Predicting responses to a heat acclimation protocol in trained triathletes.

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Abstract

Chapter One reviews the differences between performing in temperate and hot and humid environments. When compared to performance in temperate environments, heat-stressful environments acutely alter physiology heart rate, sweat rate, both core and skin temperature, plasma volume and local blood flow. Heat acclimation (HA) protocol introduced prior to competition in varying ways specific to the competition type has been shown to have large impacts on eventual performance, often summarised through heat response tests (HRT) or adaptations of thermoregulatory physiology. Individual responses to HA have been proven to vary between individuals with little evidence presented to explain why such variation occurs.

In Chapter Two, 10 endurance-trained competitive triathletes (aged 33.6 ± 10.6 years, 8 males and 2 females; VO_2 max 56.9 ± 11.1) completed a 14-day, cycling-based HA protocol (36 °C, 65% relative humidity). Participants completed two HRTs (Day 1 & Day 13), composed of 20 minutes at a steady state intensity immediately followed by a 30-kilometer time trial. Between these HRTs were seven HA sessions. Performance in the 30-kilometer time trial significantly increased as a result of the HA protocol ($p = 0.037$). Two regression models for predicting performance outcomes were generated using stepwise regression analysis. A 'best overall fit' model using baseline VO_2, sweat loss, and sweat sodium composition explains 53% of the variability of performance improvement ($R^2 = 0.53$), and a 'best practical fit' model using baseline VO_2 and sweat loss explains 49% of the variability of performance improvement ($R^2 = 0.49$). Both models are statistically significant ($p = 0.017$; $p = 0.023$). The 'best practical fit' model interprets that those with low baseline VO_2 but greater sweat loss in the first HRT demonstrated the best performance improvement, whereas those with high baseline VO_2 and low sweat loss do not see much performance improvement.

Chapter Three investigates the validity of the Kenzen™ wearable core temperature sensor. Ten participants engaged in two HRTs each (20 minutes at a steady state intensity immediately followed by a 30-kilometer time trial) whilst wearing a Kenzen™ device and a rectally inserted thermometer. Bland-Altman plots were used in conjunction with a direct comparison of the differences of the measures to determine validity. The Kenzen™ device is accurate between the range of 37-38 °C, but once core temperature measured rectally

reaches 38.5 °C, the validity of the Kenzen™ device comes into question (when rectal temperature ≥ 39 °C, mean difference = 0.79 °C). The difference in measurements suggests that the Kenzen™ is not valid once moderate hyperthermia is reached (38.5 °C).

Chapter Four presents a summary of the previous chapters. There is evidence to suggest that predicting variation in HA success is possible, potentially even more so with some refinement of the model through additional thermoregulatory measurement or protocol modification. The validity of wearable core temperature technology does not currently appear suitable in high-performance athletic environments where athletes are expected to reach core temperatures defined as hyperthermic, as most wearable sensors do not seem valid compared to gold standard measures. It is likely that the technology will advance as the popularity of such wearables increases.

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Thesis Overview

The purpose of this Thesis was to establish if it is possible to somewhat predict success of a 14-day heat acclimation protocol from a single heat response test in endurance-trained triathletes. This Thesis is comprised of four chapters. Chapter One reviews the literature regarding performance in hot thermally challenging environments and how this can be mitigated by heat acclimation. Chapter One also investigates individual differences in response to heat acclimation protocol and finishes with a research statement. Chapter Two details an experimental study in which the main aim was to create a model for predicting heat acclimation from data collected during a single heat response test exposure. Chapter Three is a validity study focusing on two core temperature recording devices, the wearable Kenzen™ and a rectal thermometer. Chapter Four summarises key findings of the previous three chapters, and presents some strengths, limitations, and future research directions of this Thesis.

Chapter One - Literature Review

Heat performance

The ability to perform in different conditions is crucial for athletes of many sports across ability levels, especially when competing requires travelling globally to countries where high temperatures and humidity conditions are expected. There is a temperature range for best performance in endurance events that are raced from 10-minutes to multi-day, and although it can vary individually and between exact disciplines of sports (cycling in a cycle race or cycling in a triathlon when wet from the swim), observational studies have found that a temperature of approximately 6-14 degrees Celsius, (or 5-10 degrees Wetbulb Globe Temperature (WBGT)) leads to faster race times (Ely et al., 2007; Galloway & Maughan, 1997; Tatterson et al., 2000). However, the reality is that most sports do not have major competitions within this temperature range. For example, the Summer Olympics, FIFA World Cup and dozens of other major world sporting events happen in the summer months. As sports become increasingly focused on the fan experience, the climate at these tournaments is only getting warmer, as exampled by the Tokyo Olympics in 2020 and the FIFA football World Cup 2022 in Qatar.

As the air temperature and WBGT increase, performance significantly decreases in aerobic-based sports (Drust et al., 2005; Ely et al., 2007; Galloway & Maughan, 1997; Tatterson et al., 2000). Managing performance expectations in competition is crucial to avoid overreaching in extreme heat, but there are also ways to manipulate physiology before a competition to become more efficient at managing environmental heat stress and resultant endogenous heat stress. Implementing a heat acclimation (HA) protocol in the weeks before competing in unfamiliarly hot or humid environments can improve the body's ability to perform closer to that expected in colder or dryer conditions (Racinais et al., 2015). Typically, HA comprises repeated artificial exposure to large heat stress for a period of 5-14 days prior to competing at a higher-than-normal temperature (Pryor et al., 2019; Pryor et al., 2021). During the HA process, several physiological systems are stressed to stimulate adaptation and increase efficiency at using, generating, or removing heat from within the body.

Research can attempt to quantify increases in performance due to HA protocols when there is a measure of performance, such as time trials or time-to-exhaustion tests. Whilst it is common to quantify the individual physiological component changes (such as heart rate or core temperature), or perhaps a statement summarising more macro-level change such as “whole-body evaporative heat loss increased by approximately 11% after 14 d of dry heat acclimation” (Poirier et al., 2015, p. 399), it is more relevant to practitioners and athletes to quantify how the physiological adaptations are manifested as performance changes.

It is important to be able to quantify performance changes through the means of outcome change or physiological change, even if the exact numbers can be somewhat trivial due to individual differences that are often seen (Racinais et al. (2021) found differences between individuals of up to 30% in end-acclimation mean power). Obtaining results of performance change that are applicable to the performance is also important, so developing and implementing the method of testing to best mimic the demands of the sport has led to dozens of testing methods. Meta-analyses have become useful for collecting information relevant for quantifying performance changes in all styles of performance tests, even if the multitude of testing styles makes direct comparison difficult. Benjamin et al. (2019) divided types of tests into five categories (VO$_2$ max, time to exhaustion, time trials, mean power, and peak power) and found the evidence supports a very large increase in time to exhaustion after completing HA protocol, especially in fitter athletes, as demonstrated by Nielsen et al. (1993). Tyler et al. (2016) concluded in their meta-analysis that on average, increases of 23% are found in time-to-exhaustion tests after HA protocols. It is worth noting that whilst time-to-exhaustion tests are excellent testing methods for inducing maximal capacity, they are not the most specific to real-world performance. Aerobic sports are based on the concept of completing set distances in the fastest time possible, not lasting the longest at a set intensity. That said, performance tests most applicable to aerobic competition are time trials or distance covered measures, which are also very effectively and positively changed through the implementation of HA protocol. A 33% increase in running distance in team sport athletes for a given time was found by Sunderland et al. (2008), with positive effects also observed similarly in elite rowers (1.5%) and sub-elite cyclists (5-7%) (Garrett et al., 2012; Lee et al., 2016; Lorenzo et al., 2010).

Physiology

Why does temperature increase matter? What happens?

Aerobic performance is dictated by the ability to remove or recycle waste products of muscular oxidation to maintain homeostatic conditions for optimal cellular function. As, the efficiency of transferring metabolic energy to mechanical work is about 20-30%, most of the waste energy that alters homeostatic conditions is heat (Whipp & Wasserman, 1969). Exceeding internal homeostatic temperature restricts the speed of muscle oxidation and the systems that remove its waste products.

Physiology of thermoregulation

Heat loss is performed by relocating excess heat from the active muscles to the periphery through temperature gradients. Skin temperature is colder than core and muscle temperature in most environments, so the temperature gradients move the heat towards the skin through increased blood flow, whereby using a combination of mostly radiation, convection, and evaporation, the excess heat is removed (Ravanelli et al., 2019). Convection and radiation are similar in their function, removing heat from the peripheral blood through the temperature gradient present at the skin. Increasing the blood flow to the skin allows for greater heat radiation and convection to enable heat dissipation.

When skin blood flow increases, the vasodilation of the peripheral arterioles that allow for increased flow also activate neural receptors and pathways, promoting sweat glands to increase sweat production, and thus increase evaporative cooling through evaporation (Flouris, 2019). These two crucial thermoregulatory methods (convection/radiation and sweating) are the primary defence against heat stress, but each has its own physiological side-effects that can affect the efficiency of aerobic work. Lastly, sweat loss induces plasma volume loss, reducing total blood volume acutely which further increases the cardiovascular load required to maintain sufficient blood pressure.

Thermoregulatory responses

As sweat rate increases, the loss of water and electrolytes lost in sweat increases. This is normally expressed as generally as plasma volume or total body water. Acute plasma volume reductions alter the efficiency and capacity of a large range of cellular functions in the chain of creating mechanical work (Meyer et al., 2015). As aerobic exercise progresses through warm conditions, water and electrolyte levels drop through increased sweat rates. Without adequate replenishment through hydration and nutrition protocols, endurance exercise performance will be negatively affected due to the strain placed on aerobic metabolism processes (Meyer et al., 2015).

A second consequence of increased thermoregulatory load, and harder to control acutely, is the increase in skin blood flow. Blood is finite, so increasing flow to one area of the body decreases flow to others, importantly skeletal muscle. Heat stress induced vasodilation, increases the flow to the skin, and takes priority over the flow to the muscle (Flouris, 2019). When the blood flow to a muscle is decreased, regardless of how efficient the local cells are at metabolising, the mechanical work output will decrease (González-Alonso & Calbet, 2003; Périard et al., 2011). As local temperatures increase, the blood supply restraints continue to increase. To maintain the mechanical work output, cardiac output must increase, causing increased metabolic stress for the same work intensity (Nielsen, 1966).

Performance changes

The earlier discussed performance reductions in environments with extreme heat or humidity are directly related to the explained skin blood flow and sweat rate (Périard et al., 2011; Sawka et al., 2011). Increased skin blood flow results in increased heart rate for the same work output, this directly correlates to a slower running/cycling/walking speed for a given heart rate in heat stressful conditions than ideal conditions (Nielsen, 1966). Given that each athlete has a maximal sustainable heart rate or total metabolic work rate for a given distance or time regardless of the environment, when less metabolic work potential is available for mechanical output, performance must decrease to be sustainable (Tyka et al., 2009). Thus, environmental thermoregulatory challenges essentially acutely lower an individual's VO_2max relative to the size of the environmental stress (Galloway & Maughan, 1997). For increasingly longer aerobic races such as marathons and ironman races, keeping a steady state and replacing fuel is crucial. Increased metabolic work for a given measurable output (Watts, km/h, or min/km) changes the substrate metabolism and electrolyte loss through sweat relative to ideal conditions (Kirwan et al., 1987). In high heat stress environments, the optimal fat utilisation work rate will be lowered and athletes are required to rely more on finite carbohydrate stores sustain high work outputs (Febbraio et al., 1994). This output incurs more electrolyte loss through sweat, resulting in appropriate nutrition requirements to sustain the output, requirements which are likely to be in themselves, unsustainable.

Knowing what induces sweating and electrolyte loss during performance is key to adequately supplementing. Due to the increased external temperature, decreased thermal gradients are seen which makes SBF less effective than in cooler climate (Johnson, 2010). This is somewhat balanced by an acute change in reduction in the internal temperature threshold to increase skin blood flow, but there is still an increased risk of heat production exceeding the rate of heat elimination (Johnson, 2010). The reduction in cooling capacity is attenuated when conditions are humid. In environments with large exogenous humidity, the evaporate power of sweat is influenced by the decreased power of the gradient between wet skin and air (Taylor, 2014). In purely humid environments, the compromised cooling capacity of sweating can be somewhat accounted for by convection/radiation. Of note also is when air temperature is approximate to or greater than skin temperature, convection and radiation are similarly compromised. The result is in hot and humid environments, the two most powerful thermoregulatory systems become significantly inhibited. Naturally, this thermoregulatory challenge has flow on consequences for performance in environments where both extreme heat and humidity are present.

Mechanisms of HA

How do you HA?

HA is not a simple, one-size-fits-all training protocol. Any number of factors can be manipulated to best suit the training goals, or to be most practical or achievable for the individual. Most important of these factors would be the temperature and humidity of the environment, but the intensity and duration of each session, time course of repeated exposures, frequency of exposures, use of passive exposure such as spas and hydration levels are all contributing factors that can be manipulated (Casadio et al., 2017).

Temperature

Temperature and humidity can be manipulated individually to optimise physiological responses. If there is a specific environment that an athlete is training for (e.g., Tokyo in August), then training in a similar environment is recommended. Living and training in a similar environment to that of the eventual competition for the weeks preceding is regarded as acclimatising, however due to many logistical reasons this is often not feasible for most athletes. Depending on the training adaptations desired, acutely exposing athletes to artificial environments with different balances of temperature and humidity can be manipulated for tailored physiological outcomes. Dry heat that combines high temperatures with low relative humidity e.g. Lee et al. (2016) who used 40 °C at 25% relative humidity or Chinevere et al. (2008) who used 40 °C at 20% relative humidity induces physiological adaptation relevant to the dry environment. These are notably the significant plasma volume increase ($p < 0.01$) and haemoglobin decrease ($p < 0.05$) seen by Lee et al. (2016), and the increased sweat rate and decreased sweat sodium concentration ($p < 0.05$) found in Chinevere et al. (2008). Sweat rate and sweat composition are trainable (Poirier et al., 2015), and increasingly important for athletes competing in types of sport where supplementation is key, think marathons and long-distance triathlon.

In contrast, hot and humid environments for HA characterised by lower temperatures (30-35 °C) and higher relative humidity (40-50%) e.g.,(Osborne et al., 2021; Reeve et al., 2019; Tebeck et al., 2020; Zurawlew et al., 2018). Hot and humid conditions reduce the power of sweat to remove excess heat, restricting the capability of total heat loss. What is seen instead in the adaptations is generally increased aerobic training effect, and acutely higher VO_2 max, heart rate and reduced gross efficiency for the same sessions, as well as increased perceived strain (Reeve et al., 2019; Tebeck et al., 2020). More extreme environmental conditions, towards 40 °C and 60% humidity, are not often seen, especially simultaneously due to the potentially extreme heat stress they can cause (Coris et al., 2004; Mee et al., 2015).

