Alleviating Heat Strain During Exercise: Hand Cooling and Thermoregulation

Alan Dean Ruddock

A thesis submitted in partial fulfilment of the requirements of Sheffield Hallam University for the degree of Doctor of Philosophy

August 2017

Abstract

Exercise capacity and performance are impaired in hot and humid environments, principally due to an increased body temperature and cardiovascular strain. Strategies that alleviate heat strain and improve exercise capability are therefore meaningful from a safety and performance perspective. These strategies are often assessed using core body temperature as a primary outcome, usually derived from inside the rectum, but increasingly from the intestinal tract using gastrointestinal telemetry pill systems. The reliability of intestinal temperature, however, was unclear. Therefore, the purpose of study 1 was to investigate the inter-day reliability of intestinal temperature during an exercise-heat challenge. Gastrointestinal temperature demonstrated good reliability but researchers and practitioners should be aware of potential heteroscedasticity as the magnitude of error increases with temperature. This information is useful when examining the effectiveness of strategies to alleviate heat strain and improve performance. Indeed, there are many interventions designed for this purpose, however, few are practical enough to be used during continuous exercise in hot environments. The objective of study 2 was to systematically identify and meta-analyse the effect of practical cooling strategies applied during exercise in hot environments. Cooling during fixed-intensity exercise before a self-paced performance trial improves endurance performance in the heat. These improvements are most likely mediated by an improved rating of perceived exertion and heat strain but not by attenuating an increase in body temperature. A potentially effective site for limiting increases in body temperature during exercise is the hands. Therefore, the purpose of study 3 was to quantify the physiological and perceptual responses to hand immersion in water during recumbent cycling in a hot environment. Hand immersion in cold water attenuated an increase in body temperature compared to a thermoneutral control and elicited beneficial effects on heart rate, skin temperature and skin blood flow. The aim of study 4 was to extend these findings to investigate the effects of prototype cooling gloves worn during exercise in a hot environment. The cooling gloves decreased indices of intestinal and skin temperature as well as heart rate. Beneficial effects were also observed for rating of perceived exertion, thermal comfort and thermal sensation. The findings from these studies have practical implications for assessments of interventions using gastrointestinal temperature, the choice of practical cooling strategy used during exercise in the heat and the application of hand cooling strategies. Future research should aim to improve the ergonomics of the cooling gloves designed in study 4 and investigate their impact on exercise capability in hot environments.

Contents

List of figures

List of tables

Acknowledgements

This project wouldn’t possible without the help of several key individuals. I couldn’t have asked for a better supervisory team; Alison, Garry and Liam, your guidance and support has helped me develop as a researcher more than I thought possible. I’d also like to extend my thanks to Prof. Edward Winter for our many chats and work together; you have helped shape my work as an academic and a person. Thank you to all the colleagues I have conducted research with and worked with on consultancy projects over these past years, this includes the participants, athletes and coaches; I've learned from you all and there’s much influence and evidence of this within this thesis.

Special thanks to my colleagues in the technical office, Helen Lloyd, Alayne Flowers, Katy Nunn, Neil Donovan, Steve Scott, Steve Thompson, Sean Hudson, Tom Parkington, Chloe Rodgers, Brent Robbins, Ian Brookes and Richard Badger not only for your technical assistance but making Sheffield Hallam University a great place to work. I’d also like to acknowledge the assistance of Kosmas Chatziopoulos and Chris Jenks, your hard work and support within the laboratory was integral.

To all those who have participated in the studies, thank you. You gave up your time to push yourself to the limits and I will be forever grateful for your efforts.

Finally thank you to my family. Rebecca, your support and inspiration has been fundamental and without you there would simply be no work. Lochlan and Indi, this is for you. This thesis is testament to what you can achieve with hard work and persistence.

Statement of Originality

I declare that the work presented in this thesis is entirely my own, with the exception of the following:

1. Study 1 represents work conducted by A.D. Ruddock, assisted by Dr. G.A. Tew and Dr. A.J. Purvis. A.D. Ruddock was responsible for the study design, ethics application, recruitment, data collection, data analysis as well as preparation, submission and revision of the manuscript to the Journal of Strength and Conditioning Research. Dr's Tew and Purvis provided supervisory and editorial support throughout the project from inception to publication.

2. Study 2 represents work conducted by A.D. Ruddock, assisted by Dr. G.A. Tew, Dr L. Bourke and Dr. A.J. Purvis and Mr B. Robbins. A.D. Ruddock was responsible for the study design, data collection, data analysis as well as preparation, submission and revision of the manuscript to Sports Medicine. Dr's Tew, Bourke and Purvis provided supervisory and editorial support throughout the project from inception to publication. B. Robbins provided assistance in methodological screening of studies and verified the digital data extraction process.

3. Study 3 represents work conducted by A.D. Ruddock, assisted by Dr. G.A. Tew and Dr. A.J. Purvis. Technical assistance was provided by Mr K. Chatziopolous and Mr T. Parkington. A.D. Ruddock was responsible for the study design, ethics application, recruitment, data collection, data analysis as well as preparation, submission and revision of the manuscript to the Journal of Sports Sciences. Dr's Tew and Purvis provided supervisory and editorial support throughout the project from inception to publication.

4. Study 4 represents work conducted by A.D. Ruddock, assisted by Dr. G.A. Tew and Dr. A.J. Purvis. Technical assistance was provided by Mr C. Jenks. A.D. Ruddock was responsible for the study design, ethics application, recruitment, data collection, data analysis as well as preparation, submission and revision of the manuscript to the Journal of Thermal Biology. Dr's Tew and Purvis provided supervisory and editorial support throughout the project from inception to publication.

With the exception of any statements to the contrary, all the data presented in this thesis are the result of my own efforts. In addition, no parts of this thesis have been copied from other sources unless referenced and acknowledged. I understand that any evidence of plagiarism and/or the use of unacknowledged third party data will be dealt with as a serious matter.

Signed:

Date:

Publications and conference presentations from this programme of research

Peer reviewed full-length articles

Ruddock, A.D., Tew, G.A. and Purvis, A.J. (2014). Reliability of intestinal temperature using an ingestible telemetry pill system during exercise in a hot environment. *Journal of Strength and Conditioning Research*, **28,** 861-869

Ruddock, A.D., Robbins, B., Tew, G.A., Bourke, L. and Purvis, A.J. (2017). Practical cooling strategies during continuous exercise in hot environments: A systematic review and meta-analysis. *Sports Medicine*, **47**, 517-532

Ruddock, A.D., Tew, G.A. and Purvis, A.J. (2017). Effect of hand cooling on body temperature, cardiovascular and perceptual responses during recumbent cycling in a hot environment. *Journal of Sports Sciences*, 35, 1466 – 1474.

In review: Ruddock, A.D., Tew, G.A. and Purvis, A.J. (2017) Effects of cooling gloves on thermoregulatory responses during exercise in a hot environment. *Journal of Thermal Biology.*

Conference abstract publications:

Ruddock, A.D, Tew, G.A. and Purvis, A.J. (2014). Effect of hand cooling on body temperature, cardiovascular and perceptual responses during recumbent cycling in a hot environment. *2nd World Congress of Cycling Science, Leeds, UK.*

Conference proceedings:

Ruddock, A.D., Tew, G.A. and Purvis, A.J. (2013). Reliability of intestinal temperature using an ingestible telemetry pill system during exercise in a hot environment. *Faculty of Health and Wellbeing Research Day, Sheffield Hallam University, UK.*

Ruddock, A.D, Tew, G.A. and Purvis, A.J. (2014). Effect of hand cooling on body temperature, cardiovascular and perceptual responses during recumbent cycling in a hot environment. *Faculty of Health and Wellbeing Research Day, Sheffield Hallam University, UK.*

Ruddock, A.D., Robbins, B., Tew, G.A., Bourke, L. and Purvis, A.J. (2015). Practical cooling strategies during continuous exercise in hot environments: A systematic review and meta-analysis. *Faculty of Health and Wellbeing Research Day, Sheffield Hallam University, UK.*

General introduction

Sport and exercise science is the scientific study of factors that influence the ability to perform exercise [1]. The physiology of exercise is the study of how the body responds and adapts to exercise; this can be quantified acutely in response to an exercise challenge or chronically in response to a period of training or some form of intervention. The quantification of these demands is not a new concept and has been *described*, albeit simplistically by modern methods, since ancient times. In recent years there has been an increasing focus on *explaining* how and why athletes respond and adapt to exercise through the disciplines of sport and exercise science. The factors that influence sports performance are complex, requiring an integrative approach between and within disciplines. At professional and Olympic standard, athletes are supported by teams of support staff who work to optimise performance often under challenging conditions and external constraints. Rarely is the path to Olympic Gold pursued without several performance problems.

Major sporting events always present constraints for athletes; notably they take place during summer months in the Northern Hemisphere and coincide with high ambient temperatures. Pieser and Reilly [2] recount four consecutive Olympic games of Paris (1900), St. Louis (1904), London (1908) and Stockholm (1912) that all took place during unseasonable heat waves (≥ 25 °C in the shade at the start of the marathon). Furthermore, a series of Summer Olympic games from 1980 to 2008 (Moscow, Los Angeles, Seoul, Barcelona, Atlanta, Sydney, Athens and Beijing) have also taken place in high ambient temperatures [2] and international sporting events are increasingly being held in hot and humid environments which poses challenges for organisers and athletes.

The combination of heat and athletic performance is so challenging that the eminent cardiovascular physiologist Loring Rowell stated; *"Perhaps the greatest stress ever imposed on the human cardiovascular system (except for severe haemorrhage) is the combination of exercise and hyperthermia. Together these stresses can present life-threatening challenges, especially in highly motivated athletes who drive themselves to extremes in hot environments"* [3]. This cardiovascular strain however, is not present in all athletic challenges. Indeed, sprint performance, which relies little on cardiovascular function is likely improved in hot environments, whereas endurance performance (2 min effort to many hours) is impaired [4]. Endurance exercise combined with heat stress has led to the investigation of strategies to attenuate high body temperature, preserve exercise capability and prevent heat illness.

Accurate quantification of temperature using standardised assessments, in particular at sites of the body identified as 'core' regions as well as components of the environment, is important during heat stress and strain [5]. Our understanding of how and why temperature influences not only human, but agricultural and manufacturing endeavours has emerged from ancient times and evolved through the merging of art, science and religion. These developments were critical to our current understanding of thermodynamics, thermometry and contemporary technological advancements that enable us to assess temperature with relative ease and in context with physiological influences. Equally important is the quantification of day-to-day temperature change because confident interpretations of data, and recommendations regarding the suitability of techniques designed to alleviate heat strain can only be made from measurement tools that have relatively low measurement error. Section 1 of this thesis introduces the quantification of temperature from divine origins to contemporary considerations for thermometry and appraisal of local temperature influences to statistical assessments of measurement error - all of which are required to understand and make confident interpretations of body temperature.

Humans attempt to maintain body temperature around 37 °C but the reasons for this are largely unknown, as are the precise mechanisms that control body temperature. Nevertheless, autonomic and behavioural thermoregulation are two broad models that describe, and in-part explain, attempts to maintain thermoneutrality. It is important to distinguish between these two distinct mechanisms, especially in sport and exercise science, as the interaction between type of activity (fixed intensity or self-paced), athlete morphology and physiology and the environment determines the rate and magnitude of metabolic heat production and subsequent heat storage. These interactions have a direct effect on physiological and perceptual responses to exercise in hot environments, which are key determinants of the ability to perform endurance exercise. Therefore, section 2 details the current understanding of how body temperature is regulated mechanistically, considers the physiological demands imposed by heat strain and finally reviews current theories for why exercise capability is impaired in hot environments.

