline) | Heat intolerance if $T_R > 38.5 \degree C$, HR $> 150$ bpm, or no plateau  
Increase of 0.45°C as a cut-off  
Increase $>0.17 \degree C$ in $T_R$ during the final 20 min. of HTT may indicate heat intolerance |
| Amit | Further defined criteria for HTT | • 40°C  
• 40% relative humidity | • 2 hours  
• Walking on a treadmill (5 km/h, 2% incline) | Heat intolerance if $T_R > 38.5 \degree C$, HR $> 150$ bpm, or no plateau  
Increase of 0.45°C as a cut-off  
Increase $>0.17 \degree C$ in $T_R$ during the final 20 min. of HTT may indicate heat intolerance |
| Moran | Evaluation of PSI, a real-time continuous measure used to show changes in both heart rate and core body temperature throughout a HTT | • 40°C | • 2 hours | Calculated by weighted changes in HR and $T_R$  
Ranges from a score of 0 to 10 in relation to the amount of strain  
Can be used to compare results of HTTs by controlling for baseline measures |

Abbreviations: HTT = heat tolerance test, EHS = exertional heat stroke, min. = minutes, cm = centimeters, hrs. = hours, W = watts, $T_R$ = rectal temperature, HR = heart rate, bpm = beats per minute, km/h = kilometers per hour, RTD = return to duty, IDF = Israel defense force, PSI = physiological strain index.
Table 6. Other Research Evaluating Heat Tolerance Testing and Changes in Temperature

<table>
<thead>
<tr>
<th>Author</th>
<th>Purpose</th>
<th>Significant Findings</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lisman(^{17})</td>
<td>• Examine associations between performance on a HTT and different parameters (i.e., age, gender, anthropometric measurements, and cardiorespiratory fitness)</td>
<td>• Heat intolerant individuals had a higher BF% and lower VO(_2)\text{max}</td>
<td>• It may be necessary to develop different HTT parameters and criteria for women and men • VO(_2)max is associated with determining heat tolerance</td>
</tr>
<tr>
<td>Mee(^{12})</td>
<td>• Evaluate the repeatability of a rHTT</td>
<td>• Test had strong repeatability and was able to differentiate between responses by the individuals during the testing</td>
<td>• Heat tolerance is a continuous variable with a person’s heat tolerance being more appropriately rated on a continuum</td>
</tr>
<tr>
<td>Smolijanic(^{30})</td>
<td>• Evaluate the effects of VO(_2)max and running economy on thermoregulation.</td>
<td>• Differences in VO(_2)max did not influence core temperature and sweat rates. • Thermoregulatory response was due to metabolic heat production and evaporative requirement for heat balance</td>
<td>Changes in temperature are determined by heat production per unit of total BM • Sweat rates are determined by evaporative requirement • To compare groups an exercise that results in the same heat production is optimal</td>
</tr>
<tr>
<td>Gisolfi(^{43})</td>
<td>• Determine the effects of a physical training program in a cool environment on participants’ tolerance to heat stress</td>
<td>• Participants exhibited a greater ability to perform a 90-minute walk on a treadmill following a training regimen</td>
<td>• Training in a cool environment may have potential uses during RTP following an EHS when patients have yet to fully recovery and cannot tolerate high temperatures and high humidity</td>
</tr>
<tr>
<td>Gibson(^{32})</td>
<td>• Determine which exercise intensity methods would be the most effective at predicting change in rectal temperature</td>
<td>• Power relative to mass had the strongest relationship with the rate of rectal temperature; %VO(_2)peak explained 32% of the variance which was still significant</td>
<td>%VO(_2)peak is used because each participant will be able to complete the exercise • In using heat production, metabolic gas exchange needs to be continually measured which is often not feasible or practical; it may be more applicable when doing group studies rather than individual evaluation</td>
</tr>
<tr>
<td>Jay(^{31})</td>
<td>• Determine if large differences in VO(_2)peak independently alter core temperature and sweating changes during exercise in a neutral environment</td>
<td>• Large differences in VO(_2)peak did not influence changes in core temperature or sweating • With similar mass and BSA, greater change in core temperature and sweating with high VO(_2)peak due to differences in heat production when exercise was performed at a relative intensity</td>
<td>• Sweating capacity and heat tolerance are improved with greater aerobic fitness • Higher VO(_2)max is beneficial in an uncompensable environment • Changes in core temperature and sweating in a neutral environment are related to metabolic heat production, BM, and BSA</td>
</tr>
<tr>
<td>Cramer(^{16})</td>
<td>• Evaluate the influences on core temperature change</td>
<td>• Biophysical factors were responsible for the majority of the core temperature variability, aerobic fitness and BF had minimal impact • Heat production was the best predictor of changes in rectal temperature; the rest of the variability could be accounted for by BSA, BM, and BF%</td>
<td>• Fitness may not influence the relationship between VO(_2)max and core temperature changes • When individuals of a smaller size exercise at a similar metabolic rate, regardless of their aerobic fitness level, they will show similar changes in core temperature</td>
</tr>
</tbody>
</table>