Environmental differences are important due to cardiovascular and thermoregulatory changes induced by each type of environment. Plasma volume expansion and reduced heart rate are both seen similarly between hot and humid conditions (Chalmers et al., 2014; Griefahn, 1997; Sunderland et al., 2008). By contrast, sweat rate, blood distribution and convective heat loss are among physiological changes that acclimate differently between hot and humid (Drust et al., 2005; Griefahn, 1997; Tebeck et al., 2020). This does not mean that sweating is redundant in humid conditions, or that convective heat loss is redundant in hot conditions, rather that there exists a continuum that the two systems balance upon, each being stimulated to varying degrees depending on the environmental conditions.

Work rate

Work rate and duration of work rate are widely variable between HA protocols. Like environmental manipulation, duration, and intensity of work within an HA protocol are determined by the outcome desired. Higher intensities (> 50% VO_2 peak) for shorter periods (30-40 min) (Booth et al., 2004), or high-intensity intervals alternating work rates (Fenemor, 2022; Kirby et al., 2021; Reeve et al., 2019; Wingfield et al., 2016) are most specific to sports with anaerobic aspects such as team sports or middle distance running (Wingfield et al., 2016). Lower work rates (40-50% of VO_2 peak) for longer durations (> 1 hour) are more common in research regarding aerobic performance and is mostly applied for the training of aerobic athletes (Lee et al., 2016; Osborne et al., 2021; Wingfield et al., 2016). Lower intensities have also been used to find the greatest performance improvements in post-HA tests (Guy et al., 2015; Wingfield et al., 2016). Measured time trials designed to finish close to exhaustion can be used within HA protocol (Lee et al., 2016), although these are mostly limited to heat response testing pre-and-post HA protocol (Benjamin et al., 2019).

In terms of measuring work rate during the protocol to ensure that individuals are working at a rate that is adequate to induce thermoregulatory adaptations, live measuring and managing of core temperature, known as controlled hyperthermia has become widely used (Garrett et al., 2012; James et al., 2018; Kirby et al., 2019; Sekiguchi et al., 2021). It has also been accepted as likely a complete and more effective stimulus for successful HA (Périard et al., 2015). Controlled hyperthermia over 5 consecutive days in 90-minute sessions has been found by Garrett et al. (2012) to increase total work output over a 2 kilometre rowing time trial. James et al. (2018) found performance in male runners was largely and significantly increased (6.6%, *p* = 0.004) following five days of controlled hyperthermia sessions. (Kirby et al., 2021)found that in female cyclists, large and significant changes due to controlled hyperthermia were also large and significant (3.2%, *p* = 0.04), following nine days of acclimation. Even after extended periods of acclimatisation, Sekiguchi et al. (2021) noted that a 60 minute daily, hyperthermic controlled acclimation period of five days could further decrease 4km run time.

Long-term HA versus short-term HA

Long-term HA (LTHA; >14 days) is often not always practical or necessary to establish most adaptations (Périard et al., 2015; Poirier et al., 2015). Rather, short-term HA (STHA; 5-7 days) may be sufficient and has been found to elicit significant performance and/or physiological changes (Lorenzo et al., 2010; Poirier et al., 2015; Pryor et al., 2021; Tebeck et al., 2020). STHA protocol is typically recommended to involve higher exercise intensities than LTHA protocol (Pryor et al., 2021) to sufficiently stress homeostatic relationships, but this may also be counter-productive if another training stimulus is compounding additional stress (Reeve et al., 2019). Thermoregulatory adaptations can struggle to respond in shorter periods, so this must also be considered when designing protocol (Guy et al., 2015; Pryor et al., 2021). Specifically, plasma volume and a lower heart rate for an absolute, sub-maximal work rate are found to adapt to heat stress quickly (within a few days), whilst others such as sweat rate and sweat composition can take up to 2 weeks to adapt fully (Garrett et al., 2012; Kirby et al., 2019; Poirier et al., 2015; Pryor et al., 2021). The longest time-to-adaptation of applicable physiological markers of heat performance is likely haemoglobin count and other red blood cell adaptations, although they may not have the greatest effect on end performance outcomes (Oberholzer et al., 2019; Rønnestad et al., 2021). STHA may be more practical and provide sufficient adaptations, but LTHA ensures the greatest chance of optimal adaptations and if possible, is still likely the best HA length (Tyler et al., 2016).

Intermittent HA exposure

The frequency of HA exposures can vary from twice daily (Willmott et al., 2018) to once a week (Benjamin et al., 2022). The frequency of exposures is increased to somewhat increase the speed of some physiological responses, although not all responses will be positively affected by increasing beyond once daily (Willmott et al., 2018). An intermittent protocol can be effective at inducing the same physiological changes over an equal time course (Gill & Sleivert, 2001; Sunderland et al., 2008); however, the magnitude of these changes are not guaranteed to be as significant (Gill & Sleivert, 2001). The relevance of intermittent HA protocol is fitting around other training requirements or maintaining HA adaptations through a period where frequent exposure is not possible. Intermittent protocol (1-2 exposures a week) can also be used to limit the decay of changes after the completion of a protocol (Pryor et al., 2019).

Passive heat exposure

Passive heat exposure such as spas and saunas provide alternatives to the active exposures previously discussed. For example, hot-water immersion (HWI) post-temperate exercise can be used as a substitute for exercising in the heat and was found to induce a ~5% self-paced treadmill time trial reduction in 33 °C (but not 18 °C) after just 6 days (Zurawlew et al., 2016). However, on further examination, this may be limited to the recreationally active and not trained, as the stimulus may be too low for endurance-trained (Zurawlew et al., 2018). Using HWI as a pre-temperate training stimulus is also a potential method for HA, however, this has been explored less as a potential avenue for HA (Booth et al., 2004). Using saunas for temperate exercise performance can also be successful (Bartolomé et al., 2021; Kirby et al., 2021), but most research fails to quantify improvements in hot or humid environments. Rather they quantify physiological changes, which, whilst significant (Kissling et al., 2022), only provide a partial description of performance. Despite the magnitude of heat stress experienced in spa and sauna exposures being large, it is likely that spa or sauna alone is not as stimulating as exercising in the heat (Kissling et al., 2022).

Other methods

Dehydration is very difficult to prevent when exercising in the heat (Stand, 1996), and can provide a further stimulus for adaptation (Garrett et al., 2014); however, it also impairs performance acutely (Merry et al., 2010). Garrett et al. (2014) found that some functional adaptations such as fluid retention through aldosterone control were improved through permissively dehydrated HA protocol. Restrictive clothing attenuates physiological strain in a similar fashion to dehydration, providing another stimulus for heat stress added to the environment. As Willmott et al. (2018) describe, using restrictive clothing is potentially a more practical replacement for conventional HA in environmental chambers for those unable to access facilities capable of producing adequate environmental stimulus.

Decay

As with any physiological adaptations, all the cardiovascular and thermoregulatory changes brought about through HA protocol can be reversed with the removal of the stimulus that initiated them (Armstrong & Maresh, 1991). While the exact duration that some of the adaptations last are disputed between a few days and up to a month (Weller et al., 2007) the order in which they diminish is somewhat agreed upon. Garrett et al. (2011) summarised the order with data from Pandolf et al. (1977) and Saat et al. (2005) that heart rate and other cardiovascular adaptations are first to be lost, followed by the adaptations that took longer to occur, such as sweat rate (Daanen et al., 2018).

Who should use HA?

Everyone can benefit in some way from even the most basic of well-prescribed HA protocols. However, there are differences in how separate demographics respond and what types of individuals HA protocol provides performance-relevant adaptations for. Firstly, HA is only relevant to performing in environments where there is extreme heat and/or humidity.

Power athletes that rely on maximal power efforts such as sprinters, throwers and weightlifters gain little-to-no benefit from implementing HA protocols (Brazaitis & Skurvydas, 2010; Sunderland et al., 2008). This is due to thermoregulatory adaptations being irrelevant as the movement time does not require thermoregulation to perform to maximal capacity; the cardiovascular adaptations mostly regard increasing efficiency and capacity of the aerobic energy pathway under heat stress, which does not have the time to accrue over true maximal exercise (Chalmers et al., 2014). Other sports where the thermoregulatory power is significantly reduced such as swimming (due to wetsuits or warm water) have been found to benefit little from sport-specific HA (Bradford et al., 2015), and may benefit more from maintaining training at regular levels than attempting to integrate an HA protocol and alterations to regular training.

Females have been found to potentially acclimate differently through conventional exercise-based HA protocol (Mee et al., 2015). Comparing males to females following the same HA protocol, Mee et al. (2015) found that males acclimated better through STHA, with females lacking the magnitude of cardiovascular and thermoregulatory adaptations that males achieved, rather increasing mostly sudomotor activity. Results such as this have been seen in low-stress HA protocol for many years (Wyndham et al., 1965), but the research regarding athletes and high-intensity exercise is limited. Full LTHA protocols see similar physiological changes in cardiovascular and thermoregulatory measures are achieved between males and females, indicating that females may need to ensure either LTHA or at least less intermittent HA protocol to achieve the same level of performance change as males (Mee et al., 2015). Kirby et al. (2019) also found that females took at least 9 days to acclimate, and 4 days was not enough to HA sufficiently for any self-paced performance improvements to be seen.

Individual differences in HA success

Other than an in-depth exploration of the sex differences experienced in HA implementation, HA protocol has been widely investigated across a range of cohorts (military, fire-fighters, endurance sport) regarding measuring how differences in the protocol can induce varying levels of adaptations in all facets of relevant physiology. What has not been measured as such is the predictability of the changes for individuals (Kissling et al., 2022). Fitness, sex, previous exposure, and protocol design have all been investigated as contributing factors (Benjamin et al., 2019; Pandolf et al., 1977; Wickham et al., 2021), and genotypes and phenotypes outside of these spectra must also play a role. When increases or decreases in the mean adaptations are reported, individuals with no performance increase tend to be hidden behind pooled improvements. Few publications include individual statistics, but when individual statistics are published, responses are incredibly varied between individuals (Alkemade et al., 2021; Corbett et al., 2018; Kissling et al., 2022; Racinais et al., 2014; Racinais et al., 2012; Racinais et al., 2021; Reeve et al., 2019).

Racinais et al. (2012) in researching haematocrit in semi-professional football players found the largest performance decrement in the player with noted haemoconcentration after the end of 6 consecutive days in 38-43 °C at 12-30% humidity, whereas haemodilution was observed in the majority of players. This variability, a 15% distance covered decrement and 6% haemoconcentration, was irrespective of hydration status and other physiological markers, as well as position and the training differences. Kissling et al. (2022) through research into several modes of both passive and active HA found significant differences in individual plasma volume response through acclimating in heat in physically active participants (40 °C, 52% relative humidity). This variability aligns with individual differences in blood composition found by Racinais et al. (2012) across 2 different populations (semi-professional footballers and recreationally active) across both steady exercise protocol (cycling at 1.75 W/kg with core temperature clamped at + 1.5 °C), and intense team sport training.

The approach taken by Alkemade et al. (2021) was to determine if body mass, body surface area (BSA) and BSA-to-mass ratio had any effect on the best method of acclimation. What they discovered among trained males and females through ten days of thermal maintenance sessions on a cycle ergometer (~38.5 °C for 60 minutes), was those with large body dimensions (large body mass and BSA, low BSA-to-mass ratio) responded better to high sudomotor methods, while participants with a high end-exercise heart rate adaptation were typically small (small body mass and BSA) (Alkemade et al., 2021). On a more generalised level, Racinais et al. (2021) when comparing alternative training stimuli (heat, altitude & heat + altitude), found that heat as a training stimuli produced performance changes that varied between individuals by nearly 40% in a high intensity intermittent running test (Yo-Yo) and mean power output of repeated 10 second sprints on a cycle ergometer. Importantly, this variation does not appear to be any more significant than regular training methods or altitude training, that saw variation of performance changes between no change and 30%, but it does confirm that heat acclimation has responders and non-responders.

Reeve et al. (2019) used a short term, five-day heat acclimation procedure with trained cyclists and discovered a negative effect on performance when tested in the heat day later. They found that unlike previous research, the outliers where the individuals that had performance improvements. It is likely that the protocol design was not adequate to elicit enough thermoregulatory stress and therefore performance improvements, and the nature of the high intensity intervals (12x1 minute maximal, 1 minute easy) every day in a condensed period did not allow for adequate recovery. However, it does illustrate that again, there were still those that improved and those whose performance decreased, confirming the theory of responders and non-responders.

Only one previous paper has attempted to relate pre-HRT data to adaptive outcomes across an HA protocol. Corbett et al. (2018) through their testing of trained males determined mean skin temperature and mean body temperature, recorded rectally, could be linked to individual variance in subsequent temperature measures post the final HRT (60 minutes at 35% of maximal VO_2 test power). This was found in trained endurance athletes, who completed 11 daily HA sessions of 90 minutes cycling at a work rate to elicit mean core temperature of approximately 38.5 °C. Specifically, “the change in mean body temperature and change in mean skin temperature recorded in the pre-HA HRT was related to the reduction in end-exercise mean body temperature, and the reduction in the within HST change in rectal temperature and change in mean body temperature following the HA intervention” (Corbett et al., 2018, p. 6).

The current research presents only limited findings regarding the ability to determine what aspects of physiology have the capacity to predict the efficacy of an HA protocol. If there was a standard testing procedure that could identify an athlete's ability to respond successfully to an HA protocol, this would be a magnificent tool for coaches and organisations, and athletes themselves to correctly apply individualised HA protocols, thus allowing for specific needs to be met in their lead-in to an event where the heat stress is going to be a limiting factor.

Research statement

HA has been shown frequently to be a useful training method for athletes, especially in endurance sports, due to its efficacy in improving thermoregulatory processes and exercise performance. However, as with every training method, not every individual responds uniformly. With the need for HA protocols only increasing in sports worldwide, there will only be an increase in the requirements of exercise science professionals to prescribe safe and effective acclimation protocols. Triathlon is a sport that can benefit from HA greatly, due to the summer conditions normally required and thermoregulatory stress. The aim of the experiment was therefore to investigate the possibility of predicting the HA benefit in triathletes from a single heat exposure test.