Alleviating heat strain and improving exercise capability in hot environments is important from occupational, military and sporting perspective. Interventions used by scientists, coaches and athletes to alleviate heat strain can be broadly categorised as heat acclimation/acclimatisation training and cooling protocols. Cooling is used as an acute strategy that has less physical and logistical demands than heat acclimation. It can be applied before exercise, at intervals or continuously during exercise and generally has favourable effects on exercise capability in hot environments [6–9]. Cooling strategies used during exercise, when the effects of heat strain are most pronounced, can be effective but there are few strategies that might be practically useful during continuous exercise in the heat. Moreover, the physiological mechanisms through which these protocols elicit their effects are unclear. Section 3 details the evidence for two main types of acute strategy designed to alleviate heat strain; pre-cooling and cooling during exercise and considers how the success of an intervention is dependent on the proceeding task, individual responses and whether the cooling strategy is applied externally or internally. These distinctions are important from a practical perspective, as is the classification of the type of exercise trial performed to investigate the efficacy of a treatment and whether or not cooling during exercise is practical or impractical.

The hands are a favourable site for cooling because they have anatomy that suits heat transfer [10] and specialised vascular structures capable of inducing large rates of blood flow [11, 12]. Most research that has investigated hand cooling has been conducted either during intervals between bouts of exercise or at the end of exercise to assess core body temperature cooling rate. Some studies have used hand cooling during exercise with success [13, 14] but the mechanical cooling device used in these studies is impractical to use during exercise. Despite the potential to be an effective and practical cooling strategy, there is a lack of research focused on hand cooling during continuous endurance exercise in the heat. Section 4 therefore, introduces the hands as a potentially effective site for cooling during exercise and critically examines the scientific literature that supports the application of hand cooling during exercise.

The success of these interventions is often determined by how practically effective they are usually assessed by comparing body temperature responses, specifically an assessment of core temperature, with a control trial. A high core temperature is associated with a wide range of integrative physiological demands, such that a successful intervention typically attenuates an increase in core temperature and associated physiological and perceptual responses. Therefore, the primary aims of the first 2 investigations in this programme of research were to systematically review and meta-analyse practical cooling strategies to describe and explain how and why these strategies influence performance and quantify the reliability of an ingestible telemetry pill system for assessment of core temperature. The 3rd and 4th investigations of this thesis examine the efficacy of hand cooling during exercise in hot environments and provide a mechanistic basis of action for future studies to develop an effective practical hand cooling strategy for use during exercise in the heat.

Chapter 1: Literature review

1.1 Historical perspectives: Religion, the arts and science

1.1.1 Medicine: Progress through ancient history, the Renaissance and European imperialism

Before civilisation, humans lead a nomadic life, foraging, scavenging and hunting prey primarily in Eastern Africa [15]. To survive, humans needed to understand when to expend energy and when to conserve it; these decisions were often dependent on an understanding of environmental conditions. For example, through rudimentary observation of environmental temperature using thermal sensation and position of the sun, they would have informally generated a simple research question; “what happens if I move in the midday heat?” They would have observed that they felt hotter in the heat and through experience assumed that physical activity would increase energy expenditure and water loss. Subsequently, they understood that resting in the shade felt better and conserved energy and adopted this approach until the environmental conditions improved to suit more extensive movement. These steps might be considered basic forms of science, or simply a *way of working.* Modern scientific endeavour shares many common characteristics with early human decision-making and has principally evolved from our requirement to learn, transfer knowledge and change practice from generation-to-generation.

Humans migrated from Eastern Africa, likely because of rapid changes in environmental conditions and settled in regions with more stable climates such as The Levant. Indeed, critical periods of hominid evolution are suggested to have occurred as a result of increasingly rapid environmental aridity [16]. The success of civilisation depended on the reproducible harvesting of food and energy sources, and new populations began to formalise a way of working that would eventually form the basis of farming. The abundance of food and water is intrinsically related to seasonal environmental conditions, and for societies that understood this link, commerce and economy developed, and civilisations prospered. Successful civilisations understood how temperature and seasonal variations influenced commodities such as livestock and grains. For those civilisations with developed economies, day-to-day life was no longer a struggle to survive because of poor energy intake, but instead, a struggle to avoid illness and disease. From these demands, basic forms of medicinal practice emerged. Early schools of medicine, with divine origins, linked temperature to illness and disease. One of the oldest forms of medical practice, Ayurveda, treats patients based on body temperature [17]. Ayurvedic medicine (*Ayur* - life, *Veda* - science) (c100BCE), which is still practised today, teaches that an imbalance in *Pitta Dosha*, a 'life force' that controls body heat is balanced by eating cool foods and massaging with cool oils. Empedocles (c490-430BCE) is credited as being the originator of the theory of the four classical elements of life; earth, water, air and fire [18], all of which had different characteristics and accordingly, temperature. Hippocrates (*c*460-360 BCE) and then Galen (*c*129-216 AD) sought to balance the "four humours", in their medical practice, and '*the cure for one which has been heated is chilling´* has been transcribed from Ancient Greek and Roman texts.

Indeed, ancient physicians were skilled at using their hands to detect temperature changes in the body and diagnose illness [19]. However, it was not until the Renaissance, when shifts from beliefs in divinity and interests in science, engineering and technology began to merge. Skilled Venetian glass blowers made reproducible glass shapes and were utilised by early scientists such as Santorio Santorio (1561-1636) and Galileo Galilei (1564-1642) to investigate the effects of temperature. Santorio was especially interested in the concept of energy balance and temperature and after each meal, he would weigh himself [20]. Santorio's experiments inevitably led to the concepts of insensible water loss, and he linked this to changes in environmental temperature. Santorio needed to quantify temperature changes in his laboratory and developed the ‘thermoscope’ using alcohol. Unfortunately, the thermoscope was not a closed system, and the alcohol solution he used was unreliable, mainly because of changes in barometric pressure. Galileo also attempted to develop a thermoscope around the same time but failed due to the same issues [21]. Sealed tubes and the predictable expansion of Mercury combined with improved Venetian glass engineering were used by Fahrenheit (1720), and later Celsius (1742) and Linnacus (1750) to produce stable temperature assessments [19]. This enabled the standardisation of thermometry using fixed points for the freezing and boiling points of water and the development of the Celsius/Centigrade (°C) and Fahrenheit (°F) temperature scales [21]. However, despite the seminal work of Professor Carl Wunderlich (1868), who pioneered the quantification of body temperature in medicine using thermometry and the Celsius scale, physical diagnosis of body temperature using the hands was still common throughout the 19th century. Wunderlich’s quantitative approach was, at the time, subject to much criticism [5, 19].

1.1.2 The industrial revolution: Standardisation, engineering and thermodynamics

In engineering, however, a change in the concept of temperature was being developed because of the industrial revolution. The Système International d'unités defines temperature in units of the thermodynamic Kelvin scale [22]. The Kelvin scale, introduced by William Lord Kelvin in 1848 has an absolute zero (-273.15 °C) as its null value, the point at which all thermal motion ceases and is a fundamental concept in the laws of thermodynamics [23]. The Kelvin is also a ratio scale because of this null value, whereas the Fahrenheit and Celsius are interval scales. The industrial revolution introduced the concept of machinery replacing animal work and with it a focus on energy, economy and effectiveness of these machines. Subsequently, engineers working to maximise the output of these systems developed principles to define the concepts of energy transfer to improve machinery. One such example is that of the steam engine designed by Boulton and Watt (1775), who needed an energy equivalent to compare theirs and other atmospheric steam engines. They called this power, it was designated the eponymous watt (W) and is equivalent to 736 horsepower [1].

The laws of thermodynamics born from industry, the formalisation of physics and mechanical engineering, define energetic relationships and principles of heat transfer [5]. Energy possessed and exchanged exists in the form of dynamic (kinetic) and static (potential: mass-, chemical-, nuclear- and force-related energies) states. This energy can be converted into another form (First Law of Thermodynamics) and used to perform work on another system by transferring energy. In myocytes, chemical energy stored in a glucose molecule is released to form adenosine triphosphate, which enables muscle to exert force. The total amount of energy possessed by an object is known as its enthalpy, which is minimal at temperatures approaching absolute zero (Third Law of Thermodynamics) and increases as pressure and volume (mass) increases. The kinetic component of energy causes sub-atomic and cellular movement and collisions. This releases thermal energy [5]; thus heat is a function of collision frequency. If a system increases proximity with a system with less enthalpy, energy is exchanged down a thermal gradient (Second Law of Thermodynamics) and transferred until a thermal equilibrium is achieved. This can be accomplished through a change in state (solid, liquid, gas) or via conductive (molecule to molecule), convective (mass flow), or radiative transfers. In accordance with Newton's cooling law (heat-transfer law), the rate of temperature change is proportional to the size of the existing thermal gradient determined by the characteristics of an object (shape, dimensions, specific mass, thermal conductivity and specific heat capacity) [5]. When three or more systems are in thermal equilibrium they transfer the same amount of energy between each other (Zeroth Law of Thermodynamics), implying that heat transfer depends upon a measurable physical characteristic- that is temperature [24].

1.2 Thermometry

1.2.1 General Considerations

Despite many advancements in medicine, thermometry has remained essentially unchanged since the 1800's [19]. The gold standard is still considered to be the mercury-based glass thermometer. However, it is not always suitable for use in sport and exercise applications, and the Health and Safety Executive recommend care when handling mercury-based thermometers [25]. Ethanol-based and digital thermometers are popular choices for the assessment of environmental conditions but are considered unsuitable for assessments of body temperature. For these applications, the use of thermistors, thermocouples, short-wave telemetry and infrared thermometry are preferred. Irrespective of the site of application, there are several requirements for adequate quantification of temperature. Firstly, the method should have agreement (systematic error) within 0.1°C of a certified, calibrated gold-standard [19] and its random error should be homoscedastic throughout the measurement range. It should not be influenced by the environment unless intended, for example, a black globe thermometer should be influenced by radiant heat, whereas a device that measures skin temperature should not, even in direct sunlight. An important consideration is the applicability of the thermometer for the site of application; a sensor too large might not fit appropriately on the site of interest and confound data collection. Similarly, misapplication by the user might cause invalid data. Finally, and particularly important for less sensitive thermometers, is the requirement for the measurement site to be in thermal equilibrium with the measurement device [19].

1.2.2 Infrared thermometry

In infrared thermometry, emissivity (radiative energy) of a surface or surfaces is absorbed within a device, such as a camera or a probe, causing changes in electrical resistance, manifesting as a colour palette displayed on a visual screen [26]. The same principles apply to commonly used tympanic temperature assessments used in routine medical practice, and field-based thermometry which have been recommended for use in clinical practice [27, 28]. These systems appear to produce valid assessments of temperature in stable and static environments, for example at rest and during walking [29]. Thermal cameras, however, appear to be less valid during exercise [26] primarily because sweat on the skin surface can vary emissivity and decrease reliability. Furthermore, infrared assessments of tympanic temperature can be influenced by environmental conditions and the positioning of the probe in relation to the tympanic membrane [19].

1.2.3 Thermocouples and thermistors

Two other common methods of temperature quantification are the thermocouple and thermistor. A thermocouple consists of two different conductors, both contact each other at a temperature sensor, then split towards separate reference junctions of a known temperature. A measurable voltage, proportional to the temperature difference is then used to infer temperature. The use of thermistors are more common for human body temperature quantification than thermocouples. Resistors are used to increase or reduce electrical current flow dependent on temperature or a conductor that resides within the region of interest; hence the term thermistor. The voltage is proportional to temperature and is valid within a pre-specified range. Thermistors are relatively low-cost, low-maintenance and because these methods generally have good sensitivity to temperature changes are the preferred assessment method for body temperature during exercise; although, hardwired connections to data loggers make ambulatory field testing unfeasible.