Abbreviations: HTT = heat tolerance test, BF% = body fat percentage, VO\(_2\)\text{max} = maximal oxygen consumption, rHTT = running heat tolerance test, BM = body mass, RTP = return to play, EHS = exertional heat stroke, %VO\(_2\)peak = percentage of peak oxygen consumption, VO\(_2\)peak = peak oxygen consumption, BSA = body surface area, BF = body fat.
### Table 7. Anthropometric Data

<table>
<thead>
<tr>
<th></th>
<th>Overall</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N 32</td>
<td>19</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
</tr>
<tr>
<td>Age (years)</td>
<td>45 ± 12</td>
<td>48 ± 12</td>
<td>40 ± 9</td>
</tr>
<tr>
<td>Height (cm)*</td>
<td>174.9 ± 9.2</td>
<td>179.2 ± 8.5</td>
<td>168.3 ± 6.0</td>
</tr>
<tr>
<td>Body Mass (kg)*</td>
<td>74.0 ± 13.7</td>
<td>80.9 ± 12.7</td>
<td>63.8 ± 7.1</td>
</tr>
<tr>
<td>Body Surface Area (m²)*</td>
<td>1.9 ± 0.2</td>
<td>2.0 ± 0.2</td>
<td>1.7 ± 0.1</td>
</tr>
<tr>
<td>Body Mass Index*</td>
<td>24 ± 3</td>
<td>25 ± 3</td>
<td>22 ± 2</td>
</tr>
<tr>
<td>VO₂max (mL/kg/min)</td>
<td>42.26 ± 7.08</td>
<td>43.45 ± 7.55</td>
<td>40.38 ± 6.10</td>
</tr>
</tbody>
</table>

Abbreviations: cm = centimeter, kg = kilogram, m² = meters squared, mmHg = millimeter of mercury, VO₂max = maximal oxygen consumption, mL/kg/min = milliliters of oxygen per kilogram of body weight per minute. * Significant differences at p<0.05.

### Table 8. Laboratory Testing Physiological Data

<table>
<thead>
<tr>
<th></th>
<th>Overall</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>19</td>
<td>13</td>
</tr>
<tr>
<td>Δ USG</td>
<td>0.009 ± 0.006</td>
<td>0.006 ± 0.066</td>
<td>0.012 ± 0.005</td>
</tr>
<tr>
<td>Δ Urine Color</td>
<td>3 ± 1</td>
<td>3 ± 2</td>
<td>4 ± 1</td>
</tr>
<tr>
<td>% Body Mass Loss</td>
<td>1.38 ± 0.55</td>
<td>2.14 ± 0.55</td>
<td>1.48 ± 0.55</td>
</tr>
<tr>
<td>mHTT Speed (km/h)</td>
<td>8.2 ± 1.0</td>
<td>8.5 ± 1.0</td>
<td>7.7 ± 0.6</td>
</tr>
<tr>
<td>HR Baseline (bpm)</td>
<td>88 ± 11</td>
<td>87 ± 11</td>
<td>90 ± 12</td>
</tr>
<tr>
<td>HR Peak (bpm)</td>
<td>158 ± 12</td>
<td>157 ± 13</td>
<td>160 ± 11</td>
</tr>
<tr>
<td>TR Baseline (°C)</td>
<td>37.57 ± 0.35</td>
<td>37.59 ± 0.39</td>
<td>37.53 ± 0.30</td>
</tr>
<tr>
<td>TR Peak (°C)</td>
<td>38.94 ± 0.62</td>
<td>39.13 ± 0.60</td>
<td>38.66 ± 0.57</td>
</tr>
</tbody>
</table>

Abbreviations: Δ = change, USG = urine specific gravity, mHTT = modified heat tolerance test, km/h = kilometers per hour, HR = heart rate, bpm = beats per minute, TR = rectal temperature.
Table 9. Field Testing Physiological Data