Chapter Two - Experimental Study

Abstract

Introduction: Heat acclimation (HA) has become a well-researched, fundamental training tool for athletes preparing to compete in environments where the ambient temperature is significantly different to the environment in which the athlete regularly trains. Not every athlete responds equally to HA protocol, with noticeable non-responders seen frequently. This research attempts to form a model in which response to an HA protocol can be predicted from a single heat response test (HRT).

Methods: Ten triathlete participants (33.6 ± 10.6 years, 8 males and 2 females; VO_2 max 56.9 ± 11.1) completed a 14-day cycling-based HA protocol (36 °C, 50% relative humidity). Adaptation was determined by heat response tests (20-minute steady state followed by 30 km time trial) that were either side of seven HA sessions. Measures taken during HRT1 were used to attempt to retrospectively predict HRT2 performance.

Results: The HA protocol was successful in inducing performance improvements (74 seconds, $p = 0.037$). Of the other thermoregulatory markers, none were significantly changed due to the HA protocol. Stepwise regression analysis determined two models ('best overall fit & 'best practical fit') that account for approximately half of the variation in performance improvement ($R^2 = 0.53$ & $p = 0.017$; $R^2 = 0.49$ & $p = 0.023$). A combination of low baseline VO_2 max, large sweat loss and large sweat sodium concentration during HRT1 correlated with better performance improvements.

Conclusion: Performance can be moderately predicted by responses to an initial HRT. Measuring baseline VO_2 max prior to an HA protocol and recording sweat loss and sweat sodium during an initial heat response test can provide with 50% accuracy an indication of the potential performance improvements seen in an HA protocol in trained triathletes.

Introduction

The ability to perform in hot and humid conditions is an important consideration for athletes of many sports, especially when competing requires travelling globally to countries where ambient temperatures differ markedly from normal training conditions, such as the Summer Olympics, FIFA World Cup, and dozens of other major world sporting events that are scheduled in the summer months. The climate at these tournaments is only getting warmer, as exemplified by the Tokyo Olympics in 2020 and the FIFA football World Cup 2022 in Qatar. Observational studies have found that a temperature of approximately 6-14 degrees Celsius, (or 5-10 degrees WBGT) leads to the fastest race times, and as air temperatures and WBGT increase, performance significantly decreases in aerobic-based sports (Drust et al., 2005; Ely et al., 2007; Galloway & Maughan, 1997; Tatterson et al., 2000). Managing performance expectations in competition is crucial to avoid overreaching in environments with extreme conditions, but implementing an HA protocol in the weeks before competing in unfamiliarly hot or humid environments can improve the body's ability to perform closer to that expected in colder or dryer conditions (Racinais et al., 2015). Typically, HA comprises repeated artificial exposure to large heat prior to competing at a higher-than-normal temperature to induce adaptations in several physiological systems and increase efficiency at using, generating, or removing heat from within the body (Pryor et al., 2019; Pryor et al., 2021).

Aerobic performance is dictated by the rate of waste product removal, most significantly heat (Whipp & Wasserman, 1969). Heat loss, or thermoregulation, is the relocation of excess heat through temperature gradients and increased local blood flow between the core, skin, and environment to be removed using a combination of mostly radiation, convection, and evaporation (Ravanelli et al., 2019). Blood is finite, and under thermoregulatory stress increased skin vasodilation takes priority over the flow to the muscle (Flouris, 2019). Reduced blood flow to a muscle, regardless of how efficient the local cells are at metabolising, decreases mechanical work output (González-Alonso & Calbet, 2003; Périard et al., 2011). If the same work output is desired in such conditions, cardiac output must increase, increasing metabolic stress for the same work intensity (Nielsen, 1966). As exogenous temperature increases, especially when humid (high WBGT, (Taylor, 2014)) blood supply restraints are attenuated, but the thermoregulatory challenge due to loss of sweating efficiency restricts performance capacity further.

An HA protocol is not simple as the exogenous temperature, work rate, duration and frequency of exposure, and the type of exercise mode induce responses in varying magnitudes (Casadio et al., 2017). The intended outcome of the protocol determines the design, mostly regarding the thermoregulatory requirements of the performance environment and what adaptations need to be induced in the athlete. Thermoregulatory adaptations to a successful HA protocol are expansive, such as plasma volume expansion, heart rate reduction, skin and core temperature reductions, increased sweat rate and increased electrolyte conservation to name a few. It is well noted that not all thermoregulatory pathways adapt at the same rate, and neither do all individuals, with females noted to take slightly longer acclimating (Périard et al., 2015; Périard et al., 2016; Wickham et al., 2021).

What is less known is what causes individual variances often seen in end performance or thermoregulatory change after an HA protocol. Haemoconcentration, body surface area (BSA) and BSA-to-mass ratio, and initial changes in core temperature in the first exposure have been associated with individual variance in HA success (Alkemade et al., 2021; Corbett et al., 2018; Racinais et al., 2012), but no characteristic, physiological marker or initial response has been linked successfully on multiple occasions. The aim of this research is to link or predict an eventual HA performance change to a measured physiological marker taken before, during, or immediately after an initial HRT.

Methods

Participants

Participants were recruited through advertising on the local Triathlon Tauranga Facebook page. To be included, the participants were required to be 18-60 years old, healthy, endurance-trained triathletes or cyclists. Endurance-trained in our context was defined as engaging in deliberate exercise for at least 30 minutes, at least four times a week and being capable of maximal effort during exercise. Additionally, the participants were required to be able to cycle at a steady intensity for 7.5 hours a week over five separate sessions for two weeks consecutively, in order to complete the experimental protocol).

Participants were excluded if they had any injuries, medical conditions, or medications that prevented them from exercising for extended periods of time (up to 90 minutes), or at high intensities in a hot environment. Additional exclusion criteria included, taking any medications that alter heart performance or recent travel that included consistent exposure to a hot environment (for example holidaying in 30 °C temperatures), or regularly engaging in spa or sauna bathing (≥ 2 hours a week).

After initial expressions of interest, participants were sent an information sheet to decide whether they would participate. If they were interested, they were invited to begin with a no obligation maximal oxygen uptake (VO_2 max) test, a tour through the facility where the testing and HA protocol would be completed, and thoroughly talked through all the procedures. Once participants were satisfied and had an opportunity to ask any questions, consent forms were signed, and the protocol begun. Participants were ten endurance-trained triathlete volunteers (aged 33.6 ± 10.6 years, 8 males and 2 females; VO_2 max 56.9 ± 11.1) that had at least two years of competitive training.

Protocol

General

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	HRT	HA	X	HA	HA	X	HA
Week 2	HA	X	HA	HA	X	HRT	X

Figure 1: HA protocol.

The intermittent HA protocol is shown in Figure 1 and consisted of seven heat exposure book-ended by two heat response tests (HRT) over a 14-day period. The protocols were approved by the University of Waikato Human Ethics Committee (HREC(Health)2022#34). Written informed consent was required before the procedure began and was provided by all participants.

Participants completed ten sessions in total, one maximal VO_2 max test, followed within seven days by the beginning of the heat acclimation protocol. The data collected during the maximal VO_2 capacity test was used to calculate work rates for the nine sessions to be completed inside the environmental chamber (described below). Two types of sessions were completed inside the environmental chamber, the first and last being an HRT, separated by eleven days and seven HA sessions. Environmental conditions were 36 °C at 65% relative humidity (Wet-Bulb temperature = 30.3 °C).

Maximal oxygen uptake test (VO_2 max)

An Elite Suito interactive cycle trainer was used as the cycling ergometer, fitted with the participants own bicycle and the correct running equipment (10-speed/11-speed/12-speed). The training device was calibrated using the Elite eTraining application before each test according to manufacturer's instructions for accurate data collection. The process of the test was explained before participants were fitted with the Garmin HRM Pro (Garmin, Olathe, KS, USA) and Parvo Medics TrueOne 2400 gas analysis system (Parvo Medics Inc, Salt Lake City, UT, USA) to begin the test.

The VO_2max test protocol began at 100 W, and the controlled wattage was incremented by 20 W every 1 minute. Heart rate was logged every minute, two seconds before the point of wattage increase. Gas analysis was recorded breath-by-breath.

Heat response test (HRT)

Participants measured their nude weight before, then self-fitted the rectal thermometer (U thermistor, Grant Instruments Ltd., Cambridge, United Kingdom) and Kenzen™ (Kenzen, Silicon Valley, CA, USA). The rectal thermometer was connected to the data logger (Squirrel 2020 series data logger, Grant Instruments Ltd., Cambridge, United Kingdom), and the Kenzen™ device was connected to the mobile application. Ten minutes of resting data were collected outside the environmental chamber, followed by the collection of blood for haemoglobin measurement (Hemo Control, EKF Diagnostics, Cardiff, Wales), and the fitting of a sweat patch (Tegaderm +Pad, 3M, Saint Paul, MN, USA). Participants drinking vessels were filled and weighed. In the case of participants requiring replacement fluid during the test, the empty vessel was weighed, refilled, and subsequently weighed again before handing back to the participant in the chamber. Water consumption was not controlled, rather participants were instructed to drink to thirst. Participants then entered the climatic chamber to begin the test and fitted to a Wattbike Pro (Wattbike, Nottingham, United Kingdom). Once participants were fitted as they found comfortable, all measurements were recorded to ensure a standardised setup for each participant in each subsequent exposure.

The HRT comprised two parts, the first being a sub-maximal 20-minute effort at the heart rate corresponding to 45% of the calculated VO_2 max. After the 20-minute period, participants had three minutes rest to reset the Wattbike, before a 30 km time trial effort was completed. During this time trial, participants were blinded to most metrics normally available on the Wattbike display, only being able to see their total time and distance covered. A large industrial fan was located approximately two meters in front of the participant. Heart rate and core temperature were continuously measured throughout the HRT, but only core temperature was recorded, on both the Squirrel and Kenzen™ devices. Times were recorded at halfway (15 km) and at completion of the 30 km.

After the time trial, a five-minute rest period outside of the environmental chamber followed to track the recovery of heart rate and core temperature. The sweat patch was removed and frozen for later sweat composition analysis. At the completion of the five minutes, participants measured their nude weight again, and final water consumption was calculated to enable determination of sweat loss. Before the participants left the laboratory after HRT1 they were instructed to download the Kenzen™ application and were sent home with an assigned Kenzen™ device. Participants were instructed to use the Kenzen™ device as used during HRT1 for any other cycling or running training they were to complete between the completion of HRT1 and HRT2. This was to record any further significant thermal inertia (over 38.5 °C) they incite during supplementary training sessions. Sweat sodium composition (parts per million) was measured after every participant had completed the entire protocol, using a sodium analyser (Horiba C-122, Kyoto, Japan).

Heat acclimation (HA)

The seven HA sessions were identical, all consisting of 90 minutes at a steady state intensity. The work rate was the same as the first 20 minutes of the HRT (the heart rate corresponding to 45% of the calculated VO_2 max). Prior to the first HA only that occurred the day immediately following the initial HRT, participants were asked to rest for 10 minutes to obtain a resting haemoglobin measurement to enable calculation of the haemoglobin change resultant from the HRT. The Kenzen™ devices were used during the HA sessions rather than rectal thermometry to record core temperature. All HA sessions followed the same water consumption procedure as used for the HRTs. No heart rate or power metrics were recorded, but they were provided in real-time for the participants to track and measure their effort.

Data processing

Performance is defined the time in seconds taken to complete the 30 km time trial. Performance change was consequently the difference between 30 km HRT times on Day 1 and Day 13 of the experimental protocol. VO_2 max is defined as the highest 15-second average in the duration of the test, expressed as mL/min/kg.

A stepwise linear regression analysis was performed for each physiological marker recorded before, during, or immediately after HRT1 to investigate the responses that best predicted the changes in performances in HRT2. The best fitting linear regression and the best practical linear regression results were calculated using the equation:

$$y = b_1x_1 + b_2x_2 + c$$

Each participant's performance improvement was plotted against their 'best overall fit' and 'best practical fit' regression result in Figure 4 and Figure 4. The 'best overall fit' is the most accurate prediction equation using all available data from HRT1, including total time spent above 38.5 °C in all training as ascertained by the Kenzen™ device. The 'best practical fit' equation is using only data that can be easily recorded or accurately estimated using basic equipment that will be available to most athletes.

Calculation of Cohen's effect size. $\frac{M_A - M_B}{SD_{pooled}}$ Correction for smaller sample sizes was used, as recommended when the sample is <50. $\frac{n-3}{n-2.25}\sqrt{\frac{n-2}{n}}$ where n = n1 + n2.

Results

Adaptation

Every participant who begun the protocol completed the experimental procedure in full and attended every HRT and HA session required.

	HRT1	HRT2	Change in mean	p-value	Cohen's ES
Finish time (s)	2995 (± 203)	2921 (± 200)	-74 (± 96)	0.0374*	1.40 (-0.03-2.83)
Sweat sodium concentration (ppm)	1304 (± 594)	1141 (± 432)	-163 (± 385)	0.2134	0.77 (-0.66-2.20)
Sweat loss (mL)	2423 (± 515)	2760 (± 516)	337 (± 528)	0.0743	-1.16 (-2.59-0.27)
Haemoglobin (g/dL)	14.06 (± 1.63)	13.46 (± 1.21)	-0.60 (±0.87)	0.0578	1.24 (-0.19-2.67)
Time above 38.5 °C (s)	2049 (± 1409)	1995 (± 1097)	-54 (± 497)	0.7390	0.20 (-1.23-1.63)
Peak temperature (°C)	39.01 (± 0.40)	38.99 (± 0.31)	-0.02 (±0.18)	0.6780	0.25 (-1.18-1.68)
VO_2 max (mL/min/kg)	56.93 (±11.11)			-	-

*Table 1: Mean (± SD) for each HRT and the change in mean (± SD) between HRT1 and HRT2 of finish time, sodium concentration, sweat loss, haemoglobin, peak rectal temperature, and time above 38.5°C. Cohen's effect size (95% confidence intervals) and p-values of paired t-test analysis for each data type included. *Denotes a statistically significant difference form paired t-test (α = 0.05).*

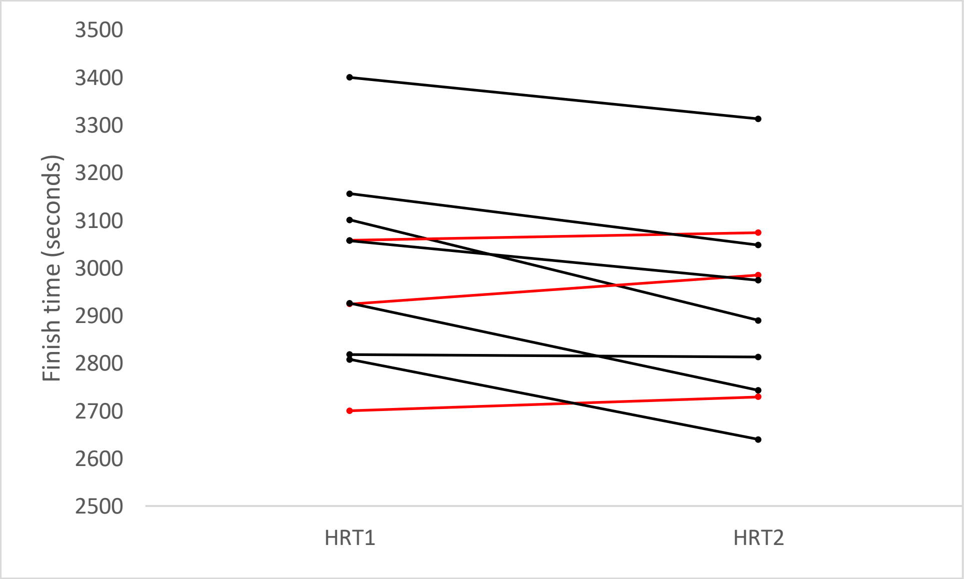

Figure 2: Individual changes in performance between HRT1 and HRT2. Performance improvements in black, performance decreases in red.