1.3 Quantifying body temperature

1.3.1 Core body temperature

In sports science locations frequently chosen for assessment of core body temperature include the oesophagus, rectum, gastrointestinal tract and tympanic membrane; these choices usually reflect the practicality of a measurement site for the sole purpose of assessing temperature. Often, each of these sites are termed ‘core temperature’ and are thought of as critical locations for afferent temperature relay. The importance of core temperature is reflected in the assignment of larger weightings in the calculation of mean body temperature which can range from 0.95 to 0.65 in hot and moderate temperatures, whereas skin temperature might only represent 0.05 to 0.35 of mean body temperature [30]. In reality, some organs have a high metabolic rate (brain, liver, heart and kidney), particularly skeletal muscle during exercise and are primary heat sources; while less-active tissues function as heat sinks [5]. Even under steady-state conditions, thermal energy is redistributed throughout the body via conductive and convective heat exchange and different regions of the body have different resting temperatures (Figure 1). This is because tissue temperature is the sum of three variables; tissue heat capacity, local metabolism and local blood flow. Care should be taken when interpreting temperature between regions, because even if similar in magnitude they might not reflect the same underpinning mechanisms. This highlights the need to consider whether changes in temperature are due to changes in local conductive heat transfer, local or central blood temperature and metabolism. Indeed, a primary appraisal of these three variables at the sites commonly used to assess core body temperature is warranted to understand how tissue temperature is influenced by exercise or interventions designed to manipulate body temperature, ideally before conclusions are drawn.

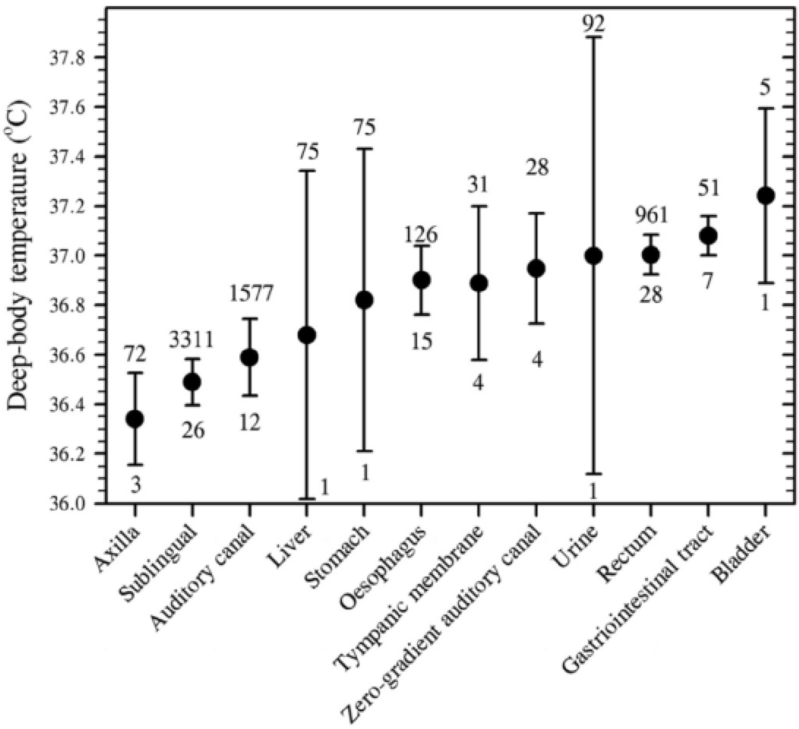

Figure 1: Variances in resting body temperature

Black dots represent mean, error bars are 95% confidence intervals. Numbers above error bars indicates total number of participants within data sample. Numbers below error bars indicate number of studies included in the analysis. Extracted from [5]

1.3.2 Rectal temperature

Rectal temperature assessed using a thermistor is the most frequently used location in sports science and medical practice. The superior rectal artery supplies blood to the region of the rectum typically assessed at 12 to 15 cm. However, this and the haemorrhoidal veins are small relative to the size of the rectum. Thus the rectum is an under-perfused site and changes in temperature are primarily based on conductive heat transfer and subject to the temperature of surrounding tissues [5]. This limited blood supply also makes rectal temperature less sensitive than changes in skin temperature, which can be problematic when manipulating skin temperature relative to rectal temperature. Indeed, concerns have been raised regarding the suitability of rectal temperature to assess phase delays to reach steady state temperature, or in the case of short rapid heating and cooling, never attaining a steady state [5]. Moreover, thermoeffector responses might precede established temperature thresholds when assessed at the rectum [31], complicating the interpretation of thermophysiological responses during exercise and heat stress. Due to these limitations, some authors exert caution when utilising rectal temperature assessments [5]. Nevertheless, the rectum has been recommended for use in clinical and applied practice because of its practicality and reliability [32, 33].

1.3.3 Oesophageal temperature

On the contrary, oesophageal assessments are impractical but might be an ideal location from which to assess changes in core body temperature. An oesophagal probe is typically advanced to a location between the spinal column, left bronchus, the heart and several major blood vessels including major cardiac arteries and veins (Figure 2). The oesophagus has a low heat capacity and because it is near vessels and organs is influenced by rapid convective heat transfer and closely tracks central blood temperature. This is the likely mechanism supporting the rapid time delay (80 s) in oesophageal temperature assessment and a clear advantage for this measurement site [34]. In most situations, however, researchers and applied practitioners avoid oesophageal assessment because inserting the probe is difficult for both researcher and participant.

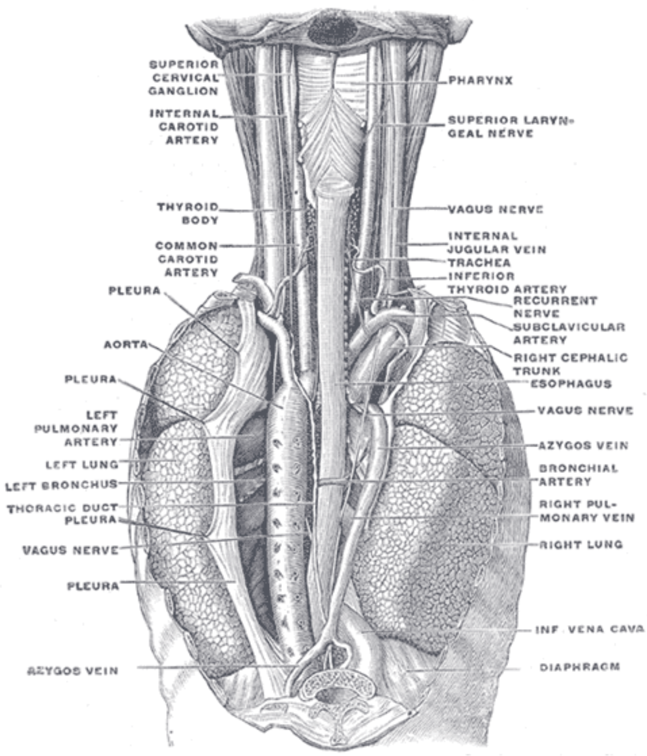

Figure 2: Anatomical positioning of the oesophagus

Extracted from [288]

1.3.4 Tympanic temperature

The tympanic membrane has similar qualities to the oesophagus. It has low heat capacity, no metabolic heat production and blood is supplied from vessels derived from the carotid artery. However, carotid blood temperature is cooler than jugular venous blood [35], and is unlikely to represent true central blood temperature. Moreover, head temperature, and subsequent heat conductance to the auditory canal, as well as ambient temperature and air flow might influence tympanic temperature assessments [33]. In addition, for valid assessment of tympanic temperature, the probe must reside on the surface of the tympanic membrane to satisfy the principles of thermometry. Finally, infrared assessments of tympanic temperature are subject to the same issues of emissivity and equilibration with the auditory canal as previously mentioned [36].

1.3.5 Intestinal temperature

Intestinal temperature is typically assessed using an ingestible telemetry pill because advancing a thermistor to a fixed location within the intestinal tract is unfeasible during exercise. Although this provides options for ambulatory assessment of temperature, the absence of a fixed anatomical position presents a number of problems [37] relating to the principles of thermometry. Firstly, because of gastric motility it is difficult to determine the precise local temperature influencers. Depending on the time from ingestion the pill might reside in the stomach or any part of the intestine without a clear understanding of the exact location. These concerns can be limited somewhat by standardising ingestion and recording times, assuming that gastric emptying times and motility are reliable. Nevertheless, there is the possibility that the location of the ingestible pill will reside in different locations of the intestinal tract between individuals, changing the magnitude of influence on temperature from various sources.

Even if the telemetry pill has exited the stomach and resides within the intestine, there is still chance for the pill to be influenced by stomach temperature because if the pill is located in the duodenum or transverse colon it might come in close contact with the stomach and be influenced conductively by its temperature, especially if cold fluids have been ingested [38, 39]. Moreover, naturally the gastrointestinal tract has a temperature gradient, evidenced in animal studies and through comparisons between oesophageal and rectal comparison [37]. At rest the gastrointestinal tract is well perfused by the celiac, superior mesenteric, and inferior mesenteric arteries [40]; however, during moderate intensity cycling at 65% $\dot{V}O_{2peak}$ blood flow to splanchnic regions is decreased, due to a 50% reduction in the hepato-splenic and a 25% reduction in the mesenteric blood flow [41]. This changes the underpinning local temperature influences from a combination of convective and conductive heat transfer to predominantly conductive heat transfer, similar to the mechanisms that influence rectal temperature. Intestinal temperature might also be influenced by proximity to metabolically active tissues, although the kidneys are closest in proximity to the gastrointestinal tract they produce relatively little heat compared to skeletal muscle [42]. Nevertheless, intestinal sites appear to respond faster than rectal assessments to changes in temperature but more slowly than oesophageal, but whether this relationship is maintained at higher intensities of exercise and thermally stressful environments is unclear [37].

1.4 Statistical assessments of error: defining of statistical terminology

When a site has been appraised mechanistically, logistically and practically it is important that the assessment device and the location is valid, reliable and sensitive. These are key metrics that underpin the interpretation of quantifiable data and are often associated with other terms such as precision, reproducibility, agreement and accuracy.

1.4.1 Validity

1640's - "Sufficiently supported by facts or authority, well grounded" [43]

In sport science, validity is; "*the ability of an assessment tool to reflect what it is designed to assess*" [44]

1.4.2 Precision

Mid-15th century Middle French precis "condensed, cut short", from latin praecisus "abrupt, abridged, cut off". [45]

Can be thought of as the number of significant figures to which an assessment has been made, for example a measurement of 0.01 cm is more precise than 1 cm.

1.4.3 Reliability, reproducibility and agreement

These terms are often used interchangeably.

> *Reliability from religate; latin religare "fasten, bind fast," from re-, intensive prefix (see re-), + ligare "to bind"* [46]
>
> *Reproducibility from reproduce - 1610s, "to produce again," from re- "again" + produce (v.), probably on model of French reproduire (16c.). Sense of "make a copy" is first recorded 1850; that of "produce offspring" is from 1894.* [47]
>
> *Agreement - In Middle English is from late 15c. Of things "to coincide," from 1520's.* [48]

More simply they can be thought of as the consistency, or magnitude of error between results [44].

The suitability of an assessment tool is usually determined by a researcher or practitioner based on the magnitude of error and intended purpose. It might even be considered on its merits of its sensitivity in relation to the size of the expected treatment effect.

1.4.4 Sensitivity

> *From sensitive; "late 14c. Meaning "easily affected".* [49]

That is, can the assessment tool, in relation to the measurement error and a typical intervention be sensitive enough to ascertain a true effect. Otherwise thought of as a signal:noise ratio [50], where the signal is the magnitude of improvement after an intervention and the noise is the error in the assessment tool. Having an assessment that has little error is an advantageous starting point to determine the effectiveness of an intervention.

When the above concepts are combined successfully, the assessment tool is generally regarded as *accurate,* although, this is sometimes mistakenly interchanged with validity.

1.4.5 Accuracy

> *From accurate; 1610's done with care from latin accuratus "prepared with care, exact".* [51]

An accurate assessment is, therefore, one that is valid, precise and reliable.