<table>
<thead>
<tr>
<th></th>
<th>Overall</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δ USG</td>
<td>-0.002 ± 0.015</td>
<td>0.000 ± 0.019</td>
<td>0.004 ± 0.019</td>
</tr>
<tr>
<td>Δ Urine Color</td>
<td>0 ± 2</td>
<td>0 ± 1</td>
<td>0 ± 2</td>
</tr>
<tr>
<td>% Body Mass Loss</td>
<td>1.87 ± 0.95</td>
<td>2.02 ± 0.85</td>
<td>1.64 ± 1.08</td>
</tr>
<tr>
<td>Average Race Pace (km/h)</td>
<td>14.8 ± 3.0</td>
<td>14.6 ± 3.7</td>
<td>15.1 ± 1.7</td>
</tr>
<tr>
<td>HR Baseline (bpm)</td>
<td>81 ± 13</td>
<td>78 ± 13</td>
<td>86 ± 12</td>
</tr>
<tr>
<td>HR Peak (bpm)</td>
<td>177 ± 13</td>
<td>174 ± 14</td>
<td>182 ± 10</td>
</tr>
<tr>
<td>T&lt;sub&gt;GI&lt;/sub&gt; Baseline (°C)</td>
<td>37.13 ± 0.53</td>
<td>37.01 ± 0.57</td>
<td>37.30 ± 0.45</td>
</tr>
<tr>
<td>T&lt;sub&gt;GI&lt;/sub&gt; Peak (°C)</td>
<td>39.54 ± 0.88</td>
<td>39.47 ± 1.03</td>
<td>39.63 ± 0.65</td>
</tr>
</tbody>
</table>

Abbreviations: Δ = change, USG = urine specific gravity, km/h = kilometers per hour, HR = heart rate, bpm = beats per minute, T<sub>GI</sub> = rectal temperature.

Table 10. Independent T-Test Statistical Analyses

<table>
<thead>
<tr>
<th></th>
<th>Male Mean ± SD</th>
<th>Female Mean ± SD</th>
<th>95 % CI of the Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (cm)*</td>
<td>179.2 ± 8.5</td>
<td>168.4 ± 6.0</td>
<td>5.271</td>
</tr>
<tr>
<td>Body Mass (kg)*</td>
<td>80.9 ± 12.7</td>
<td>63.8 ± 7.1</td>
<td>9.184</td>
</tr>
<tr>
<td>Body Surface Area (m&lt;sup&gt;2&lt;/sup&gt;)*</td>
<td>2.0 ± 0.2</td>
<td>1.3 ± 0.1</td>
<td>0.153</td>
</tr>
<tr>
<td>Body Mass Index*</td>
<td>25 ± 3</td>
<td>22 ± 2</td>
<td>0.664</td>
</tr>
<tr>
<td>Lab vVO&lt;sub&gt;2&lt;/sub&gt;max (km/h)*</td>
<td>14.1 ± 1.7</td>
<td>12.8 ± 1.2</td>
<td>0.106</td>
</tr>
<tr>
<td>Δ T&lt;sub&gt;R&lt;/sub&gt; Lab (°C)*</td>
<td>1.55 ± 0.42</td>
<td>1.22 ± 0.50</td>
<td>0.102</td>
</tr>
<tr>
<td>Δ USG Lab*</td>
<td>0.006 ± 0.006</td>
<td>0.012 ± 0.005</td>
<td>-0.005</td>
</tr>
<tr>
<td>Sweat Rate (L/h)*</td>
<td>1.49 ± 0.36</td>
<td>0.90 ± 0.15</td>
<td>0.376</td>
</tr>
</tbody>
</table>

Abbreviations: SD = standard deviation, CI = confidence interval, vVO<sub>2</sub>max = velocity at maximal oxygen consumption, km/h = kilometers per hour, Δ = change, T<sub>R</sub> = rectal temperature, USG = urine specific gravity, L/h = liters per hour. * Significant differences at p<0.05.
Table 11. Paired T-Test Statistical Analyses

<table>
<thead>
<tr>
<th>Factor</th>
<th>Laboratory (mHTT)</th>
<th>Field (Race)</th>
<th>95 % CI of the Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (km/h)*</td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td>Lower</td>
</tr>
<tr>
<td></td>
<td>7.9 ± 1.8</td>
<td>11.2 ± 1.5</td>
<td>1.634</td>
</tr>
<tr>
<td>Average Rate of Rise in Temperature (°C per minute)*</td>
<td>0.02 ± 0.01</td>
<td>0.04 ± 0.02</td>
<td>-0.023</td>
</tr>
<tr>
<td>% Difference Temperature (TR or TG)</td>
<td>3.6 ± 1.3</td>
<td>6.0 ± 2.7</td>
<td>-3.444</td>
</tr>
</tbody>
</table>

Abbreviations: mHTT = modified heat tolerance test, CI = confidence interval, SD = standard deviation, km/h = kilometers per hour, TR = rectal temperature, TG = gastrointestinal temperature. * Significant differences at p<0.05.