Correlation

The regression equation used to calculate the regression score representing the ‘best overall fit’ shown graphically in Figure 3 is as follows. Sweat concentration (SC) and sweat loss (SL) are used in millilitre units, VO_2 max in mL/min/kg:

$$(2.985 \times VO_2max) + (-0.033 \times SC) + (-0.074 \times SL) - 23.447$$

The regression equation used to calculate the regression score representing the ‘best practical fit’ shown graphically in Figure 4 is as follows:

$$(3.073 \times VO_2) + (-0.084 \times SL) - 45.724$$

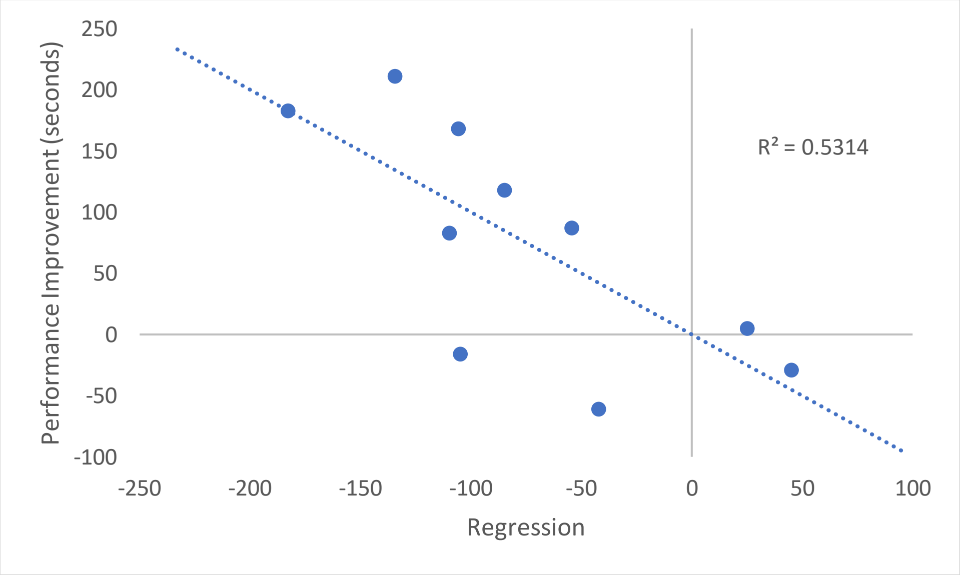

Figure 3: Regression analysis comparing the observed and predicted performance improvement values, using the ‘best overall fit’ stepwise regression analysis of pre-acclimation VO_2 max, HRT1 sodium concentration and HRT1 sweat loss, with the R^2 value presented.

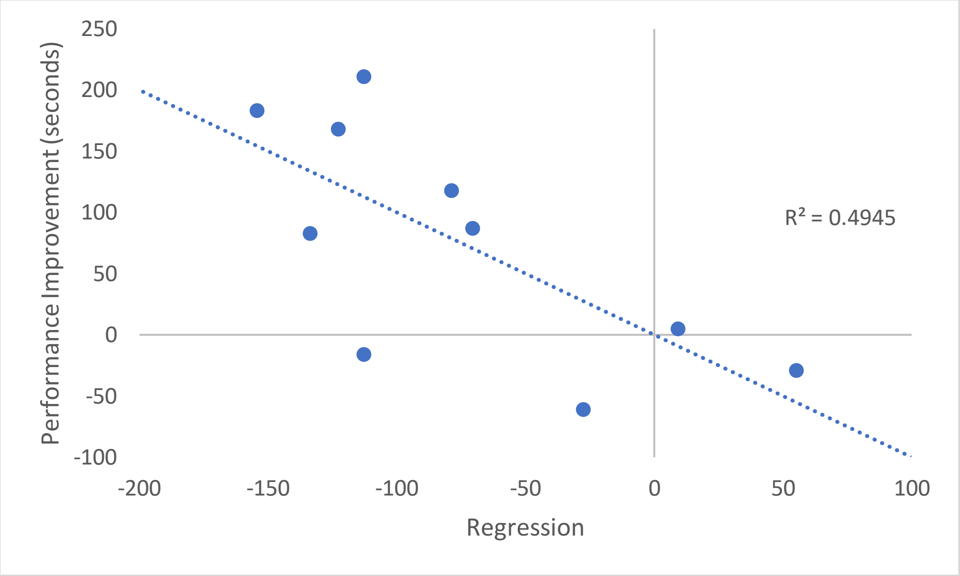

Figure 4: Regression analysis comparing the observed and predicted performance improvement values, using the 'best practical fit' stepwise regression analysis of pre-acclimation VO_2 max and HRT1 sweat loss, with the R^2 value presented.

The best fit stepwise regression analysis in Figure 4 identified that VO_2 max, HRT1 sweat loss and HRT1 sweat sodium composition were predictors of time trial performance change ($R^2 = 0.531$, $p = 0.017$) in HRT2. The best practical fit regression analysis in Figure 4 presents VO_2 max and HRT1 sweat loss alone were also predictors of time trial performance change ($R^2 = 0.495$, $p = 0.023$) in HRT2. Other physiological measures were not found significantly predict HRT2 performance changes.

The orientation of the best fit stepwise analysis in Figure 3 is such that a large HRT1 sweat loss, large HRT1 sweat sodium concentration and low pre-HRT VO_2 max correlate with best performance improvement. Similar is described in Figure 4, in that large sweat loss in HRT1 and low pre-HRT1 VO_2 max correlate with best performance improvement.

Discussion

The performance change between HRT1 and HRT2 was both clear (2.5% finish time reduction) and significant ($p = 0.037$) proving that, despite mixed evidence supporting intermittent HA protocol designs, an HA protocol that is somewhat intermittent can provide a performance benefit. Other physiological markers of improved thermoregulatory capacity showed no significant change between HRT1 and HRT2 (sweat rate $p = 0.074$, sweat sodium $p = 0.213$, haemoglobin $p = 0.058$).

Figure 3 illustrates the best possible regression model for predicting change in performance outcomes in well trained triathletes. Large sweat loss volume in HRT1, high sweat sodium concentration in HRT1 and low pre-HA VO_2 max were found to contribute to eventual performance change. The stepwise regression model did not determine any of the change between HRTs in other variables (haemoglobin, time spent above 38.5 °C, max core temperature) to correlate with eventual performance improvement. The 'best overall fit' regression presented in Figure 3, whilst significant in explaining 53% of the variation in performance improvement, only predicts 4% more variation than the 'best practical fit' regression using only HRT1 sweat loss and pre-HA VO_2 max ($R^2 = 0.49$) seen in Figure 4. Practically, this difference is negligible and both models predict approximately 50% of the variation is performance improvement. To note is that whilst being able to account for 50% of improvement variation is important, it also leave the other 50% of the variation unexplained. This could be due to a multitude of reasons, mostly likely due to other thermoregulatory adaptations that were not measured during the HRTs. Acute responses or potential lack of response in variables such as plasma volume, skin temperature, heat shock proteins or heart rate have been found to be responsible for performance capacity in environments where increased thermoregulatory requirements are necessary (Gibson et al., 2016; Périard et al., 2015). None of these were measured across the HRTs, but likely may have been as important to the prediction of performance improvements as the variables that were able to be recorded.

Given sweat rate is expected to increase, it is an interesting result that those with already high baseline sweat rates showed the best response to an HA protocol, given that the most effective thermoregulation method is evaporation. Perhaps, given that sweat capacity increases are seen as a consequence of standard training methods (Nadel et al., 1974), those with greater sweat capacity for absolute work rate were able to cool more efficiently for a given relative work rate, meaning they got through more high intensity work through the HA protocol. Inversely, those with higher VO_2 max and lower sweat rate may have found themselves unable to sit at the same relative work rate whilst maintaining the prescribed heart rate. What can be ruled out as an explanation for the relationship between sweat rate and performance change is HRT1 time. HRT1 time has no added correlation affect with performance change, so spending greater time in the chamber (therefore inducing more sweat loss but not a greater sweat rate) does not confound the regression findings. It has been well documented that sweat loss increases during a successful HA protocol (Best et al., 2014; Racinais et al., 2012), which was a result that may have been significant had the sample size been more substantial in this protocol.

Regarding the association of low pre-HRT1 VO_2 max with performance improvement, this is a somewhat contentious issue regarding the influence of VO_2 max on HA efficacy. Early research done by Shvartz et al. (1977) and Piwonka and Robinson (1967) suggests that when a daily, low-intensity but long duration (6 kmph walk at 6% for 85 min, or 3 hr of bench stepping at 41 W) HA protocol is used in comparing endurance-trained runners (57 - 65 mL/min/kg) to the untrained, a higher VO_2 max is correlated with reduced HA efficacy. They attributed this poorer relationship for those with larger VO_2 max being due to the fact that they were partially acclimated prior to beginning an HA protocol. Thus, as a result of their high baseline fitness and capacity to process acute core temperature increases through lower sweat and thermoregulatory onset thresholds, they were less able to adapt to the heat stress. Whilst not comparing against performance improvements, Shvartz et al. (1977) suggested that in endurance-trained athletes, around 40% of the variation seen in core temperature increases measured rectally in hot environments can be linked to having a lower VO_2 max. These findings have been contested in some modern literature (Corbett et al., 2018), but also reinforced by others (Aoyagi et al., 1997; Casadio et al., 2017). The current works aligns with the majority of the HA literature that baseline levels of VO_2 max has a large correlation with HA efficacy, likely due to a ceiling effect and overlapping physiological adaptations that occur as a result of endurance training and HA.

Something worth noting is that the protocol was designed to be demanding, but not exceptionally challenging on participants. Perhaps this is a reason for the less performance change seen by those with higher pre-HRT1 VO_2 max. Since the relationship between performance change, VO_2 max and sweat loss is very clear, and sweat rate in most environments is an indication of work rate, perhaps the protocol was not challenging enough to elicit significant thermoregulatory stress and adaptation. If we had the capacity to use controlled hyperthermia rather than heart rate-based intensity control, perhaps the work rate would have been more reliably similar between participants. Of note, in this experiment, there was no significant evidence to show that those who spent the most time above the generally accepted 38.5 °C threshold for hyperthermic stress to elicit HA attained greater adaptation. This is somewhat of an anomaly, given that as previously described, research-based HA protocol are mostly prescribed in terms of this modest hyperthermic 38.5 °C threshold. Perhaps this threshold also has its limitations, or non-responders and responders, especially amongst well-trained athletes, whose thermoregulatory and aerobic capabilities are greater.

Practical Applications

Given the significance of the regression model in Figure 4, using the ‘best practical fit’ to assist in programming and tracking HA progress during a protocol implementation is recommended. Both sweat loss and VO_2 max can be accurately estimated with excellent validity reported using non-invasive and simple methods in any location with limited resources (Pallarés et al., 2019; Swain et al., 2004). Specifically, sweat loss can be calculated by tracking liquid consumption and weight change. Similarly, there are a range of valid VO_2 estimate tests that require only the use of simple timing and set distances to cover. For example, a running-based VO_2 estimate test recently proposed by Pallarés et al. (2019) starts at 13 kmph slower than estimated max speed of the test, followed by progressive increments of 1 kmph every minute until exhaustion. Such tests are easy to execute on running tracks where distances and times are easily tracked. Alternatively, with access to a lab, VO_2 max is commonly performed test with exercise-specific protocols that enable accurate estimation of oxygen uptake via indirect or direct calorimetry.

Due to the ease of collecting the data involved in predicting HA efficacy reported herein, after one session in an extreme environment recording sweat loss and knowledge of VO_2 max, the ‘best practical fit’ regression equation presented can predict with reasonable confidence the eventual likelihood of HA success.

Chapter Three – Kenzen™ Validity Study

Abstract

Introduction: Wearable technologies designed to record core temperature using non-invasive measurements and algorithms are an evolving niche in sports tracking. As athletes are engaging in more scientific and specific training protocol such as targeted heat acclimation for major events, devices such as the Kenzen™ wearable core temperature sensor are only going to increase in popularity. The accuracy and validity of these devices has yet to be proven against any of the established 'gold-standard' measurements of core temperature.

Methods: Ten trained triathletes participants (33.6 ± 10.6 years, 8 males and 2 females; VO_2 max 56.9 ± 11.1) wore a Kenzen™ core temperature device throughout an HA protocol (exercise + heat; 36 °C, 65% relative humidity). In two maximal-exercise testing sessions that were pre- and post-HA (HRT), the Kenzen™ was compared directly to a rectal thermometer.

Results: The Kenzen™ device and rectal core temperature recorded similar core temperature values when the pooled mean core temperature was in the range of 37-38 °C. When rectal temperature was ≥ 39 °C, the accuracy of the Kenzen^{TM} device is questionable (mean difference = 0.79 °C).

Conclusion: The Kenzen™ device appears accurate through low-level hyperthermia, but does not seem valid when core temperatures reach above 38.5 °C.