1.4.6 Reliability

Of all the above concepts, it is reliability that should be quantified first when determining the practical utility of an assessment tool; an assessment will not be accurate if it does not provide consistency in repeated measures under controlled conditions. Two components of variability are of interest in reliability analysis; systematic bias and random error, the sum of which is known as total error [44]. The magnitude and trend for an assessment to be different either positively or negatively is termed systematic bias. This might be caused by learning effects, insufficient recovery, training effects or motivation [52]. Random error is larger than systematic bias and might be due to biological or mechanical error, or inconsistencies in experimental protocols. Often, in physiological or performance tests, random error increases as an assessed variable increases in magnitude, in these cases data are said to be heteroscedastic [44]. However, this is not always the case as the variance in performance for high-performance athletes is typically small [50]. Conversely, when random errors are similar in magnitude as the size of the assessed value increases, the data are said to be homoscedastic. A Bland-Altman plot [53] can reveal the presence of heteroscedasticity and such an investigation can form the basis for the recommendations of suitable reliability statistics. Figure 3 illustrates examples of error spread across measurement ranges.

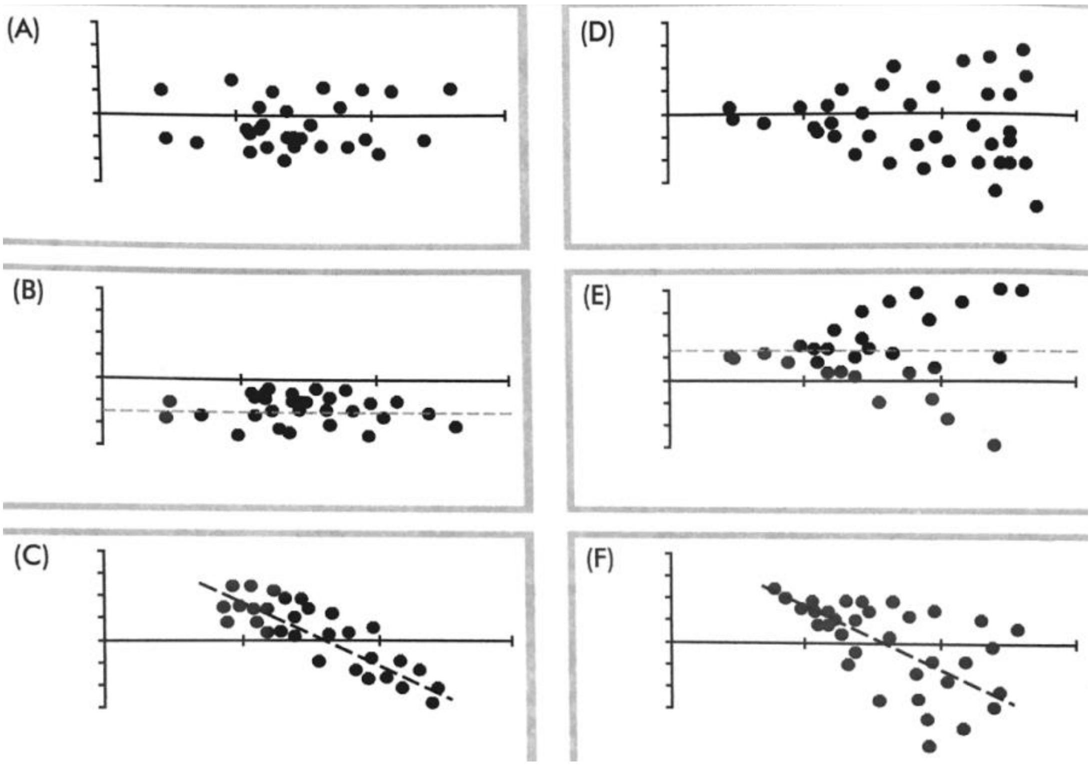

Figure 3: Examples of systematic and random error according to the size of the assessed value

Dotted line indicates systematic error. A = proportional random error; B = uniform systematic and random error; C = proportional systematic error, uniform random errors; D = no systematic error with proportional random error; E = Uniform systematic error with proportional random error; F = proportional systematic and random error. [54]

Linear regression can be used in the formal investigation of heteroscedasticity by plotting a line of best fit through the data points. If the resulting, correlation coefficient is close to zero (e.g. -0.2 to 0.2 = trivial to small correlation [55]) then the random errors can be considered consistent across the assessment range, and the data can be regarded as homoscedastic; the reliability statistic can then be reported in absolute units. If the correlation coefficient lies outside the range, the data should be assessed and reported as a relative reliability statistic. Although the data can be log-transformed to make the error more uniform. The quantification of the type of error present is important. For example, if individuals who score the best on a test also demonstrate the greatest magnitude of error between tests, it is likely that small yet beneficial treatment effects would be undetected because of this error.

1.4.7 Systematic and random error

Systematic bias can be assessed by calculating the mean difference between two samples. It can also be evaluated using a paired t-test, where a non-significant t value would denote no statistically significant difference between samples and denote good reliability. Some statisticians caution against the use of a paired t-test, since the t statistic is dependent on random variation; more specifically, the standard deviation of the sample and sample size [44]. The likelihood of detecting no statistically significant difference (Type 2 statistical error) is inflated by small sample sizes and large random variation, hence cautious interpretation of the t statistic is required. Systematic bias can also be investigated using a standardised mean difference effect size, typically reported as Cohen's d [55], or as a correction Hedges' g [56] and interpreted according to established thresholds (trivial, small, moderate, large or very large effects [55, 57]. An effect size less than 0.2 would indicate a trivial difference between assessments thus adequate reliability. These assessments do not provide the researcher with an indication of the magnitude of random errors present in the sample, thus an examination of systematic bias in isolation provides limited value. Random errors can be an investigation by generating confidence limits around the systematic bias. This is exemplified in Bland and Altman's 95% limits of agreement (LOA) statistic [53], whereby the standard deviation of the differences between samples is used to estimate the likely range of an assessment. Narrow limits of agreement are preferable since this would denote small random error. Hopkins [58], however, cautions against the use of LOA since it is dependent on sample size and suggests that 95% limits are too large for athletic populations, and that appropriate decisions regarding reliability, such as analytical goals or smallest worthwhile changes (discussed below) can be made with 47.5% limits, but this assumes that the total error in the assessment is small enough to be applied to high-performance athletes.

As well as being used to investigate systematic bias, the *t* statistic can also be used to calculate confidence limits. These confidence limits can be applied to the absolute systematic bias, or the effect size to provide information about the possible test re-test error range in the population [59], thus the potential random error present in the population. Absolute total error is quantified using the standard error of measurement or a coefficient of variation. The standard error of measurement (SEM) is another metric frequently used to examine the reliability of an assessment tool. It is essential that this statistic is only used to express reliability on homoscedastic data as it assumes the error is the same as the assessed value increases. There are many ways to calculate SEM and one method incorporates the use of the Intraclass Correlation Coefficient (ICC), a relative reliability statistic, used to calculate an absolute reliability statistic [44], which is contradictory. The coefficient of variation is a useful ratio reliability statistic because it can be used to compare the reliability of different assessment tools. The use of this statistic, however, assumes the largest errors occur at the largest values (heteroscedastic data).

Assessing reliability using correlation coefficients, such as Pearson correlation coefficient and ICC are common within sports science. These assessments simply determine how well individuals maintain their position within a sample of repeated measures thus distinguishes the consistency between participants. Correlation coefficients, however, should be interpreted with caution because they cannot determine absolute systematic and random error and *r* values are specific to sampling selection within data sets; caution should be applied when extrapolating to different samples [60].

Determining whether an assessment tool is reliable can be ascertained using conventional null-hypothesis testing, arbitrary thresholds, analytical goals, magnitude-based inferences or a sensitivity analyses [44]. For example, systematic bias can be assessed using a paired t-test and interpretation of the calculated P value. If $P > 0.05$, the null hypothesis can be rejected and the conclusion drawn that there are no statistically significant differences between samples, confirming the assessment tool is reliable. A simple arbitrary threshold can also be applied to correlation coefficients and coefficients of variation. Some have suggested that a correlation coefficient exceeding 0.8 denotes good reliability between trials as does a CV <5 or even 10%. The standardised mean difference also has similar thresholds, an effect size less than 0.2 represents good reliability, but is typically presented with a confidence interval that provides an estimate of random error. The 95% limits of agreement, however, enables researchers to think differently about the acceptable magnitude of error in terms of an analytical goal in a specific circumstance. Moreover, one can use the methods of

Hopkins et al. [61] to investigate the sensitivity of an assessment tool by determining the smallest difference that elicits a very likely change. This method however, requires the determination of the smallest worthwhile change (usually 0.2 SD, or 0.3 to 0.5 CV) and the use of the typical error calculated as the standard deviation of the change scores divided by the square root of 2, which in its absolute form assumes data is homoscedastic.

1.5 Reliability of rectal temperature during exercise

Rectal temperature is probably the most common site to assess core body temperature in sport and exercise science. Williams *et al*. [62] examined the repeatability of rectal temperature wearing protective clothing in environmental conditions of 22 °C 50% RH at intensity of 50% $\dot{V}O_{2peak}$. The authors interpreted reliability based on a t-test; *P* was greater than the set alpha of 0.05, and there was deemed to be no statistically significant difference between two trials. The absolute mean difference between trials was 0.13 °C and when expressed as a standardised mean difference is equal to a small effect size ($d = 0.37$) which masked by the sole interpretation of the *t* statistic by Williams *et al.* [62]. Moreover, the final rectal temperature within this study was 37.50 ± 0.40 °C, as such conclusions regarding the reliability of rectal temperature at higher temperatures should be interpreted cautiously. A more comprehensive approach to the assessment of the reliability of rectal temperature during exercise was taken by Mee et al. [63] and Willmott et al. [64]. Mee et al. [63] utilised repeated heat tolerance tests at 9 km·h^{-1}, 2% gradient for 30 min in 40 °C and 40% RH in male ($n = 8$) and female ($n = 8$) participants. Although heteroscedasticity was not formally investigated using linear regression, the Bland-Altman plots for mean rectal temperature indicated homoscedasticity. Systematic bias was reported as -0.04 °C and random errors expressed as 95% limits of agreement (± 0.41 °C) were supported by a non-significant *t* statistic, a trivial effect size ($d = 0.19$) and large ICC (0.92 95% CI [0.77 to 0.97]. As such the authors concluded that rectal temperature demonstrated small within-participant variability when assessed day-to-day.

Willmott et al. [64] also observed good reliability across a range of intensities in hot-dry environmental conditions (44.7 ± 1.8 °C and 18.1 ± 4.7% RH). Systematic bias was small (range 0.00 to 0.03 °C) and accompanied by small ($r = 0.23$) heteroscedasticity, trivial effect sizes ($d < 0.20$) and non-significant *t* statistics. Random errors were assessed using 95% confidence intervals (≤ 0.26 °C) and 95% LOA (≤ 0.45 °C) and relative reliability using correlation coefficients ($r = \geq 0.72$, ICC ≥ 0.75). Total error indicated by SEM was < 0.60 °C and typical error expressed as a coefficient of variation was ≤ 0.16%. Despite the caution expressed by Taylor et al. [5], rectal temperature provides a stable, low-error base from which to make decisions regarding the suitability of interventions that might influence rectal temperature. Moreover, in practice, there are only two sites that might provide sport sciences researchers with valid information regarding core body temperature during exercise in the heat, rectal temperature and gastrointestinal temperature.

1.6 Thermoregulation, physiological responses and limiters of exercise capability in hot environments

Humans attempt to regulate body temperature around 37 °C. Understanding why body temperature is regulated around this point is perhaps, more important from an academic perspective than a practical one because from an applied perspective *how* body temperature is regulated forms the basis for practical approaches to alleviate heat strain. Nonetheless, several models have been proposed but the precise mechanisms responsible for the control of body temperature are unclear. The first part of this section highlights the two primary forms of thermoregulation, autonomic control and behavioural adjustments and distinguishes between the unique characteristics and the importance of differentiating between the two when attempting to describe and explain context specific thermoregulation. Nevertheless, body temperature increases depending on the magnitude of metabolic heat production and because of several factors that influence how much heat is stored in the body. An understanding of these fundamental aspects is important to explain the interaction between athlete, the environment and any intervention designed to influence temperature and is described along with the concept of compensable and uncompensable environments in this chapter. In addition, the physiological responses integral to thermoregulation are presented in two forms - the normal physiological responses to exercise and with the addition of heat. It is important to distinguish how subtle changes causes by the addition of heat can impact on physiological responses, especially cardiovascular demands as these are often primary limiters to exercise capability. Indeed, the ability to perform endurance exercise in hot environments is limited in both fixed-intensity, and self-paced challenges and the final part of this section reviews the magnitude of this impairment and presents the proposed theories for why exercise capacity is impaired.