Table 12. Correlation Statistical Analyses

<table>
<thead>
<tr>
<th>Factor</th>
<th>Mean ± SD</th>
<th>r</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δ TR Lab</td>
<td>1.4 ± 0.50</td>
<td>0.505</td>
<td>0.003*</td>
</tr>
<tr>
<td>Lab %BML</td>
<td>1.9 ± 0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δ TG Field</td>
<td>2.31 ± 1.03</td>
<td>0.504</td>
<td>0.004*</td>
</tr>
<tr>
<td>Field %BML</td>
<td>1.9 ± 0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lab %BML</td>
<td>1.9 ± 0.6</td>
<td>0.397</td>
<td>0.024*</td>
</tr>
<tr>
<td>Field %BML</td>
<td>1.9 ± 0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VO2max</td>
<td>40.45 ± 6.81</td>
<td>-0.439</td>
<td>0.015*</td>
</tr>
<tr>
<td>Finish Time Field (Minutes)</td>
<td>64.18 ± 12.92</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: SD = standard deviation, Δ = change, TR = rectal temperature, %BML = percent body mass loss, TG = gastrointestinal temperature, VO2max = maximal oxygen consumption. * Significant correlation at p<0.05.

Table 13. Linear Regression Statistical Analyses

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Independent Variable</th>
<th>df</th>
<th>F</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δ TR Lab</td>
<td>Lab %BML</td>
<td>(1,30)</td>
<td>10.255</td>
<td>0.255</td>
</tr>
<tr>
<td></td>
<td>Lab %BML, Lab Peak HR</td>
<td>(2,29)</td>
<td>13.198</td>
<td>0.476</td>
</tr>
<tr>
<td>Δ TG Field</td>
<td>Field %BML</td>
<td>(1,29)</td>
<td>9.890</td>
<td>0.254</td>
</tr>
</tbody>
</table>

Abbreviations: df = degrees of freedom, TR = rectal temperature, TG = gastrointestinal temperature, %BML = percent body mass loss, HR = heart rate.
Table 14. Characteristics of Subjects A, B, C, & D

<table>
<thead>
<tr>
<th></th>
<th>Subject A</th>
<th>Subject B</th>
<th>Subject C</th>
<th>Subject D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motivation (Classified by SMS-28)</td>
<td>Internal</td>
<td>Internal</td>
<td>Internal</td>
<td>Internal</td>
</tr>
<tr>
<td>VO₂max</td>
<td>Excellent</td>
<td>Excellent</td>
<td>N/A</td>
<td>Superior</td>
</tr>
<tr>
<td>Activity Level</td>
<td>Vigorous</td>
<td>Vigorous</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Number of Races Completed in the Last Year</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Hours of Training per Week</td>
<td>5</td>
<td>9</td>
<td>4</td>
<td>2.5</td>
</tr>
<tr>
<td>Type of Training</td>
<td>Running (90%) Cross Training (10%)</td>
<td>Running (80%) Cross Training (10%)</td>
<td>Running (90%) Strength Training (10%)</td>
<td>Running (100%)</td>
</tr>
<tr>
<td>Sweat Rate (Laboratory)</td>
<td>0.90 L/h</td>
<td>1.04 L/h</td>
<td>0.84 L/h</td>
<td>1.34 L/h</td>
</tr>
<tr>
<td>Laboratory Speed</td>
<td>7.2 km/h</td>
<td>7.3 km/h</td>
<td>7.7 km/h</td>
<td>8.7 km/h</td>
</tr>
<tr>
<td>Average Field Speed</td>
<td>8.6 km/h</td>
<td>9.2 km/h</td>
<td>11.5 km/h</td>
<td>10.8 km/h</td>
</tr>
<tr>
<td>Predicted Race Finish Time</td>
<td>63 minutes</td>
<td>74 minutes</td>
<td>60 minutes</td>
<td>58 minutes</td>
</tr>
<tr>
<td>Race Finish Time</td>
<td>80 minutes</td>
<td>75 minutes</td>
<td>60 minutes</td>
<td>64 minutes</td>
</tr>
<tr>
<td>Lab Temperature Rise</td>
<td>0.61°C</td>
<td>1.53°C</td>
<td>1.63°C</td>
<td>2.24°C</td>
</tr>
<tr>
<td>Field Temperature Rise</td>
<td>1.98°C</td>
<td>2.25°C</td>
<td>2.09°C</td>
<td>2.67°C</td>
</tr>
<tr>
<td>Lab Temperature Average Rate of Rise</td>
<td>0.015°C</td>
<td>0.026°C</td>
<td>0.027°C</td>
<td>0.037°C</td>
</tr>
<tr>
<td>Field Temperature Average Rate of Rise</td>
<td>0.025°C</td>
<td>0.03°C</td>
<td>0.035°C</td>
<td>0.042°C</td>
</tr>
</tbody>
</table>

Abbreviations: SMS-28 = sport motivation scale, VO₂max = maximal oxygen consumption, N/A = not applicable, km/h = kilometers per hour, L/h = liters per hour.
Figure 1.