Introduction

The process of heat acclimation (HA) is designed to acutely increase core temperature and stress the thermoregulatory system to induce change in physiology. Without increasing core temperature acutely in an HA protocol, it is unlikely to be successful. Acclimating by increasing core temperature to ≥ 38.5°C has long been recommended and accepted as common practice (Fox et al., 1963) and even with the advancement of this training niche, this recommendation has remained as underpinning successful HA protocol (Daanen et al., 2018). However, without measuring core temperature during an HA protocol, it remains unknown whether the desired temperature change is occurring.

Core temperature is difficult to measure in most environments outside of the laboratory, as it typically recorded using invasive rectal or oesophageal thermometers (Byrne & Lim, 2007; Taylor, 2014). Thermometers such as these require connections to data recorders and are therefore not feasible in most practical applications. Alternatively, the advancement of technology such as temperature recording digestible pills is becoming more accessible and valid and provide a potential alternative for field-based testing (Bongers et al., 2018). Digestible thermometers are not without their limitations; they are susceptible to interference from ingestion and are single-use and expensive to supply on the frequency required for frequent monitoring through an acclimation protocol.

Wearable sensors that record skin temperature in conjunction with other physiological and environmental measures are now available providing a practical alternative, provided that they are deemed to be valid measuring tools. Verdel et al. (2021) and Moyen et al. (2021) have recently explored the validity of such wearable sensors and found that the validity of such devices should not be assumed yet. The CORE™ sensor was tested by Verdel et al. (2021) in two environmental conditions under two workloads whilst cycling, low-to-moderate heat stress, and moderate-to-high heat stress. Both low-to-moderate (60min at ventilatory threshold 1 (VT1) in 19 °C at 30% relative humidity), and moderate-to-high (10 minutes graded increase to respiratory compensation, then 60 minutes at VT1 in 31 °C at 39% relative humidity) experienced similar validity errors. They pre-defined a validity threshold of > 0.3 °C difference between the CORE™ wearable and rectal thermometer signifying an invalid result, of which they found only half of the data met. This result has since been reinforced by Goods et al. (2023) who found that in field hockey players in conditions ranging between 27-31 °C at 40-80% relative humidity, approximately half of all recorded data was outside the same ± 0.3 °C range for difference between measures. Moyen et al. (2021) compared a Kenzen™ device to an ingestible BodyCap thermometer pill with participants undergoing usual daily activities, not maximal activity. Whilst their results were deemed valid in comparison to a gold standard, there were still noticeable differences across temperature ranges, and analysis of the product under exercising conditions is still needed, if it is to be used in the context of heat acclimation.

The previously mentioned Kenzen™ device "monitors heart rate (via PPG), skin and ambient temperature, relative humidity of the skin and environment, and activity (via accelerometry)" (Moyen et al., 2021). The Kenzen™ is marketed towards heavy industry and hot working conditions (manufacturing, mining, emergency service, military), but may be used in the sports industry in the future. For this reason, it is worthwhile investigating how the algorithm compares in thermoregulatory demanding physical testing environments commonly employed to elicit heat acclimation. Maximal exercise training induces much greater maximal core temperatures than is normally seen in any other activity in healthy populations. Therefore, inducing high core temperatures in a hot and humid environment in an athletic population to test the validity of the algorithm across a range of core temperatures is the aim of this research.

Methods

Procedure

Participants were ten endurance-trained triathlete volunteers (aged 33.6 ± 10.6 years, 8 males and 2 females) that have had at least two years of competitive training (VO_2max 56.93 ± 11.11).

Eight Kenzen™ devices (Kenzen, Silicon Valley, CA, USA) were acquired to use for validity research alongside an HA protocol, to be compared against rectal thermometers (U thermistor, Grant Instruments Ltd., Cambridge, United Kingdom; Squirrel 2020 series data logger, Grant Instruments Ltd., Cambridge, United Kingdom) The Squirrel data logger was calibrated to the correct voltage channel for recording core temperature. They were to be compared in two identical trials per participant, the initial heat response test (HRT1) and the final heat response test (HRT2) which bookended a 13-day HA protocol in 36 °C at 65% relative humidity. The HRT comprised two parts, the first being a sub-maximal 20-minute effort at the heart rate corresponding with 45% of previously recorded VO_2 peak. Heart rate was self-controlled by the participants, who were all comfortable doing this, as they were all experienced with this in their own training. After the 20-minute period, participants had three minutes rest to reset the Wattbike, before a 30km time trial effort was completed. A large industrial fan was located approximately two meters in front of the participant. Core temperature was recorded on both the Squirrel and Kenzen™ devices throughout the entirety of the protocol, as well as for ten-minutes before and five-minutes after. This resulted in 20 recorded comparisons between the rectal thermometer and the Kenzen™. The environment for the HRT's was maintained in an environment chamber, set to 36 °C and 65% relative humidity.

Data Analysis

The Kenzen™ devices recorded data at minimum 15 second intervals, while the rectal thermistor and Squirrel recorded data points every second. To match the data points from each dataset for each Kenzen™ data recording, the origin times were matched, and the Squirrel data was filtered to extract the time corresponding data to match the Kenzen™ data. Both sets of data were then cleaned of any outliers, by identifying temperatures outside the normal physiological range (37 to 41 °C), or differences of greater than 2 °C. A total of 551 outliers were removed (16.5%).

Correlations between the rectal thermistor and the Kenzen™ device were determined and the shared variance (R^2) was quantified based on thresholds of small (0.20 – 0.39), moderate (0.40 – 0.59) and large (≥ 60) (Cohen, 1988). A series of Bland-Altman plots were also created to quantify the agreement between the 'gold standard' rectal thermistor and the Kenzen™ device. The pooled mean of each corresponding data recording was calculated, as well as the difference between the means. Confidence intervals of the difference between the mean (95% CI) were calculated using the equation: $CI = \bar{x} \pm z\sigma$. As the confidence intervals were set to 95%, z = 1.96 where σ is the standard deviation of the difference of the mean.

Results

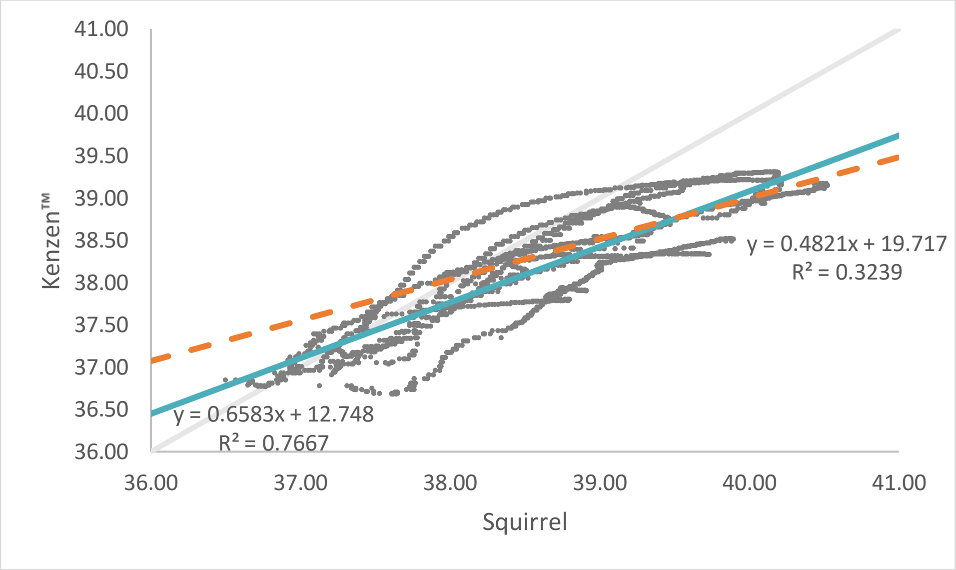

Figure 5: Kenzen™ vs Squirrel Core Temperature. Regression equation and R² values included (n = 2796). Dashed regression line indicates Squirrel ≥ 39 °C. Solid regression line indicates all data.

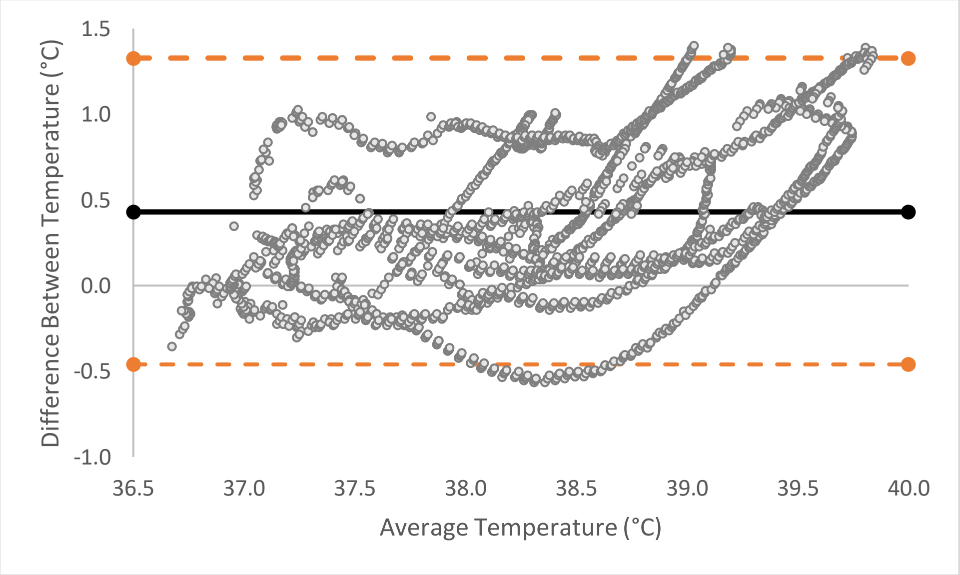

Figure 6: Bland-Altman plot comparing Squirrel data to Kenzen™ data. Dotted lines represent confidence intervals of 95% (-0.46 – 1.33).

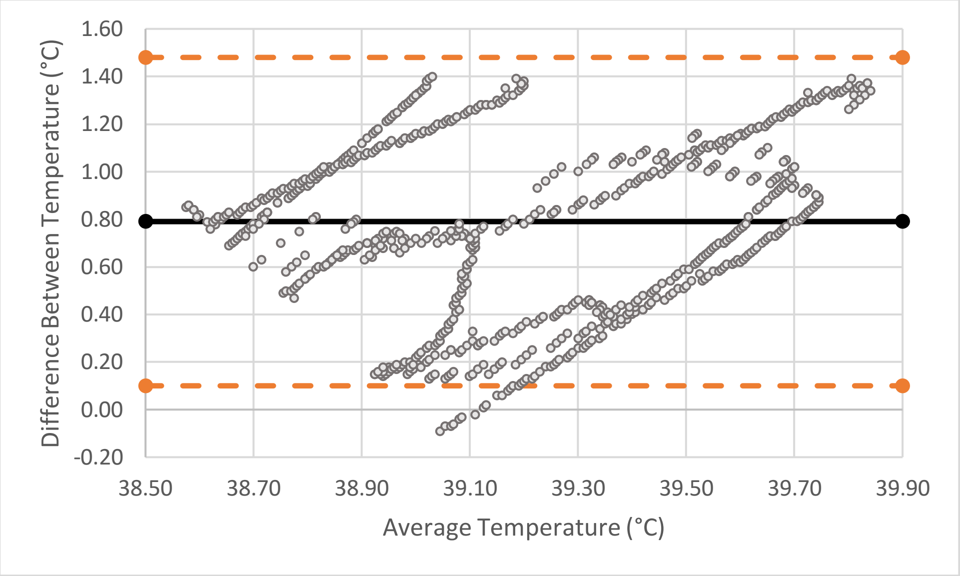

Figure 7: Bland-Altman plot comparing Squirrel data to Kenzen™ data when Squirrel > 39 °C. Dotted lines represent confidence intervals of 95% (0.10 – 1.48).

The R^2 value from the regression plot of the 2,796 paired data points was 0.7667 and represents a moderate correlation (

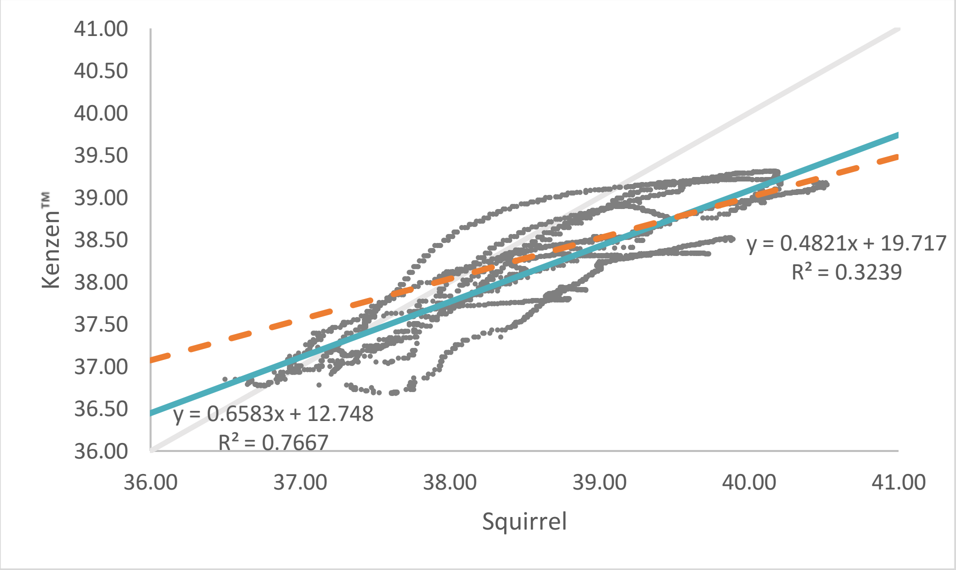

Figure 5: Kenzen™ vs Squirrel Core Temperature. Regression equation and R^2 values included (n = 2796). Dashed regression line indicates Squirrel ≥ 39 °C. Solid regression line indicates all data.). The validity of the Kenzen™ is described by Bland-Altman plots in **Error! Reference source not found.**, **Error! Reference source not found.** and **Error! Reference source not found.**. The complete data pool is presented in Figure 6, of which 3.1% (*n* = 87) of the 2,796 data points

representing the measurement differences lay outside the confidence intervals. In Figure 6, when the pooled mean is within 37-38 °C, the difference between the measures is stable, all data falls between the confidence intervals (-0.46 – 1.33). Between 38-39 °C the difference between the measures begins to vary more ranging closer to and outside of the confidence intervals. Above a pooled mean of 39 °C, the difference is always above zero and often much higher than the mean of the differences. Figure 7 details that when the Squirrel recording is greater than 39 °C, the average difference in the measures is 0.79 °C, noted is the confidence intervals are also above zero (0.10 - 1.48). The data in Figure 7 was used to report the second regression equation in Figure 5 that represents the difference in relationship between Kenzen™ and Squirrel when the Squirrel recording ≥ 39 °C. As displayed in Figure 5, a regression equation to determine Kenzen™ temperature from the Squirrel recording is: $y = 0.6583x + 12.748$. When just the Squirrel ≥ 39 °C data is used to determine the relationship between the two devices, the regression equation is $y = 0.4821x + 19.717$.