1.7 Thermoregulation

The term 'thermoregulation' (temperature regulation) implies there is a definable region of the body whereby a temperature control system attempts to maintain thermoneutrality [65]. This regulated temperature is generally assumed to be the temperature of the 'body core', rather than the 'shell'. An attempt to maintain body temperature close to 37 °C or achieve thermal equilibrium is a physiological challenge. The maintenance of this value is so important that a large integrative physiological response is required for homeokinesis. Yet the reason for this value of 37 °C is unclear.

Several propositions have been put forward to explain why body temperature is regulated around a temperature of 37 °C. Water temperature near 40 °C is associated with the least thermodynamic stress; there is an exponential increase in water vapour expiration via respiration above 40 °C; the speed of muscle shortening is faster at higher temperatures, and nerve conduction is faster, and Paramecia tend to avoid extremes of cold and heat and congregate around 25 °C [66]. There is, however, no clear evidence regarding a link between environmental temperature and human evolution, but higher body than environmental temperature might have been preferable to limit heat gain from the environment and allow body water (sweat) to be regulated at thresholds that would not place the early human at risk of excessive water loss and dehydration [66]. A more convincing interpretation is that natural selection pressures might have forced higher body temperatures simply as a result of metabolism (physical activity, metabolism, growth, reproduction and digestion). Indeed, as figure 1 demonstrates local tissue temperature is different depending on anatomical position, which reflects metabolism and heat transfer activity in close proximity to these sites.

1.7.1 Automatic thermoregulation

Despite several propositions the mechanisms responsible for controlling body temperature around 37 °C are also unclear. Figure 4 depicts theoretical autonomic thermoregulatory control mechanisms. In these simple models a control centre is suggested to act, in engineering terms, like a thermostat, monitoring a controlled variable or variables in a 3-phase system comprising; afferent thermosensation, central regulation and efferent response.

It is generally accepted that the primary control centre for thermoregulation is in the hypothalamus [67], whereby a 'set-point' for homoeostasis, considered to be equivalent to 37 °C is regulated. It is worth noting, however, that the 'set-point' is a mathematical concept useful for describing the regulation of effector responses but is not a temperature *per se* [65]. Taylor et al. [5] and Werner et al. [68] however, propose there is no anatomical location, central or otherwise, that references instantaneous temperature against a set-point. Instead, a stable mean body temperature, at rest or during exercise, is simply reflected by a balance between heat production, transfer and autonomic regulation. Indeed, a wide range of organ and vascular-specific basal temperatures are evident, the mean of which appears to reside around 37 °C, as does the mean of random observations of rectal temperature [5]. Nevertheless, these conceptual models provide simple illustrations of human thermoregulatory responses [67] and most agree when body temperature reaches a temperature sensitive threshold for warmth heat loss mechanisms are initiated [69].

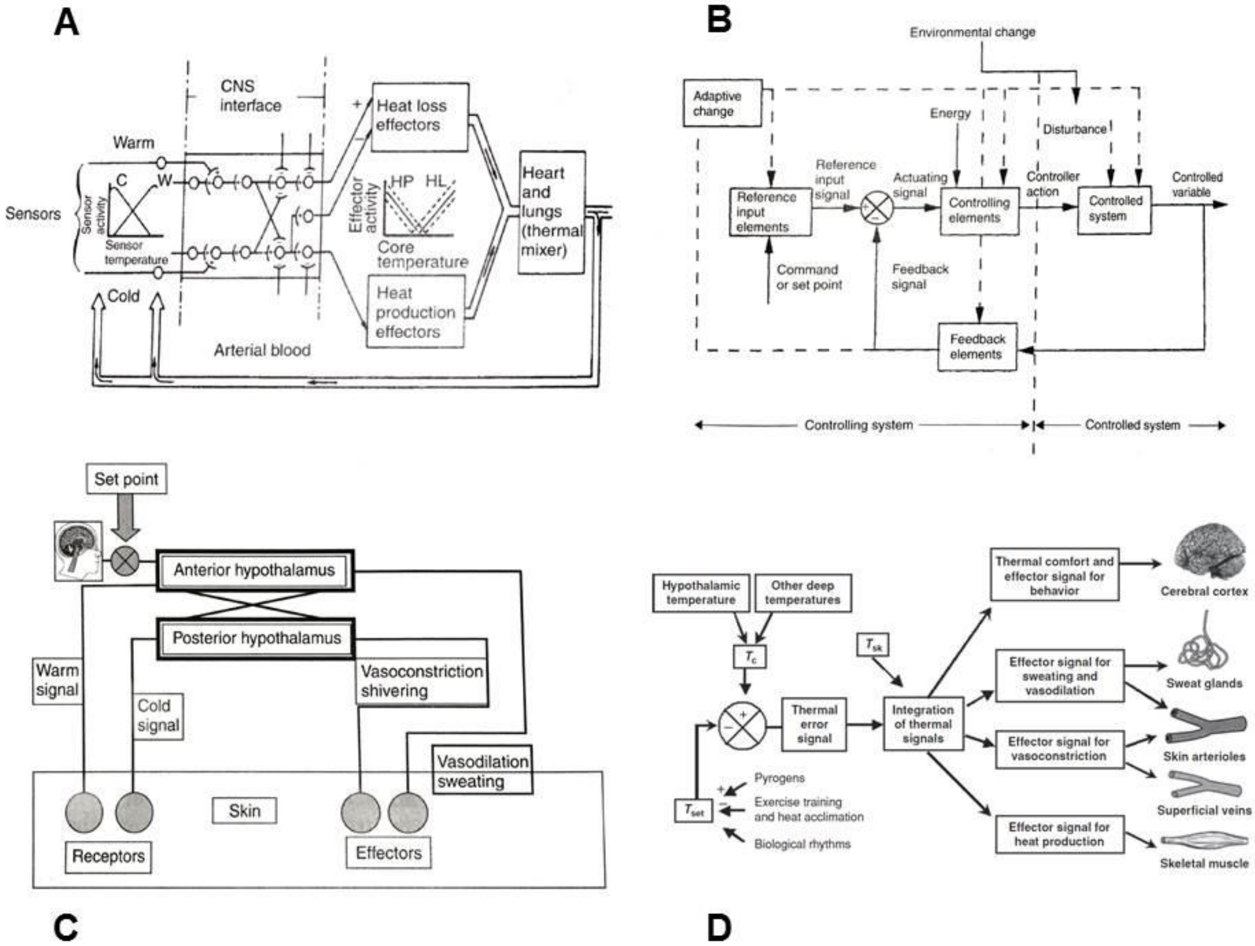

Figure 4: Models of autonomic thermoregulatory control

Extracted from [67, 69].

There appear to be ‘central’ temperature sensors in the medulla and spinal cord, and ‘peripheral’ sites in the gastrointestinal tract, epidermis and blood vessels [67]. These thermosensitive sites, transfer thermal signals (either 'warm' or 'cold') via afferent neural pathways to a hierarchy of structures extending through the hypothalamus, brainstem and spinal cord [70] which integrate, process and transform these inputs to effector signals and physiological outcomes. Lesion studies demonstrate that the hypothalamus, specifically the pre-optic anterior region, seems to be responsible for the control of a range of thermoregulatory responses, including heat loss mechanisms [71].

‘Warm signals’ are processed by the anterior hypothalamus [72]. The mechanisms by which this occurs are not fully understood [67] but evidence suggests that affector signals are transmitted to the anterior hypothalamus by warm-sensitive transient-receptor potential channels (TRPM8) [73, 74]. A neural comparison between the firing rates of warm-sensitive neurones and temperature insensitive neurones might form the basis for the theoretical notion of a ‘set-point’ temperature [70]. Thermal effector responses are proportional to the difference in ‘the reference variable’ ie. hypothalamic excitatory and inhibitory inputs from warm-sensitive neurones and the ‘regulated variable’ i.e. the balance between excitation and inhibition (‘set-point’) and is represented by a theoretical ‘load error’. When the hypothalamus processes neural signals that are greater than those expected for the ‘set point’, a heat ‘load error’ will induce proportional magnitudes of effector responses in an attempt to reduce the ‘error load’ signal and maintain heat balance [67].

The relationships between “set-point”, “load-error” and effector responses are conceptualised in figure 5 [65]. An increasing “load-error” (LE) elicits a proportional effector response (R). A rightward shift in the R would suggest an increase in set point, as the initiation of a response occurs at a higher core temperature (abscissa). A leftward shift would indicate a reduction in "set-point", this is represented in figure 5b. An increase in the slope of the relationship would suggest a faster thermal effector response, whereas a decrease would suggest a slower response (figure 5c). Although these representations of thermoregulation are simple, support for the notion of "set-point" and thermal command signals exist in observations that effector responses are shifted simultaneously and to a similar extent by circadian rhythms, pyrogens (bacterial infection) and heat acclimation [69]. Furthermore, at rest and during exercise, there is a reliable core temperature threshold for the onset of skin vasodilation [75] and for the initiation of sweating [64]. Indeed, analogies of thermoregulatory control from technology may be misleading given the extensive co-coordinative thermophysiological responses required to defend thermoneutrality. Perhaps these models are more appropriate to describe autonomic thermophysiological that have an experimental, laboratory-based origin, rather than more natural behavioural thermoregulatory responses.

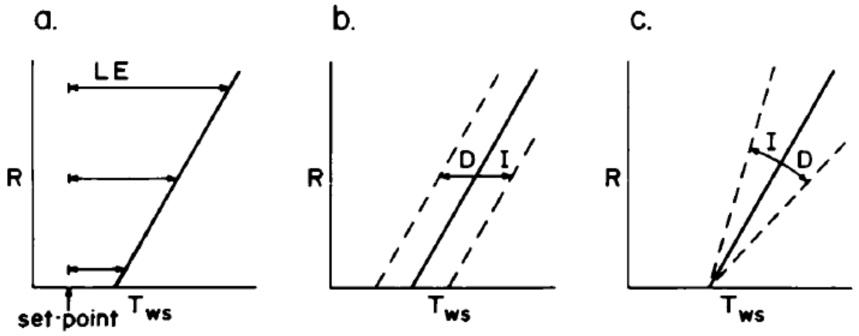

Figure 5: Relationship between "set-point", "load-error" and effector response

a) R changes linearly with load error; b) change in threshold for effector response; c) change in gain (rate of response). R = effector response; T_{ws} = weighted sum temperature; LE = load error; I = increase; D = decrease.

1.7.2 Behavioral thermoregulation

Depending on environmental biophysics and the capability of an individual to dissipate heat, autonomic thermoregulatory responses have limited effectiveness, whereas behavioural capabilities are essentially unlimited [76]. It is well accepted that humans defend against cold temperatures by seeking warmth, either by changing environments or layering clothing; and will defend against hot temperatures by seeking cooler environments, shade or removing clothing. Decisions to take these actions occur consciously and before autonomic thermoregulatory responses in healthy individuals, presumably because acting in this manner serves as a defence against unnecessary sweat loss and potential dehydration [73, 76].

Figure 6 provides a model of human behavioural response to thermal environments, much like the autonomic models, afferent thermoreceptors integrate with central command centres. However, behavioural responses are also dependent on motivation, previous experiences, anticipation, mood and finally thermal sensation and comfort before a decision is made to change behaviour (figure 7). Warmth sensation is initially dependent on skin temperature and then core temperature [77], while discomfort is dependent of skin wettedness [78].