**DATA COLLECTION**
- $T_R$: every 2.5 minutes
- HR: every 2.5 minutes
- WBGT, Air Temperature, Humidity: every 15 minutes

**Pre Measurements**
- Urine Sample
- Height
- Resting Blood Pressure
- Body Composition
- $V_{O_2}\max$ Test
- Nude Body Mass

**mHTT**
- 60% of VO$_2\max$ at a 2.0% incline
- 27°C and 50% humidity

**Stopping Criteria:**
- Reaching 7.1 miles
- Volitional fatigue
- $T_R \geq 39.99°C$
- Signs and symptoms such as: angina, shortness of breath, wheezing, lightheadedness, nausea, confusion, ataxia, pallor, cyanosis

**Post Measurements**
- Nude Body Mass
- Urine Sample
- Sweat Rate Calculation

Figure 2.

**Dietary Intake Logs:**
- Food, beverages, medications
- Type, amount, brand name
- Method of food preparation
- Calories

Avoidance of alcoholic beverages

3 Days Prior

**Timeline of Participant Self-Recorded Data and Requirements**

- 3 Days Prior
- 4 Weeks Prior
- Race Day

**TRAINING LOGS**

**Wahoo Fitness Application:**
- Outdoor workouts
- Time of day
- Duration
- Distance
- Location
- Weather conditions

**Workout Log:**
- Indoor workouts
- Workout type
- Duration
- Speed
- Distance
- Intensity

**Pre-race diet log**
Falmouth Road Race

MORNING DATA COLLECTION
(2-3 hours prior to race start)
- Urine Sample
- Body mass with minimal clothing
- GI temperature

POST-RACE DATA COLLECTION
(Immediately after crossing the finish line)
- GI temperature*
- Body mass with minimal clothing
- Urine Sample
Figure A1.

Figure A2.
Figure A3.

![Subject A Lab Temperature Graph](image)

Temperature (°C)

Time (Minutes)

Figure A4.

![Subject A Temperature at Final 20 Minutes of Exercise Graph](image)

Temperature (°C)

Time (Minutes)

$T_{Gi}$ Slope: -0.0024

$T_{R}$ Slope: 0.0125
Figure B1.

SUBJECT B

Figure B2.

SUBJECT B FIELD TEMPERATURE

- Greatest Rate of Rise
- Up to 39.5°C
- 39.5°C
Figure B3.

SUBJECT B LAB TEMPERATURE

Figure B4.

SUBJECT B TEMPERATURE AT FINAL 20 MINUTES OF EXERCISE

Lab $T_R$

Field $T_{gi}$

$T_R$ Slope: 0.0149

$T_{gi}$ Slope: 0.0107

$-39.5^\circ C$
Figure C1.

**SUBJECT C**

![Graph showing heart rate and temperature over time](image)

- Red dots: HR Lab
- Blue dots: HR Field
- Yellow line: Temp Lab
- Green line: Temp Field

Figure C2.

**SUBJECT C FIELD TEMPERATURE**

![Graph showing field temperature over time](image)

- Blue triangles: Greatest Rate of Rise
- Green squares: Up to 39.5°C
- Black dots: >39.5°C
- Red line: 39.5°C
Figure C3.

![Subject C Lab Temperature Graph](image1)

Figure C4.

![Subject C Temperature at Final 20 Minutes of Exercise Graph](image2)

- TGI Slope: 0.018
- TR Slope: 0.0102
- Lab TR
- Field TGI
- 39.5°C
Figure D1.

SUBJECT D

Figure D2.

SUBJECT D FIELD TEMPERATURE

Greatest Rate of Rise
Up to 39.5°C
>39.5°C
≤39.5°C
Figure D3.

SUBJECT D LAB TEMPERATURE

0 2 4 6 8 10 12 14 16 18 20
TEMPERATURE (°C)
TIME (MINUTES)

SUBJECT D TEMPERATURE AT FINAL 20 MINUTES OF EXERCISE

Figure D4.

SUBJECT D TEMPERATURE AT FINAL 20 MINUTES OF EXERCISE
REFERENCES