Discussion

In general, as the Squirrel temperature recordings increased, regression analysis identified that the Kenzen™ increased at a lower rate (approximately 66%). As seen in both Figure 5 and Figure 6, Squirrel and Kenzen™ recorded similarly at 37 °C and as core temperatures increased, so did the differences in readings. The regression equation calculates a 0.1 °C when Squirrel equals 37 °C, and a 0.92 °C difference when Squirrel equals 40 °C.

These results are replicated in the series of Bland-Altman plots. Differences in the measures are seen to be mostly between 0 and the mean of the differences between pooled means of 37 °C and 39 °C. After a pooled mean of 39 °C, the difference between the mean is seen to tend much more towards or above the upper confidence limit, indicating the Squirrel records much higher core temperatures at this range. Not all of the previous work on wearable core temperature sensors has found this to be true, with Bongers et al. (2018) and Verdel et al. (2021) finding that as true core temperature went up, the devices (ingestible and CORE™) recorded more similarly to each other than at lower temperatures. The varying validity of these devices is highlighted by the findings of Goods et al. (2023), who determined when using the CORE™ devices and BodyCap pills a very similar pattern as determined in this research. Initially (37 -38 °C) the two measures were similar, then as core temperature rose above 38.5 °C the difference in the measures rose to about 1 °C at 40 °C core temperature.

It was suspected that due to the Kenzen™ device being marketed towards working in environments where maximal thermal inertia is not intended, the algorithm may struggle to accurately predict core temperatures in high ranges (> 39 °C). We note that the device itself is designed to alert the wearer when the estimated core body temperature rises above 38.5 °C. In an athletic population, this limits the validity of the device, especially in HA protocol or similar where the main objective of the stimulus is to elicit large increases in core temperature, potentially well above this 38.5 °C threshold. Whilst the Bland-Altman plots did not determine this as a range more likely to produce meaningfully invalid differences, the regression plot equation determined substantial differences in recordings at temperatures above 39 °C. According to the split regression equations presented in Figure 5, when the Squirrel recorded core temperature above 39 °C, the Kenzen™ devices were recording temperature increases at half of the rate of the Squirrel data logger.

There is no other known data outside of the work of Moyen et al. (2021) that crosschecks the validity of the Kenzen™ wearable. Their results suggest that at temperature ranges between 37°C - 38°C the Kenzen™ wearable is accurate and valid. The presented data does not show anything outside of this range, so it is not possible to compare results above the 38.5 °C threshold that the device has programmed. More analysis regarding the validity of readings at higher core temperatures needs to be performed to be confident of the validity at such temperatures, especially when the current validity of comparable wearable sensors at such temperature ranges is inconsistent.

Chapter Four - Summary

Summary

Heat acclimation is a powerful training tool to elicit beneficial physiological change, increasing performance capacity in thermally challenging environments. There are a number of different HA prescription methods that have been reported to achieve successful acclimation, but applying such methods to achieve optimal results in specific sports requires knowledge of the physiological demands of the nature of the sport, and the thermoregulatory demands of the environment in which the event is held in. As with any exercise prescription, there are those who respond well, and those who respond either at a slower rate or not at all, and this individualised nature of response remains true for HA training. Chapter One summarises the physiology and methods of standardised HA protocols, and introduced this idea of individual responsiveness, and the mechanisms behind said responses.

Chapter Two reports a predictive model intended to determine whether an individual will attain a performance benefit from a 14-day intermittent HA protocol. The regression models created indicate that there is some feasibility in attempting to predict heat acclimation success, at least in trained triathletes. The two regression models created in Chapter Two account for approximately half of the variation in performance improvements using a few variables, some of which can readily be measured without extensive laboratory testing. This information is helpful and practically applicable for both well-resourced high-performance environments, and non-elite athletes who have major competitions (e.g.

marathons or Ironman triathlons) who want to get the best performance on race day in hot and humid environments.

The research in Chapter Three explored the validity of a new wearable core temperature device, the Kenzen™ against the gold standard rectal thermometry. The Kenzen™ device was tested using the same HRT protocol as the prediction model in Chapter Two, and was found to be accurate through low-level hyperthermia when compared to rectal core temperature, but not as accurate at recording core temperatures above the programmed 'stop-work' threshold of 38.5 °C. Assuming that wearables such as the Kenzen™ will become increasingly more accurate compared to gold standard measurement techniques, which has been seen in most wearable (micro)sensor technology as more data can be collected, the algorithms refined and general improvements in the technology, they may prove to be some of the most useful training aids to assist preparing for competition in environments that restrict regular performance capacity, but are currently limited in their performance outside of the described performance range.

Strengths

A strength of the experimental study in Chapter Two was the participant base of entirely trained endurance athletes. Heat acclimation protocol is most used in trained and elite athletes, so using untrained participant pools is not useful for making identifying significant results. The recruitment process required potential participants to have experience in triathlon training, and all participants were members of the local triathlon club. There was a range of VO_2 max capability and general performance capacity amongst the participants (45.40 – 77.39 mL/min/kg) that allowed for a broader range of baseline measures to explore the predictive capabilities of heat acclimation. This range allows us to confidently say that we tested both actively competitive age group athletes and elite athletes in our sample (2 athletes VO_2 max > 75 mL/min/kg).

Participants were required to use the Kenzen™ device in other bike and run training sessions they were completing through the duration of the heat acclimation protocol. This was so the effect of supplemental thermal inertia in training (core temperature rise above 38.5 °C) outside of the experimental protocol could be tracked and the potential confounding effect of this examined. To our knowledge, no other studies that have quantified thermal inertia outside of the laboratory when examining an HA protocol, so this is a novel aspect of the current work. Only two participants logged any extra time with core temperature above 38.5 °C during the experimental time period, and this additional thermal inertia was not found to be a significant contributor to the predictive model. This means it can be said with some confidence that the performance change results of the protocol are due to the physiological changes induced by the protocol, not due to external training load. Out-of-laboratory thermal inertia will be dependent on the environmental conditions of the location or season that testing occurs in, and the lack of contribution of such thermal inertia is likely to be somewhat linked to the experiment taking place during late-season New Zealand winter.

Limitations

The first limitation of the experimental study is that only ten participants were recruited, of which only two were female. Using small sample sizes does not allow for much confidence in any results that are found or may hide any effects due to a handful of non-responders. Ideally, the number of participants would have been fifteen to twenty; however, due to the intensive nature of the experiment and the frequent visits to the laboratory required, several potential participants were not able to partake in the research.

A second limitation in Chapter Two was the measures available within the restraints of the skills of the data collectors and resources of the university. Ideally, physiological markers such as plasma volume or heat shock proteins would have been measured, but due to the training and equipment required this was not possible for this experiment.

Whilst triathletes are a very applicable participant base for heat acclimation experiments due to the nature of their summer competition season, they also have specific demands not replicated by many other sports. Whilst results seen in triathlete participant samples may be applicable to the component sports (cycling and running) in terms of heat acclimation affects, it is not a given that any effects seen in triathletes will be seen in athletes of the component sports, given cyclists have little to no use of full body aerobic systems. Triathletes may also experience a pre-cooling effect in practical or race environments due to swim conditions, something that the component sports do not experience.

As is the case with most HA experiments, these results are specific to the HA protocol used in terms of frequency of exposure to a thermally challenging environment, and the environment itself. Different combinations of HA protocol duration, frequency and environmental conditions would likely yield different results in terms of the predictive capacity of the model presented.

Future Directions

As mentioned in the limitations section, using different measurement techniques such as plasma volume, heat shock proteins, or clamping workload through core temperature rather than heart rate during the heat acclimation sessions could be a way to explore the predictive capacity of heat acclimation in the future. However, none of these measures or techniques are practical in field-based sessions, so exploring this model of prediction using race distance tests or different populations is the best advancement of this research.

Using a cross-over study to determine the adaptation-inducing potential of this HA protocol against the same protocol in temperate conditions would determine at the least that when using this semi-intermittent HA protocol, the majority of participants will see adaptations that cannot be obtained through regular training. Whilst professional athletes may have the resources and time to acclimate daily, most endurance athletes are not professional athletes or are time poor. If the results of daily heat acclimation can be replicated through acclimating on alternate days, this would be a valuable training tool for those athletes who do not have the time or practical means to acclimate daily.

Determining the best alternative for those who have been predicted to not respond well to this HA protocol is also worth exploring. This could include a range of supplementary heat exposure such as sauna bathing, extended duration or sessions or protocol (2-3 hour HA sessions or a 21 day exposure period), or increasing the intensity of the thermal inertia by increasing the WBGT or introducing more work into the HA sessions.

References

Alkemade, P., Gerrett, N., Eijsvogels, T. M. H., & Daanen, H. A. M. (2021). Individual characteristics associated with the magnitude of heat acclimation adaptations. *European Journal of Applied Physiology*, *121*(6), 1593-1606. https://doi.org/10.1007/s00421-021-04626-3

Aoyagi, Y., McLellan, T. M., & Shephard, R. J. (1997). Interactions of physical training and heat acclimation. *Sports Medicine*, *23*(3), 173-210. https://doi.org/10.2165/00007256-199723030-00004

Armstrong, L. E., & Maresh, C. M. (1991). The induction and decay of heat acclimatisation in trained athletes. *Sports Medicine*, *12*(5), 302-312. https://doi.org/10.2165/00007256-199112050-00003

Bartolomé, I., Siquier-Coll, J., Pérez-Quintero, M., Robles-Gil, M. C., Grijota, F. J., Muñoz, D., & Maynar-Mariño, M. (2021). 3-Week passive acclimation to extreme environmental heat (100± 3 °C) in dry sauna increases physical and physiological performance among young semi-professional football players. *Journal of Thermal Biology*, *100*. https://doi.org/10.1016/j.jtherbio.2021.103048

Benjamin, C. L., Sekiguchi, Y., Armstrong, L. E., Manning, C. N., Struder, J. F., Butler, C. R., Huggins, R. A., Stearns, R. L., Lee, E. C., & Casa, D. J. (2022). The efficacy of weekly and bi-weekly heat training to maintain the physiological benefits of heat acclimation. *Journal of Science and Medicine in Sport*, *25*(3), 255-260. https://doi.org/10.1016/j.jsams.2021.10.006

Benjamin, C. L., Sekiguchi, Y., Fry, L. A., & Casa, D. J. (2019). Performance changes following heat acclimation and the factors that influence these changes: meta-analysis and meta-regression. *Frontiers in Physiology*, *10*, 1448. https://doi.org/10.3389/fphys.2019.01448

Best, S., Thompson, M., Caillaud, C., Holvik, L., Fatseas, G., & Tammam, A. (2014). Exercise-heat acclimation in young and older trained cyclists. *Journal of Science and Medicine in Sport*, *17*(6), 677-682. https://doi.org/10.1016/j.jsams.2013.10.243

Bongers, C. C. W. G., Daanen, H. A. M., Bogerd, C. P., Hopman, M. T. E., & Eijsvogels, T. M. H. (2018). Validity, reliability, and inertia of four different temperature capsule systems. *Medicine & Science in Sports & Exercise*, *50*(1), 169-175. https://doi.org/10.1249/mss.0000000000001403

Booth, J. D., Wilsmore, B. R., MacDonald, A. D., Zeyl, A., Storlien, L. H., & Taylor, N. A. S. (2004). Intramuscular temperatures during exercise in the heat following pre-cooling and pre-heating. *Journal of Thermal Biology*, *29*(7), 709-715. https://doi.org/10.1016/j.jtherbio.2004.08.044

Bradford, C. D., Lucas, S. J. E., Gerrard, D. F., & Cotter, J. D. (2015). Swimming in warm water is ineffective in heat acclimation and is non-ergogenic for swimmers. *Scandinavian Journal of Medicine & Science in Sports*, *25*(S1), 277-286. https://doi.org/10.1111/sms.12351

Brazaitis, M., & Skurvydas, A. (2010). Heat acclimation does not reduce the impact of hyperthermia on central fatigue. *European Journal of Applied Physiology*, *109*(4), 771-778. https://doi.org/10.1007/s00421-010-1429-3

Byrne, C., & Lim, C. L. (2007). The ingestible telemetric body core temperature sensor: a review of validity and exercise applications. *British Journal of Sports Medicine*, *41*(3), 126. https://doi.org/10.1136/bjsm.2006.026344

Casadio, J. R., Kilding, A. E., Cotter, J. D., & Laursen, P. B. (2017). From lab to real world: heat acclimation considerations for elite athletes. *Sports Medicine*, *47*(8), 1467-1476. https://doi.org/10.1007/s40279-016-0668-9

Chalmers, S., Esterman, A., Eston, R., Bowering, K. J., & Norton, K. (2014). Short-term heat acclimation training improves physical performance: a systematic review, and exploration of physiological adaptations and application for team sports. *Sports Medicine*, *44*(7), 971-988. https://doi.org/10.1007/s40279-014-0178-6

Chinevere, T. D., Kenefick, R. W., Cheuvront, S. N., Lukaski, H. C., & Sawka, M. N. (2008). Effect of heat acclimation on sweat minerals. *Medicine and Science in Sports and Exercise*, *40*(5), 886-891. https://doi.org/10.1249/MSS.0b013e3181641c04

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). L. Erlbaum Associates.