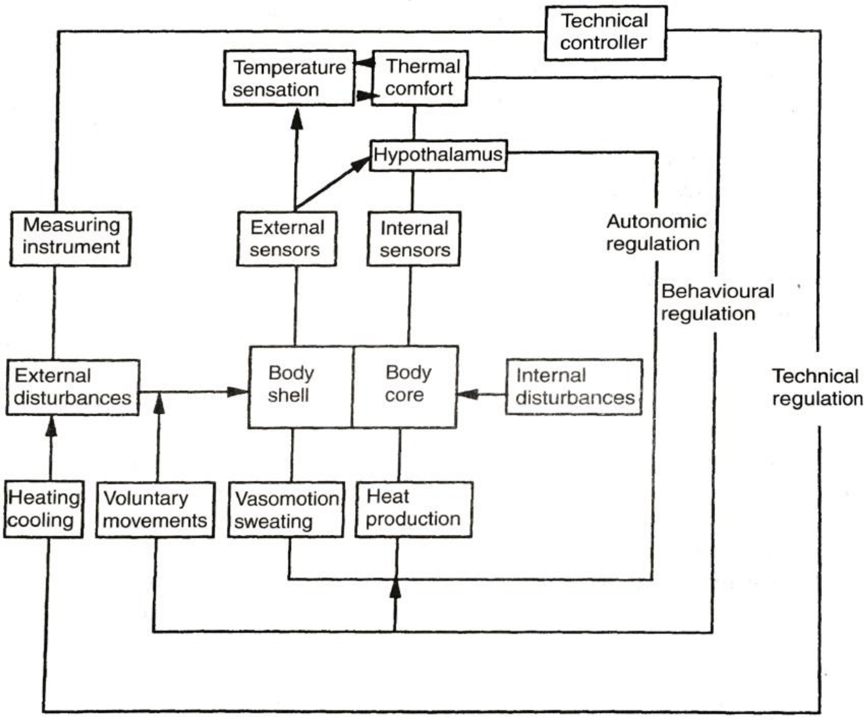

Figure 6: Behavioural regulation as a concept in thermoregulation

Extracted from [79]

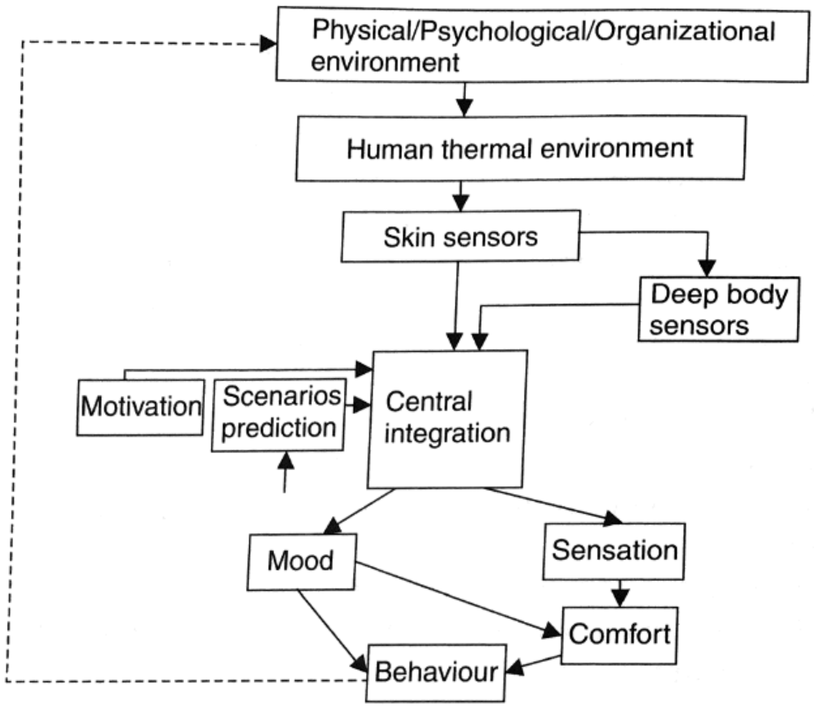

Figure 7: Integration between behaviour and internal and external environments; including thermal and psychological influences

Extracted from [67]

Thermal comfort is defined as a subjective indifference with the thermal environment, while thermal sensation identifies the relative intensity of the temperature being sensed [76]. For example, ‘cold-uncomfortable’ relates to the sensation of feeling ‘cold’ and being ‘uncomfortable’ with the cold, similarly ‘warm-uncomfortable’ relates to the sensation of feeling ‘warm’ and being ‘uncomfortable’ with the warmth. The model proposed above, suggests that sensation and comfort are one-way inputs to behaviour, however, this does not take into account transient thermal perceptions, whereby a change towards a thermoneutral temperature is perceived as improved comfort. For example, Gagge et al. [80] observed that during heating from ‘cold-uncomfortable’, skin temperatures that were previously perceived as ‘warm-uncomfortable’ were judged to be ‘warm-comfortable’. This suggests that perceptions of thermal comfort, and the anticipatory nature of acquiring comfort, requires subjective processing of thermosensitive afferents to make a whole-body behavioural effort to thermoregulate which are not always fixed and one-directional [76]. However, the key modulators, although postulated in figure 7 are yet to be fully discerned. Indeed, simple two-compartment ‘shell’ and ‘core’ models do not appreciate the allesthesial sensitivity of different regions of the skin surface [81], and it is methodologically difficult to influence deep tissue thermoreceptors to ascertain their input into behavioural models. Furthermore, the relative influence of the psychological aspects of thermal sensation and comfort have yet to be elucidated. Nevertheless, it is reasonable to conclude that when given a choice, behavioural responses precede thermal autonomic responses thus care should be taken to interpret the distinct differences between autonomic and behavioural responses when examining responses to heat stress.

1.8 Metabolic heat production

At an ultrastructural level, ATP is required for myosin head detachment from actin-myosin cross bridges and for Ca^{2+} transport across the sarcoplasmic reticulum. Hydrolysis of phosphate bonds enables muscle action and manifests as concentric, eccentric or isometric activity. As a result of concentric or eccentric activity, work (measured in joules J) is performed by a limb usually on another object, for example a pedal stroke in cycle ergometry, and mechanical work is performed. This is typically quantified as the rate of doing work ($J \cdot s^{-1}$) in watts (W). Metabolic heat production is reflected as the difference between metabolic rate (M) and external power (W), typically cited to be in the region of 80% for M and 20% for W, and often erroneously referred to as 'efficiency' [30]. True calculations of efficiency require complete quantification of input and output, and in exercise science is difficult to achieve largely because of unclear protein contribution to metabolism, lack of 'steady state' exercise, failure to include energy expenditure required to move the limbs at zero load, or resting metabolic rate or apply corrections that factor in the loss of useful energy via the ergometer [1, 82]. Nevertheless, metabolic heat production can be calculated as:

$$M - W$$

M can estimated from indirect calorimetry using energy equivalents of carbohydrate (21130 J) and fat (19630 J) oxidation per litre of oxygen when a submaximal, steady-state intensity (typically achieved in 1 to 3 minutes) has been attained [30].

$$M = \left(\frac{\dot{\mathrm{V}}\mathrm{O}_2 \ \cdot \ \left[\frac{\mathrm{RER} \ - 0.7}{0.3} \ \mathrm{e}_c \ + \frac{1 - \mathrm{RER}}{0.3} \ \mathrm{e}_f \right]}{60} \right)$$

Where; RER = respiratory exchange ratio $= \left(\frac{\dot{V}CO_2}{\dot{V}O_2} \right)$, e_c = energy equivalent per litre of oxygen (21130 J), e_f = energy equivalent per litre of oxygen (19630 J).

Initial increases in metabolism result in a corresponding increase in muscle temperature, the magnitude of which is determined by the intensity of activity. However, the rate of heat production is not initially offset by an increase in heat loss; this temporal dissociation is reflected in the rate of body heat storage (S) until heat loss mechanisms are activated. During submaximal fixed-intensity exercise metabolic heat production reaches steady state within 5 min, but whole-body heat loss is much slower to respond and typically attains steady state in 30 to 60 min (figure 8) [83]. The greater the difference between rate of heat production and heat loss and therefore body heat storage will determine the magnitude of increase in body temperature. As exercise continues the rate of heat storage will progressively decrease until the rate of heat loss matches metabolic heat production, heat storage becomes zero and core temperature attains a steady-state. This assumes the individual's maximum evaporative capacity is not constrained by the evaporative potential of the environment.

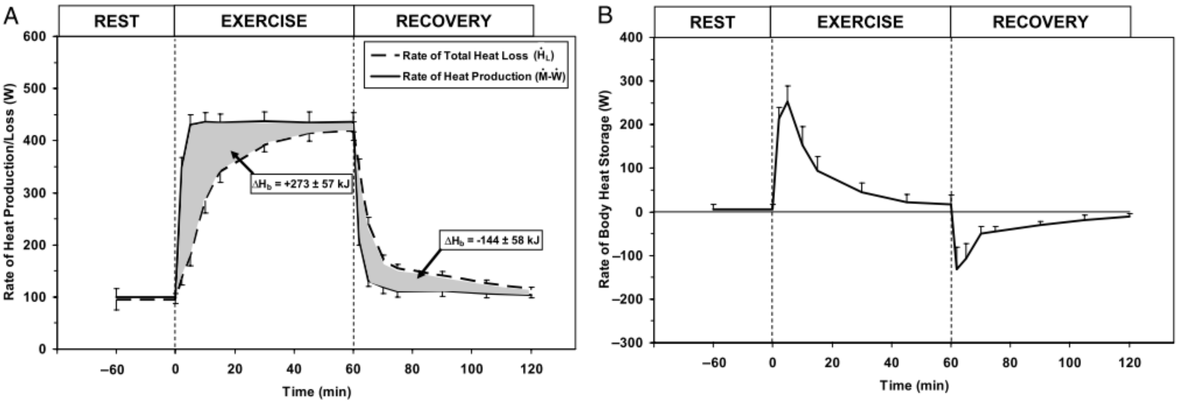

Figure 8: Rate of heat production and heat storage during exercise

A) Rate of heat production cycling at 70 W in 30 ± 0.1 °C, 30% RH. B) Rate of heat storage which increases rapidly at the onset of exercise. Note the total rate of heat production, which reaches steady state around 5 min of exercise, exceeds the rate of total heat loss, which attains steady state after 60 min exercise extracted from [83].

1.9 Basic parameters that determine heat balance

Four basic parameters determine heat balance; *Air temperature*; the temperature of the surrounding air [67]; *Radiant temperature*; mainly electromagnetic/solar radiation; *Air velocity*, the movement of air around the human body, including wind and; *Humidity*; the amount of vapour (mass) suspended within the environment.

1.10 The conceptual heat balance equation transfer

According to the law of energy conservation, in order for the human body (as an open system) to maintain thermal equilibrium the rate of energy input must equal the rate of energy output [30]. Therefore, the rate of metabolic heat production (M - W) must be balanced by the rate of net heat loss by dry (H_{dry}) and evaporative heat loss (H_{evap}) at the skin surface and through respiration (H_{resp}).

$$M - W = (H_{dry} + H_{evap} + H_{resp}) + S$$

This is referred to as the conceptual heat balance equation, whereby H_{dry} is further divided into radiation (R), Convection (C) and Conduction (K).

$$\mathrm{M - W = (R + C + K) + E + S}$$

1.11 Avenues of heat transfer

1.11.1 Radiation

Heat exchanged via radiative transfer might be positive (gain) or negative (loss) and is defined by the following equation.

$R = K_r(T_s - T_r)$

Where K_r = constant

T_s = Skin temperature

T_r = Radiant temperature

Gains can occur directly from solar radiation, diffuse (scattered) and reflected, in the 6 hours around midday solar radiative heat loads can range from 100 to 200 W [84]. Radiative heat loss can occur when skin temperature exceeds the radiant temperature.

1.11.2 Convection

Internal convective heat transfer involves four simultaneously occurring and related processes. Conduction of heat from a surface to immediately adjacent fluid particles - including from muscle to capillary; absorption and storage of the conducted energy with subsequent elevation of their internal energy (enthalpy); movement of higher energy particles to regions of lower temperature (2nd Law of Thermodynamics) and; transport of the energy by movement of the fluid (e.g. blood flow) [67]. External convective heat transfer is dependent upon the speed of movement over the skin or clothing surface, thermal resistance of the clothing, mean air temperature and mean skin temperature. When air-flow is high and ambient temperature is less than skin temperature, heat is transferred to the environment. However, when skin temperature is lower than ambient temperature, heat is gained from the environment.