Corbett, J., Rendell, R. A., Massey, H. C., Costello, J. T., & Tipton, M. J. (2018). Inter-individual variation in the adaptive response to heat acclimation. *Journal of Thermal Biology*, *74*, 29-36. https://doi.org/10.1016/j.jtherbio.2018.03.002

Coris, E. E., Ramirez, A. M., & Van Durme, D. J. (2004). Heat illness in athletes: the dangerous combination of heat, humidity and exercise. *Sports Medicine*, *34*, 9-16. https://doi.org/10.2165/00007256-200434010-00002

Daanen, H. A. M., Racinais, S., & Périard, J. D. (2018). Heat acclimation decay and re-induction: a systematic review and meta-analysis. *Sports Medicine*, *48*(2), 409-430. https://doi.org/10.1007/s40279-017-0808-x

Drust, B., Rasmussen, P., Mohr, M., Nielsen, B., & Nybo, L. (2005). Elevations in core and muscle temperature impairs repeated sprint performance. *Acta Physiologica Scandinavica*, *183*(2), 181-190. https://doi.org/https://doi.org/10.1111/j.1365-201X.2004.01390.x

Ely, M. R., Cheuvront, S. N., Roberts, W. O., & Montain, S. J. (2007). Impact of weather on marathon-running performance. *Medicine and Science in Sports and Exercise*, *39*(3), 487-493. https://doi.org/10.1249/mss.0b013e31802d3aba

Febbraio, M. A., Snow, R., Hargreaves, M., Stathis, C., Martin, I., & Carey, M. (1994). Muscle metabolism during exercise and heat stress in trained men: effect of acclimation. *Journal of Applied Physiology*, *76*(2), 589-597. https://doi.org/10.1152/jappl.1994.76.2.589

Fenemor, S. P. (2022). *Heat management strategies in elite rugby sevens.* The University of Waikato].

Flouris, A. D. (2019). Human Thermoregulation. In J. D. Périard & S. Racinais (Eds.), *Heat Stress in Sport and Exercise: Thermophysiology of Health and Performance* (pp. 3-27). Springer International Publishing. https://doi.org/10.1007/978-3-319-93515-7_1

Fox, R. H., Goldsmith, R., Kidd, D. J., & Lewis, H. E. (1963). Acclimatization to heat in man by controlled elevation of body temperature. *The Journal of Physiology*, *166*(3), 530-547. https://doi.org/10.1113/jphysiol.1963.sp007121

Galloway, S. D., & Maughan, R. J. (1997). Effects of ambient temperature on the capacity to perform prolonged cycle exercise in man. *Medicine and Science in Sports and Exercise*, *29*(9), 1240-1249. https://doi.org/10.1097/00005768-199709000-00018

Garrett, A. T., Creasy, R., Rehrer, N. J., Patterson, M. J., & Cotter, J. D. (2012). Effectiveness of short-term heat acclimation for highly trained athletes. *European Journal of Applied Physiology*, *112*(5), 1827-1837. https://doi.org/10.1007/s00421-011-2153-3

Garrett, A. T., Goosens, N. G., Rehrer, N. J., Patterson, M. J., Harrison, J., Sammut, I., & Cotter, J. D. (2014). Short-term heat acclimation is effective and may be enhanced rather than impaired by dehydration. *American Journal of Human Biology*, *26*(3), 311-320. https://doi.org/10.1002/ajhb.22509

Garrett, A. T., Rehrer, N. J., & Patterson, M. J. (2011). Induction and decay of short-term heat acclimation in moderately and highly trained athletes. *Sports Medicine*, *41*(9), 757-771. https://doi.org/10.2165/11587320-000000000-00000

Gibson, O. R., Tuttle, J. A., Watt, P. W., Maxwell, N. S., & Taylor, L. (2016). Hsp72 and Hsp90α mRNA transcription is characterised by large, sustained changes in core temperature during heat acclimation. *Cell Stress and Chaperones*, *21*(6), 1021-1035. https://doi.org/10.1007/s12192-016-0726-0

Gill, N., & Sleivert, G. (2001). Effect of daily versus intermittent exposure on heat acclimation. *Aviation, Space, and Environmental Medicine*, *72*(4), 385-390.

González-Alonso, J., & Calbet, J. A. L. (2003). Reductions in systemic and skeletal muscle blood flow and oxygen delivery limit maximal aerobic capacity in humans. *Circulation*, *107*(6), 824-830. https://doi.org/10.1161/01.CIR.0000049746.29175.3F

Goods, P. S. R., Maloney, P., Miller, J., Jennings, D., Fahey-Gilmour, J., Peeling, P., & Galna, B. (2023). Concurrent validity of the CORE wearable sensor with BodyCap temperature pill to assess core body temperature during an elite women's field hockey heat training camp. *European Journal of Sport Science*, *23*(8), 1509-1517. https://doi.org/10.1080/17461391.2023.2193953

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

Guy, J. H., Deakin, G. B., Edwards, A. M., Miller, C. M., & Pyne, D. B. (2015). Adaptation to hot environmental conditions: an exploration of the performance basis, procedures and future directions to optimise opportunities for elite athletes. *Sports Medicine*, *45*(3), 303-311. https://doi.org/10.1007/s40279-014-0277-4

James, C. A., Richardson, A. J., Watt, P. W., Willmott, A. G. B., Gibson, O. R., & Maxwell, N. S. (2018). Short-term heat acclimation and precooling, independently and combined, improve 5-km time trial performance in the heat. *Journal of Strength and Conditioning Research*, *32*(5), 1366-1375. https://doi.org/10.1519/JSC.0000000000001979

Johnson, J. M. (2010). Exercise in a hot environment: the skin circulation. *Scandinavian Journal of Medicine & Science in Sports*, *20*(s3), 29-39. https://doi.org/10.1111/j.1600-0838.2010.01206.x

Kirby, N. V., Lucas, S. J. E., Cable, T. G., Armstrong, O. J., Weaver, S. R., & Lucas, R. A. I. (2021). Sex differences in adaptation to intermittent post-exercise sauna bathing in trained middle-distance runners. *Sports Medicine*, *7*(1), 51. https://doi.org/10.1186/s40798-021-00342-6

Kirby, N. V., Lucas, S. J. E., & Lucas, R. A. I. (2019). Nine-, but not four-days heat acclimation improves self-paced endurance performance in females. *Frontiers in Physiology*, *10*. https://doi.org/10.3389/fphys.2019.00539

Kirwan, J. P., Costill, D. L., Kuipers, H., Burrell, M. J., Fink, W. J., Kovaleski, J. E., & Fielding, R. A. (1987). Substrate utilization in leg muscle of men after heat acclimation. *Journal of Applied Physiology*, *63*(1), 31-35. https://doi.org/10.1152/jappl.1987.63.1.31

Kissling, L. S., Akerman, A. P., Campbell, H. A., Prout, J. R., Gibbons, T. D., Thomas, K. N., & Cotter, J. D. (2022). A crossover control study of three methods of heat acclimation on the magnitude and kinetics of adaptation. *Experimental Physiology*, *107*(4), 337-349. https://doi.org/10.1113/EP089993

Lee, B. J., Miller, A., James, R. S., & Thake, C. D. (2016). Cross acclimation between heat and hypoxia: heat acclimation improves cellular tolerance and exercise performance in acute normobaric hypoxia. *Frontiers in Physiology*, *7*. https://doi.org/10.3389/fphys.2016.00078

Lorenzo, S., Halliwill, J. R., Sawka, M. N., & Minson, C. T. (2010). Heat acclimation improves exercise performance. *Journal of Applied Physiology*, *109*(4), 1140-1147. https://doi.org/10.1152%2Fjapplphysiol.00495.2010

Mee, J. A., Gibson, O. R., Doust, J., & Maxwell, N. S. (2015). A comparison of males and females' temporal patterning to short- and long-term heat acclimation. *Scandinavian Journal of Medicine & Science in Sports*, *25*(S1), 250-258. https://doi.org/10.1111/sms.12417

Merry, T. L., Ainslie, P. N., & Cotter, J. D. (2010). Effects of aerobic fitness on hypohydration-induced physiological strain and exercise impairment. *Acta Physiologica*, *198*(2), 179-190. https://doi.org/10.1111/j.1748-1716.2009.02051.x

Meyer, F., Szygula, Z., & Wilk, B. (2015). *Fluid balance, hydration, and athletic performance*. Taylor & Francis Group.

Moyen, N., Bapat, R., Tan, B., Esfahani, M., & Mundel, T. (2021). Accuracy of a wearable device to non-invasively predict continuous core body temperature. *The FASEB Journal*, *35*(S1). https://doi.org/10.1096/fasebj.2021.35.S1.03140

Nadel, E. R., Pandolf, K. B., Roberts, M. F., & Stolwijk, J. A. (1974). Mechanisms of thermal acclimation to exercise and heat. *Journal of Applied Physiology*, *37*(4), 515-520. https://doi.org/10.1152/jappl.1974.37.4.515

Nielsen, B. (1966). Regulation of body temperature and heat dissipation at different levels of energy-and heat production in man. *Acta Physiologica Scandinavica*, *68*(2), 215-227. https://doi.org/10.1111/j.1748-1716.1966.tb03420.x

Nielsen, B., Hales, J., Strange, S., Christensen, N. J., Warberg, J., & Saltin, B. (1993). Human circulatory and thermoregulatory adaptations with heat acclimation and exercise in a hot, dry environment. *The Journal of Physiology*, *460*(1), 467-485. https://doi.org/10.1113/jphysiol.1993.sp019482

Oberholzer, L., Siebenmann, C., Mikkelsen, C. J., Junge, N., Piil, J. F., Morris, N. B., Goetze, J. P., Meinild Lundby, A.-K., Nybo, L., & Lundby, C. (2019). Hematological adaptations to prolonged heat acclimation in endurance-trained males. *Frontiers in Physiology*, *10*. https://doi.org/10.3389/fphys.2019.01379

Osborne, J. O., Stewart, I. B., Borg, D. N., Beagley, K. W., Buhmann, R. L., & Minett, G. M. (2021). Short-term heat acclimation preserves knee extensor torque but does not improve 20 km self-paced cycling performance in the heat. *European Journal of Applied Physiology*, *121*(10), 2761-2772. https://doi.org/10.1007/s00421-021-04744-y

Pallarés, J. G., Cerezuela-Espejo, V., Morán-Navarro, R., Martínez-Cava, A., Conesa, E., & Courel-Ibáñez, J. (2019). A new short track test to estimate the VO2max and maximal aerobic speed in well-trained runners. *The Journal of Strength & Conditioning Research*, *33*(5). https://doi.org/10.1519/JSC.0000000000003121

Pandolf, K. B., Burse, R. L., & Goldman, R. F. (1977). Role of physical fitness in heat acclimatisation, decay and reinduction. *Ergonomics*, *20*(4), 399-408. https://doi.org/10.1080/00140137708931642

Périard, J. D., Cramer, M. N., Chapman, P. G., Caillaud, C., & Thompson, M. W. (2011). Cardiovascular strain impairs prolonged self-paced exercise in the heat. *Experimental Physiology*, *96*(2), 134-144. https://doi.org/10.1113/expphysiol.2010.054213

Périard, J. D., Racinais, S., & Sawka, M. N. (2015). Adaptations and mechanisms of human heat acclimation: applications for competitive athletes and sports. *Scandinavian Journal of Medicine & Science in Sports*, *25*(S1), 20-38. https://doi.org/10.1111/sms.12408

Périard, J. D., Travers, G. J. S., Racinais, S., & Sawka, M. N. (2016). Cardiovascular adaptations supporting human exercise-heat acclimation. *Autonomic Neuroscience*, *196*, 52-62. https://doi.org/10.1016/j.autneu.2016.02.002

Piwonka, R. W., & Robinson, S. (1967). Acclimatization of highly trained men to work in severe heat. *Journal of Applied Physiology*, *22*(1), 9-12. https://doi.org/10.1152/jappl.1967.22.1.9

Poirier, M. P., Gagnon, D., Friesen, B. J., Hardcastle, S. G., & Kenny, G. P. (2015). Whole-body heat exchange during heat acclimation and its decay. *Medicine & Sciene in Sports & Exercise*, *47*(2), 390-400. https://doi.org/10.1249/MSS.0000000000000401

Pryor, J. L., Pryor, R. R., Vandermark, L. W., Adams, E. L., VanScoy, R. M., Casa, D. J., Armstrong, L. E., Lee, E. C., DiStefano, L. J., Anderson, J. M., & Maresh, C. M. (2019). Intermittent exercise-heat exposures and intense physical activity sustain heat acclimation adaptations. *Journal of Science and Medicine in Sport*, *22*(1), 117-122. https://doi.org/10.1016/j.jsams.2018.06.009

Pryor, R. R., Pryor, J. L., Vandermark, L. W., Adams, E. L., Brodeur, R. M., Armstrong, L. E., Lee, E. C., Maresh, C. M., & Casa, D. J. (2021). Short term heat acclimation reduces heat strain during a first, but not second, consecutive exercise-heat exposure. *Journal of Science and Medicine in Sport*, *24*(8), 768-773. https://doi.org/10.1016/j.jsams.2021.03.020

Racinais, S., Buchheit, M., Bilsborough, J., Bourdon, P. C., Cordy, J., & Coutts, A. J. (2014). Physiological and performance responses to a training camp in the heat in professional Australian football players. *International Journal of Sports Physiology & Performance*, *9*(4), 598-603. https://doi.org/10.1123/IJSPP.2013-0284

Racinais, S., Mohr, M., Buchheit, M., Voss, S. C., Gaoua, N., Grantham, J., & Nybo, L. (2012). Individual responses to short-term heat acclimatisation as predictors of football performance in a hot, dry environment. *British Journal of Sports Medicine*, *46*(11), 810. https://doi.org/http://dx.doi.org/10.1136/bjsports-2012-091227

Racinais, S., Periard, J. D., Karlsen, A., & Nybo, L. (2015). Effect of heat and heat acclimatization on cycling time trial performance and pacing. *Medicine and Science in Sports and Exercise*, *47*(3), 601-606. https://doi.org/10.1249/MSS.0000000000000428

Racinais, S., Périard, J. D., Piscione, J., Bourdon, P. C., Cocking, S., Ihsan, M., Lacome, M., Nichols, D., Townsend, N., Travers, G., Wilson, M. G., & Girard, O. (2021). Intensified training supersedes the impact of heat and/or altitude for increasing performance in elite rugby union players. *International Journal of Sports Physiology and Performance*, *16*(10), 1416-1423. https://doi.org/10.1123/ijspp.2020-0630

Ravanelli, N., Bongers, C. C. W. G., & Jay, O. (2019). The Biophysics of Human Heat Exchange. In J. D. Périard & S. Racinais (Eds.), *Heat Stress in Sport and Exercise: Thermophysiology of Health and Performance* (pp. 29-43). Springer International Publishing. https://doi.org/10.1007/978-3-319-93515-7_2

Reeve, T., Gordon, R., Laursen, P. B., Lee, J. K. W., & Tyler, C. J. (2019). Impairment of cycling capacity in the heat in well-trained endurance athletes after high-intensity short-term heat acclimation. *International Journal of Sports Physiology and Performance*, *14*(8), 1058-1065. https://doi.org/10.1123/ijspp.2018-0537

Rønnestad, B. R., Hamarsland, H., Hansen, J., Holen, E., Montero, D., Whist, J. E., & Lundby, C. (2021). Five weeks of heat training increases haemoglobin mass in elite cyclists. *Experimental Physiology*, *106*(1), 316-327. https://doi.org/10.1113/EP088544

Saat, M., Sirisinghe, R. G., Singh, R., & Tochihara, Y. (2005). Decay of heat acclimation during exercise in cold and exposure to cold environment. *European Journal of Applied Physiology*, *95*(4), 313-320. https://doi.org/10.1007/s00421-005-0012-9

Sawka, M. N., Leon, L. R., Montain, S. J., & Sonna, L. A. (2011). Integrated physiological mechanisms of exercise performance, adaptation, and maladaptation to heat stress. *Comprehensive Physiology*, 1883-1928. https://doi.org/10.1002/cphy.c100082

Sekiguchi, Y., Benjamin, C. L., Manning, C. N., Struder, J. F., Armstrong, L. E., Lee, E. C., Huggins, R. A., Stearns, R. L., Distefano, L. J., & Casa, D. J. (2021). Effects of heat acclimatization, heat acclimation, and intermittent exercise heat training on time-trial performance. *Sports Health*, *0*(0). https://doi.org/10.1177/19417381211050643

Shvartz, E., Shapiro, Y., Magazanik, A., Meroz, A., Birnfeld, H., Mechtinger, A., & Shibolet, S. (1977). Heat acclimation, physical fitness, and responses to exercise in temperate and hot environments. *Journal of Applied Physiology*, *43*(4), 678-683. https://doi.org/10.1152/jappl.1977.43.4.678

Stand, P. (1996). Exercise and Fluid Replacement. *Medicine and Science in Sports and Exercise*, *28*.

Sunderland, C., Morris, J. G., & Nevill, M. E. (2008). A heat acclimation protocol for team sports. *British Journal of Sports Medicine*, *42*(5), 327. https://doi.org/10.1136/bjsm.2007.034207

Swain, D. P., Parrott, J. A., Bennett, A. R., Branch, J. D., & Dowling, E. A. (2004). Validation of a new method for estimating V̇O2max based on V̇O2 reserve. *Medicine & Science in Sports & Exercise*, *36*(8). https://doi.org/10.1249/01.MSS.0000135774.28494.19

Tatterson, A. J., Hahn, A. G., Martini, D. T., & Febbraio, M. A. (2000). Effects of heat stress on physiological responses and exercise performance in elite cyclists. *Journal of Science and Medicine in Sport*, *3*(2), 186-193. https://doi.org/10.1016/S1440-2440(00)80080-8

Taylor, N. A. S. (2014). Human heat adaptation. *Comprehensive Physiology*, 325-365. https://doi.org/10.1002/cphy.c130022

Tebeck, S. T., Buckley, J. D., Bellenger, C. R., & Stanley, J. (2020). Differing physiological adaptations induced by dry and humid short-term heat acclimation. *International Journal of Sports Physiology and Performance*, *15*(1), 133-140. https://doi.org/10.1123/ijspp.2018-0707

Tyka, A., Pałka, T., Tyka, A., Cisoń, T., & Szyguła, Z. (2009). The influence of ambient temperature on power at anaerobic threshold determined based on blood lactate concentration and myoelectric signals. *International Journal of Occupational Medicine and Environmental Health*, *22*(1), 1-6. https://doi.org/10.2478/v10001-009-0005-8

Tyler, C. J., Reeve, T., Hodges, G. J., & Cheung, S. S. (2016). The effects of heat adaptation on physiology, perception and exercise performance in the heat: a meta-analysis. *Sports Medicine*, *46*(11), 1699-1724. https://doi.org/10.1007/s40279-016-0538-5

Verdel, N., Podlogar, T., Ciuha, U., Holmberg, H.-C., Debevec, T., & Supej, M. (2021). Reliability and validity of the CORE sensor to assess core body temperature during cycling exercise. *Sensors*, *21*(17).

Weller, A. S., Linnane, D. M., Jonkman, A. G., & Daanen, H. A. M. (2007). Quantification of the decay and re-induction of heat acclimation in dry-heat following 12 and 26 days without exposure to heat stress. *European Journal of Applied Physiology*, *102*(1), 57-66. https://doi.org/10.1007/s00421-007-0563-z

Whipp, B. J., & Wasserman, K. (1969). Efficiency of muscular work. *Journal of Applied Physiology*, *26*(5), 644-648. https://doi.org/10.1152/jappl.1969.26.5.644

Wickham, K. A., Wallace, P. J., & Cheung, S. S. (2021). Sex differences in the physiological adaptations to heat acclimation: a state-of-the-art review. *European Journal of Applied Physiology*, *121*(2), 353-367. https://doi.org/10.1007/s00421-020-04550-y

Willmott, A. G. B., Gibson, O. R., James, C. A., Hayes, M., & Maxwell, N. S. (2018). Physiological and perceptual responses to exercising in restrictive heat loss attire with use of an upper-body sauna suit in temperate and hot conditions. *Temperature*, *5*(2), 162-174. https://doi.org/10.1080/23328940.2018.1426949

Willmott, A. G. B., Hayes, M., James, C. A., Dekerle, J., Gibson, O. R., & Maxwell, N. S. (2018). Once- and twice-daily heat acclimation confer similar heat adaptations, inflammatory responses and exercise tolerance improvements. *Physiological Reports*, *6*(24), e13936. https://doi.org/10.14814/phy2.13936

Wingfield, G. L., Gale, R., Minett, G. M., Marino, F. E., & Skein, M. (2016). The effect of high versus low intensity heat acclimation on performance and neuromuscular responses. *Journal of Thermal Biology*, *58*, 50-59. https://doi.org/10.1016/j.jtherbio.2016.02.006

Wyndham, C. H., Morrison, J. F., & Williams, C. G. (1965). Heat reactions of male and female caucasians. *Journal of Applied Physiology*, *20*(3), 357-364. https://doi.org/10.1152/jappl.1965.20.3.357

Zurawlew, M. J., Mee, J. A., & Walsh, N. P. (2018). Post-exercise hot water immersion elicits heat acclimation adaptations in endurance trained and recreationally active individuals. *Frontiers in Physiology*, *9*. https://doi.org/10.3389/fphys.2018.01824

Zurawlew, M. J., Walsh, N. P., Fortes, M. B., & Potter, C. (2016). Post-exercise hot water immersion induces heat acclimation and improves endurance exercise performance in the heat. *Scandinavian Journal of Medicine & Science in Sports*, *26*(7), 745-754. https://doi.org/10.1111/sms.12638

Appendices

Appendix A – Ethics approval form

The University of Waikato
Private Bag 3105
Gate 1, Knighton Road

Hamilton, New Zealand

Human Research Ethics Committee
Roger Moltzen
Telephone: +64021658119
Email:humanethics@waikato.ac.nz

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

17 November 2022

Liam Miller
Te Huataki Waiora - School of Health
DHECS
By email: liammiller.1055@gmail.com

Dear Liam

HREC(Health)2022#34 : Can the physiological response of heat acclimation be predicted?

Thank you for your responses to the Committee feedback.

We are now pleased to provide formal approval for your project.

Please contact the Committee by email (humanethics@waikato.ac.nz) if you wish to make changes to your project as it unfolds, quoting your application number with your future correspondence. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

We wish you all the best with your research.

Regards,

____

Emeritus Professor Roger Moltzen MNZM
Chairperson
University of Waikato Human Research Ethics Committee

Appendix B – Participation consent form

University of Waikato Sport Science Laboratory

Informed Consent Form

I (print name) _________________________ consent to participate in physiological assessment on the following terms:

1. I have read the Explanation of Physiological Assessment Procedures attached and have understood what I will be required to do. I have had the opportunity to ask questions and received satisfactory explanations about the assessment/s to be conducted.

2. I understand that I will be undertaking physical exercise at or near the extent of my physical capacity and there is possible risk in the physical exercise at that level, such as episodes of transient light-headedness, fainting, abnormal blood pressure, chest discomfort. I understand that this may occur although the staff in this laboratory will take all proper care in the conduct of the assessment, and I fully assume that risk.

3. I understand that I can withdraw my consent, freely and without prejudice, at any time before, during or up to two weeks after the last data collection session.

4. I have told the person conducting the assessment of any illness or health condition I have that may contribute to the level of that risk.

5. I understand that the information obtained from the test will be treated confidentially. However, the information may be used for statistical or scientific purposes with privacy retained.

6. I release this laboratory and its employees from any liability for any injury or illness that I may experience during the assessment as well as any subsequent injury or illness that is connected to or to any extent influenced by the assessment.

7. I will indemnify this laboratory with respect to any liability it may incur in relation to any other person in connection with the assessment.

8. I hereby agree that I will present myself for testing in a suitable condition and have abided by any requirements for diet and activity prescribed to me by laboratory staff.

Athlete/Participant Signature ______________________ Date ______________

Witness Name ______________________ Signature ______________________ Date ______________

Appendix C – Participation information form

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

Predicting responses to a heat acclimation protocol in trained triathletes.

Introduction

Endurance performance has been found in many sporting disciplines to be impaired in hot climates. Given the increasing prevalence of endurance events in such hot climates, the implications of heat are becoming more relevant for every athlete, not just those at the elite level. Dozens of interlinked physiological systems are responsible for said performance impairments, all of which can be trained or improved through a heat acclimation protocol. Heat acclimation is the process of artificially exposing yourself to heat stress to train your physiology to become more efficient at heat loss.

We are aiming to measure certain performance markers in the hope of being able to predict how well individuals can acclimate. This would benefit endurance athletes, especially long-distance such as marathons and Ironman, to train and prepare for a performance in the heat best for their specific ability and genetics.

This project forms a part of Liam Miller's Master's research through the Te Huataki Waiora School of Health, University of Waikato.

Who can participate?

If you are an 18-60-year-old, healthy, endurance-trained triathlete or cyclist, then you are who we are looking for. By endurance-trained, we mean engaging in deliberate exercise for at least 30 minutes, at least four times a week and are capable of maximal effort during exercise. You must also be capable of cycling at a steady intensity for 7.5 hours a week over five separate sessions for two weeks consecutively.

You will unfortunately not be able to participate in the study if you have:

- Any injuries, medical conditions or medications that prevent you from exercising for extended periods of time (up to 90 minutes), or at high intensities in a hot environment. Taking any medications that alter heart performance will also make you unable to participate.
- If you have recently been consistently exposed to a hot environment, for example holidaying in 30°C+, or regularly engaging in spa or sauna bathing (≥2 hours a week).

If you agree to participate, you may withdraw from the study at any time during the process of collecting data, and up to 2 weeks after you have completed your final research session.

What will I be asked to do?

All testing will be at the University of Waikato Adam's Centre for High Performance. Following an initial fitness test, you will undergo nine exercise sessions in the Climatic Simulation Chamber at the Adam's Centre.

The study involves:

- An initial briefing and screening session.
- A maximal aerobic fitness test (VO_2 max test) on your own bike, on a supplied interactive trainer. A VO_2 max test involves approximately twelve minutes of cycling with an incrementing workload until you can no longer continue cycling. You will then be explained through the rest of the sessions and arrange a loose schedule for the repeated sessions.

- You will be completing two types of sessions, heat response tests and heat acclimation sessions. All the sessions will be at 36°C, with 65% relative humidity.
- The first and last sessions in the climatic chamber will be heat response tests. These will consist of 20 minutes at a moderately stressful intensity, followed directly by a 30km time trial.
- For the 24 hours prior to the heat response tests you will be asked to refrain from any alcohol consumption or intense exercise. Arriving well-hydrated for all sessions is also requested.
- All heat acclimation sessions follow the same design. They require 90 minutes of continuous cycling at a moderate intensity which will be determined from the VO_2 test and will be the same intensity for the beginning period of the heat response tests.
- You will be required to measure thermal load across your normal training sessions outside of the laboratory sessions. When you have completed your first heat stress test, you will be assigned a wearable device to use in any other exercise that is practically applicable. This is to measure thermal changes, and the device is very similar to the wearable phone-holders that are worn around the upper arm. The details will be explained further before the first fitness test, but all we require is the temperature data from the wearable, not the specifics of the session.

	Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**
Week 1	HRT	HA	X	HA	HA	X	HA
Week 2	HA	X	HA	HA	X	HRT	X

What are the benefits for me?

- Participants will receive a summarised spreadsheet of all data collected throughout the research to use as you wish for your own sport participation. This will include useful practical measures such as sweat rate, sweat concentration, and VO_2 max. Once it has been sent to you, it is your property, and you may use it as you wish.

- You will experience a heat acclimation protocol which may be relevant to any future competition you are going to travel for in an extreme and unfamiliar environment.

What are the potential risks?

- At points throughout the participation, you will be required to exert maximal physical effort, which in hot conditions can be increasingly uncomfortable. Endurance exercise, especially maximal, carries risks of cardiovascular and muscular injury. Being fit and participating in supervised conditions lowers these risks, but they are still present.
- Exercising in the heat increases the likelihood of dehydration and related side effects such as nausea and fainting. To reduce the chances of this, throughout the heat exposures you will be able to drink water freely.
- You are responsible for your own physical exertion, as we do not know your own physical ability. You can stop at any point during any session, and we can stop you if we feel you are unsafe from the measurements recorded. If we suspect you are becoming too hot, then we will end the session
- Self-inserted rectal thermometers will be used to measure core temperature. These are thin (4mm), flexible, and sterile, and are individually assigned to each participant. They may provide discomfort initially, but this normally disappears very quickly. They may provide a sense of social discomfort but understand this is crucially important to the validity of measurements and will only be required for the two HRTs (i.e., only required twice of the ten sessions).

What will happen to the results?

All results will be collated and analysed individually. No other participants will have permission to view or be informed about any other data. All data published will be absent of any information that could be used to identify participants. Data collected will be used only for the purposes described above. Each participant will be assigned a participant ID, and all data from everyone will be used in the context of relevant ID in place of names. Certain personal information such as age, frequent weight measurements and physiological measures will all be anonymised through these IDs. Data will be stored in a password-protected computer. in a place and will be accessed by nearly no one other than researchers. All your data is confidential and will not be discussed with anyone outside the scope of the research project. All data is required to be stored by the university for several years and may be used for purposes of presentations and posters in addition to the main thesis. This data will not provide any information that can be used to identify participants.

Who do I contact?

To ask questions or confirm your enrolment as a participant, contact:

Liam Miller: liammilller.1055@gmail.com; 021 335056