Convective heat transfer can be expressed as;

$C = K_c V^n (T_{sk} - T_a)$

Where

K_c = thermal properties of air and the pattern of air flow over the body

V = air velocity over the body surface

1.11.3 Conduction

Heat transfer via conduction occurs when molecular energy caused by particle collision, is transferred from one body to another. It is considered minimal when standing and wearing shoes as the thermal gradient is small and is neglected in assessments of environmental heat stress and strain. However, as referred to above, conduction is also an important component of convection.

1.11.4 Evaporation

Evaporation is the only method of heat loss when ambient temperature is greater than skin temperature and the primary method of heat transfer during exercise. Indeed, evaporation can account for greater than 70% of heat transferred to the environment in hot conditions during light to-moderate metabolic heat production [85]. Maximum evaporative capacity (E_{max}) is defined by the following equation;

$$E_{max} = \frac{\omega(P_{sk,s} - P_a)}{\left[R_{e,cl} + \frac{1}{f_{cl}h_e}\right]} \times \text{BSA}$$

Where;

ω = skin wettedness

$P_{sk,s} - P_a$ = the water vapour pressure gradient between the skin surface and the environment

$R_{e,cl}$ = the evaporative heat transfer coefficient of clothing

f_{cl} = clothing factor area

h_e = evaporative heat transfer coefficient

BSA = body surface area

Water, secreted onto the skin surface via sweat glands, phase changes to water vapour, and removes heat by decreasing the kinetic energy (thus temperature) of water on the skin surface. One litre of sweat has the capacity to dissipate around 625 W of energy [86]. Metabolic heat production can exceed 1600 W in elite endurance athletes, thus in a hot environment that limits dry heat exchange, sweat rates of at least 2.5 $L \cdot hour^{-1}$ would be required to maintain heat balance. This process, however, is dependent upon a water vapour pressure gradient between the skin surface and the ambient air, and air speed over the skin surface, as this changes the pressure gradient [67]. When ambient temperature and humidity are high, water vapour pressure increases which decreases the pressure gradient between the skin surface and environment [30]. This reduces the potential for evaporation, loss of kinetic energy and heat loss through evaporation. The maximum rate of evaporation for an individual is determined by their body surface area and the fraction of this area saturated with sweat (skin wettedness) [30]. Most individuals, without heat acclimation, can achieve a maximum skin wettedness value around 0.85, which might increase closer to 1.00 after heat acclimation [30].

1.12 Heat stress and heat strain

Figure 9 provides examples of the interaction between environmental conditions and metabolic rate and their influence on core temperature. The figure is divided into two sections, CHS (compensable heat stress) whereby heat balance is achieved and is assigned the 'prescriptive zone'. Environments where a stable body temperature is unattainable are said to be uncompensable (UCHS), and are characterised by hot and humid tropical-like conditions. Specifically uncompensable heat stress is defined as an environment where the required heat transfer via evaporation (E_{req}) is greater than the maximum evaporative capacity of the environment (E_{max}) [87]. The interaction between metabolism, external intensity of exercise and the environment combine to determine the magnitude of heat strain experienced by an individual. Whereas the integrated physiological mechanisms responsible for attaining and maintaining heat balance are crucial to thermoregulation.

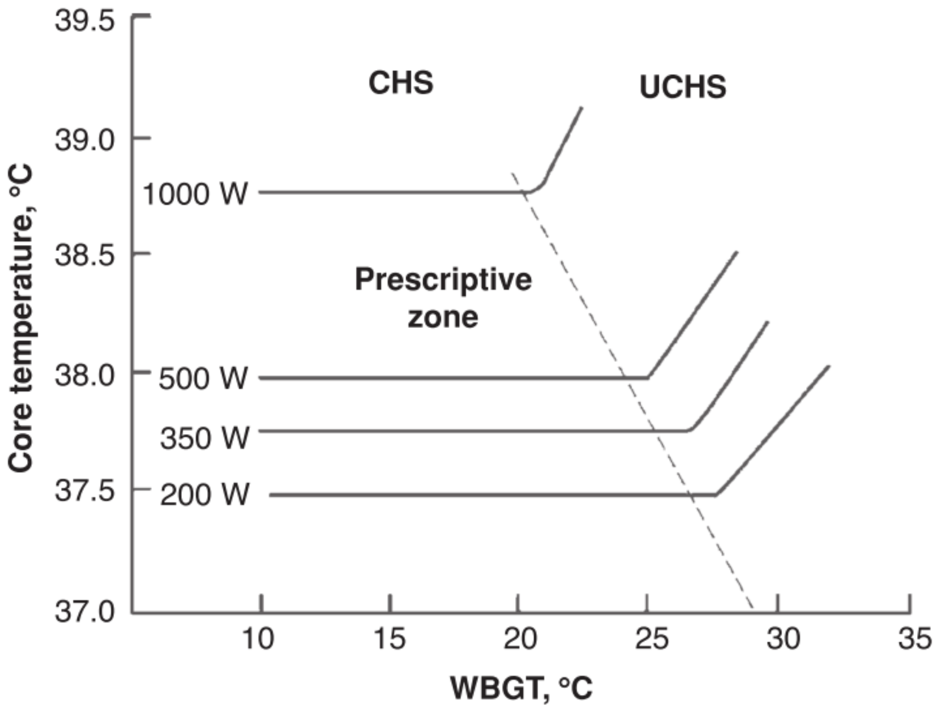

Figure 9: Examples of possible core temperature responses to exercise at different metabolic rates across a range of different environmental conditions

WBGT = Wet bulb globe temperature; CHS = compensable heat stress; UCHS = uncompensable heat stress. Extracted from [69].

1.13 Physiological responses to exercise and heat stress

1.13.1 Challenges for athletes

At the limit of human endurance performance, elite athletes undertake extraordinary physical challenges. Such feats require exceptionally coordinated and integrated physiological responses. For example, elite Grand Tour cyclists can sustain mean external mechanical power outputs around 5.8 $W\cdot kg^{-1}$ or 400 W for 40 to 60 minutes on steep mountain segments and time trials. Included in this are short duration 'attacks' lasting around 30 s where peak power around 900 W and mean power over 500 W are common. If the useful energy production of such a cyclist is around 20%, that is, only 20% of metabolism is used to perform mechanical work [30], then 80% is liberated as metabolic heat. Accordingly, 1600 W of metabolic heat generated in skeletal muscle must be transferred away from exercising muscle to prevent excessive increases in body temperature. Without the capacity to transfer heat, it is estimated that core temperature would increase by 9.4 $°C\cdot hour^{-1}$ even at a moderate intensity ($\dot{V}O_2$ = 2.5 L, estimated metabolic heat production = 880 W) [84]. The challenge, for the exercising athlete is to maintain intensity whilst controlling body temperature; failing to do so will inevitably lead to performance impairment. The mechanisms by which heat, generated at the skeletal muscle, is transferred to the environment is crucial to understanding the physiological demands imposed by exercise, even without the additional burden of high ambient temperature and relative humidity. As such this section considers the journey of heat generated at the muscle and its physiological effects on muscle blood flow, cardiovascular responses, cutaneous vasodilation and sudomotor activity, all of which influence heat transfer via conduction, convection, radiation and evaporation and thermoregulation.

1.13.2 Muscle blood flow

Metabolism generates heat that must be transferred away from exercising muscle. This occurs via two primary internal heat loss avenues; 1) intercellular conductive heat transfer and 2) vascular convective heat transfer [88]. The former is regarded as a slow heat transfer process and is dependent upon the muscle-skin temperature gradient and the thermal conductivity of the musculoskeletal system. Vascular convective heat transfer (mass flow) is dependent on tissue blood flow and arteriovenous temperature difference. Since heat is generated primarily in exercising muscle, the mechanisms underpinning vascular responses are the first steps in thermoregulatory control.

Regulation of skeletal muscle blood flow is principally required to match oxygen demand with delivery [89]. At the onset of exercise there is an immediate (within 1 to 2 s) muscle action-induced rapid vasodilation, likely involving K^+ channels, Nitric Oxide Synthase (NOS) and the sympathetic nervous system [90]. Figure 10 demonstrates a rapid increase in quadriceps heat production from 80 W (external intensity) of knee extensor exercise. There is also a concomitant increase in the rate and magnitude of blood heat removal, which allows heat accumulation in muscle to decrease. These responses are likely mediated by sympathetic nervous system derived vasoconstrictor and vasodilator control of vascular tone [90]. Immediate responses to muscle action are characterised by a temporary loss of sympathetic tone, as arterial baroreflexes cause a reflex reduction in sympathetic outflow to muscle. As exercise continues, metabolic-induced vasodilation takes predominance rather than sympathetic withdrawal. A number of compounds formed as part of the physiological and mechanical response to exercise and heat strain, such as Acetylcholine and Adenosine Tri-Phosphate are released from blood cells and skeletal muscle and act on receptors on endothelial cells, which line the luminal sides of the vascular system. In the endothelium these activate both cyclooxygenase and endothelial NOS pathways that result in decreases in smooth muscle cell calcium concentration and the rate of myosin phosphorylation. These combined effects elicit vascular smooth muscle relaxation, vasodilation and enable an increase in muscle blood flow and is collectively known as sympatholysis [90].

When exercise is limited to a relatively small muscle mass blood flow in the region of 250 to 400 ml per 100 g per minute can occur [91]. During whole body exercise, however, when large amounts of muscle might be recruited, a cardiac output up to 40 $L \cdot min^{-1}$ would be required to match this demand; it would be difficult for even elite athletes to match these demands [92]. However, this mismatch between potential demand from muscles and the ability of cardiovascular system is controlled by mechanisms that limit muscle vascular conductance from reaching these values [91]. Nevertheless, it is important to recognise that combined effects of exercise and metabolism increase muscle blood flow which promotes convective heat exchange. Here it is worth noting that thermoafferent signals are not the sole inputs to physiological responses to increased metabolic heat production (figure 11) [93]. High and low-pressure baroreceptors responsible for the control of mean arterial pressure play an integral role in the control of vasodilation and constriction, thus muscle blood flow.

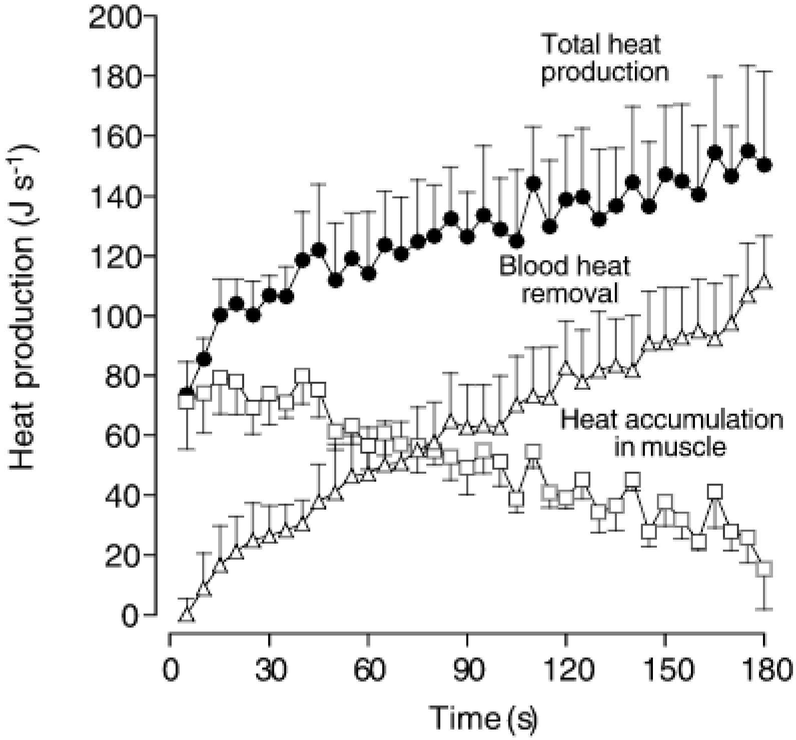

Figure 10: Heat production during knee-extensor exercise

Note the rapid onset of blood heat removal and decrease in heat accumulation in the muscle. Extracted from [88].

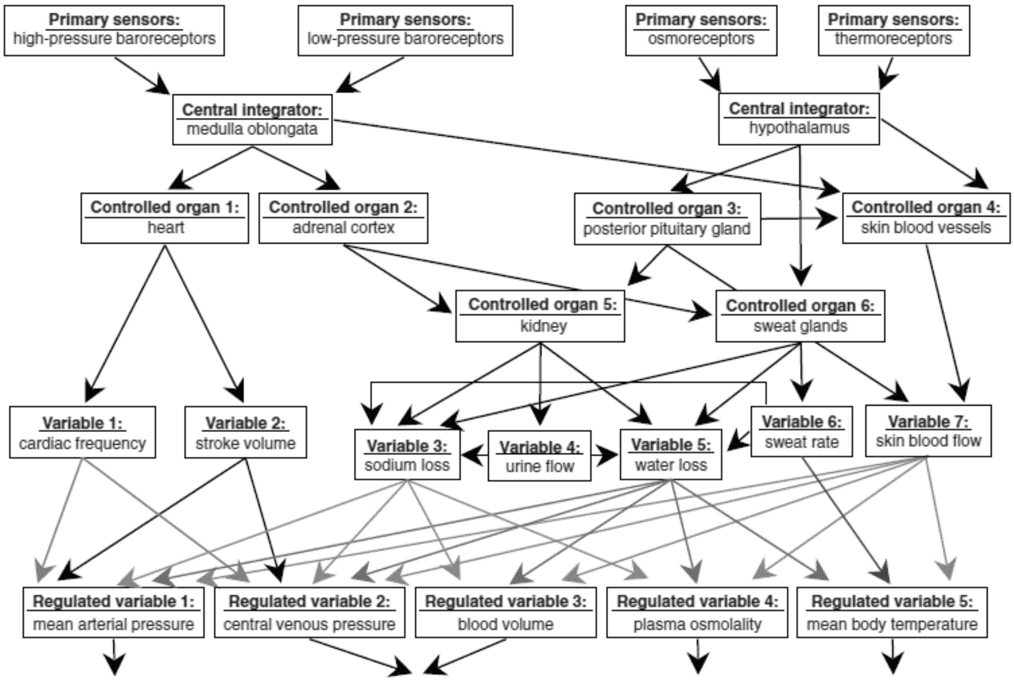

Figure 11: Overview of the complex integration of physiological responses required to maintain homeostasis in hot environments

Extracted from [93].

1.13.3 Initial circulatory adjustments to exercise

Vasodilation of active muscles requires an immediate cardiovascular response. Metabolically-induced vasodilation of muscular capillary beds decreases vascular resistance and arterial pressure. Consequently, the cardiovascular regulatory centres located in medulla oblongata, responds by increasing increasing stroke volume and heart rate, thus cardiac output to maintain perfusion pressure, match oxidative demand and improve venous return [90]. Further circulatory adjustments are made as increased sympathetic vasoconstrictor activity in vascular beds such as renal and sphlanchnic regions restricts blood flow to around 25% of resting values [94]. For example, at rest blood flow to the kidneys and liver is ~1.2 $L \cdot min^{-1}$ and ~1.6 $L \cdot min^{-1}$ respectively, meaning that approximately 2 $L \cdot min^{-1}$ of blood flow can be redirected to skeletal muscles during exercise [90]. Additionally, skeletal muscle activation compresses blood vessels, whilst relaxation either causes suction or tethers blood vessels in a way that enables blood flow to increase. Muscle pump, (mechanical actions around active musculature), promotes venous return and diastolic filling, and passively assists in maintaining perfusion pressure [90].

As exercise continues, circulatory adjustments principally help to maintain perfusion pressure at vital organs (figure 12) but also assist in heat transfer via conduction and convection. Furthermore, as heat storage increases, skin blood flow and sweat production increase to aid heat transfer to the external environment via radiation, convection and evaporation. These heat transfer processes are key to controlling body temperature; the mechanisms underpinning skin vasodilation and sudomotor function are therefore important to the understanding of human thermoregulation.

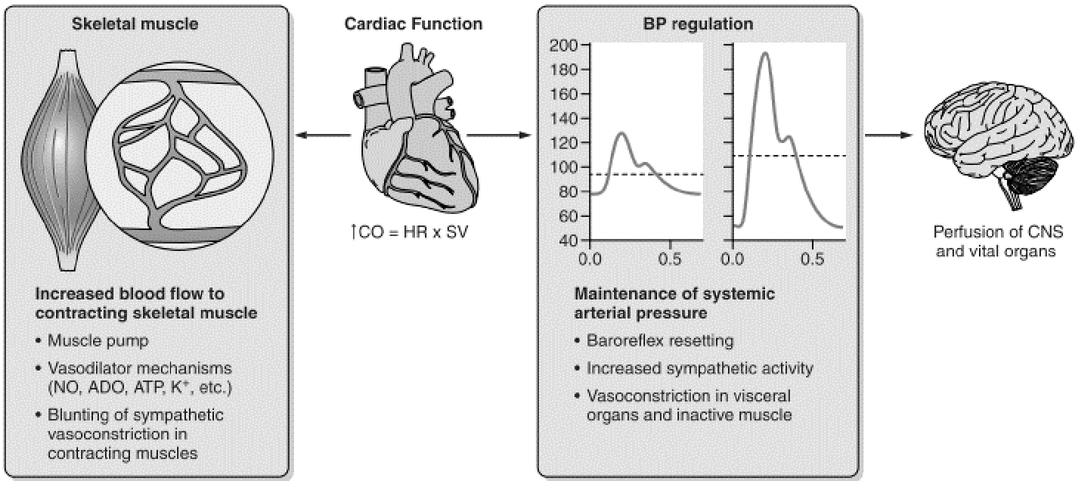

Figure 12: Relationships between local factors causing blood flow to rise in skeletal muscles, cardiac output, and arterial blood pressure regulation to ensure the perfusion of the central nervous system and other vital organs

Adapted from [90].

1.13.4 Skin Circulation

Non-glabrous skin (hairy) is under dual control of sympathetic noradrenergic nerves and cholinergic active vasodilator nerves [95]. The mechanisms controlling skin blood flow are integrative and include skin and core temperature inputs and muscle metaboreceptor and mechanoreceptor stimulation [96] and enable body temperature to be tightly controlled within narrow limits. A withdrawal in sympathetic nervous system activity occurs in body heating, but only induces moderate increases in skin blood flow [97]. More pronounced vasodilation, estimated to be within the region of 80 to 90% of maximum, occurs via the effects of the sympathetic active vasodilatory control [98], which is neurogenic and central in origin (as opposed to local heating induced hyperaemia). Initial increases in cutaneous vascular conductance (CVC) occur as a result of sympathetic nervous system withdrawal (10 to 20 min). Afterwards, an increase in CVC is mediated by active vasodilation by sympathetic cholinergic nerves. Current theory suggests, neuronal nitric oxide synthase (nNOS) stimulates the release of Acetylcholine, and co-transmitters that bind to endothelial receptors and upregulate endothelial nitric oxide synthase (eNOS) resulting in vascular smooth muscle cell relaxation thus increasing blood flow [75, 90]. Glabrous (non-hairy) skin, such as that of the palms and soles of feet are under the single control of sympathetic vasoconstrictor nerves [99, 100] yet despite the absence of an active vasodilator system can achieve larger magnitudes of blood flow than non-glabrous skin because of specialised arteriovenous anastomoses (AVA's).

Although there might be an initial increase in active vasodilation at rest in the heat, on the initiation of exercise there is an observable decrease in skin blood flow [101, 102]. This reduction is likely caused by whole-body sympathetic vasoconstrictor activity required to maintain central pressure. Initial systemic vasodilation at the skin and muscle level would likely result in an immediate decrease in mean arterial pressure and challenge blood pressure regulation. Thus, at the expense of cutaneous circulatory function and potential heat loss, exercise actually decreases skin blood flow demand.

Exercise also increases the internal temperature threshold for vasodilation [95], which is likely due to a delayed onset of cutaneous active vasodilator function [95]. This evidence is contradictory to that supporting an increase in sympathetic nervous system activity and cutaneous vasoconstriction. That is, active vasoconstriction is involved in an early exercise response, but the internal threshold for vasodilation is increased because of delayed active vasodilator function. More research is required to fully elucidate the mechanistic underpinning of cutaneous responses associated with exercise.

1.13.5 Sudomotor function

Sudomotor (*Latin Sudor* ‘sweat’) describes the activation of the physiological mechanisms that drive sweat excretion onto the skin surface to facilitate evaporative heat transfer. Early research into sweat rate and exercise by [103] linked an increase in tympanic temperature with increased sweat rate, and to a lesser extent, increased skin temperature with an increased sweat rate. Indeed, as body temperature increases due to increased metabolic heat generated by exercise, central brain temperature and secondarily mean skin temperature are heavily involved in initiating an increase in sudomotor function [104].

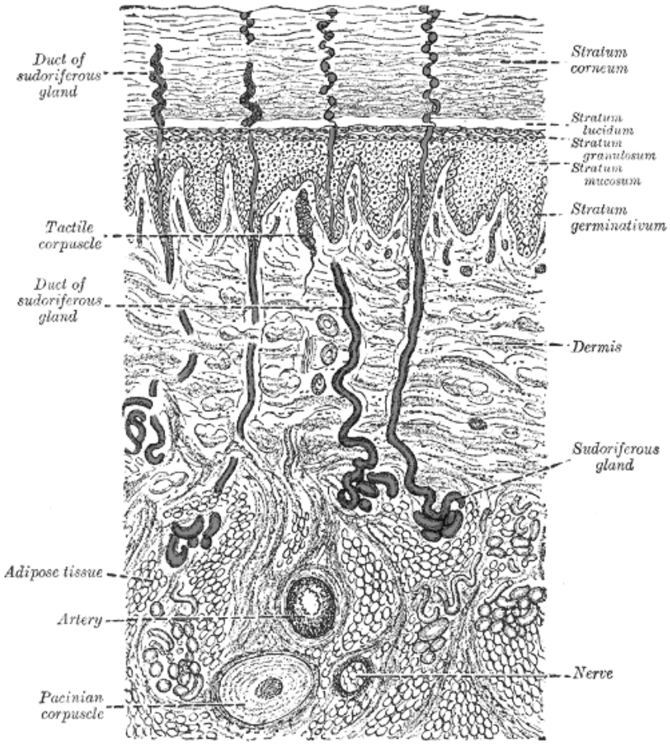

Figure 13: Anatomical structure of an eccrine sweat gland

Extracted from [105]

Figure 13 depicts the structure of an eccrine sweat gland which contains the functional bulbous secretory coil leading to a duct [104]. The secretary coil originates from the lower dermis and the duct transcends the dermal layer and opens onto the skin surface. The exact neurological pathways responsible for sweating are not entirely understood however, effector signals from the POAH are thought to innervate sympathetic nerve terminals around the secretary coil of the sweat gland [104]. Acetylcholine appears to be the primary neurotransmitter released by cholinergic sudomotor nerves which bind to muscarinic receptors on eccrine sweat glands. Intracellular Ca^{2+} concentration increases, as does the permeability of K^{+} and Cl^{-} channels, initiating the release of isotonic precursor fluid from secretory cells (figure 14). As this isotonic fluid travels up the secretory duct, Na and Cl^{-} are reabsorbed which results in a hypotonic fluid, sweat, being secreted onto the skin surface (figure 14). Now the athlete has the potential to transfer heat from the skin surface via evaporation to the environment, should the evaporative heat transfer capacity of the environment permit.

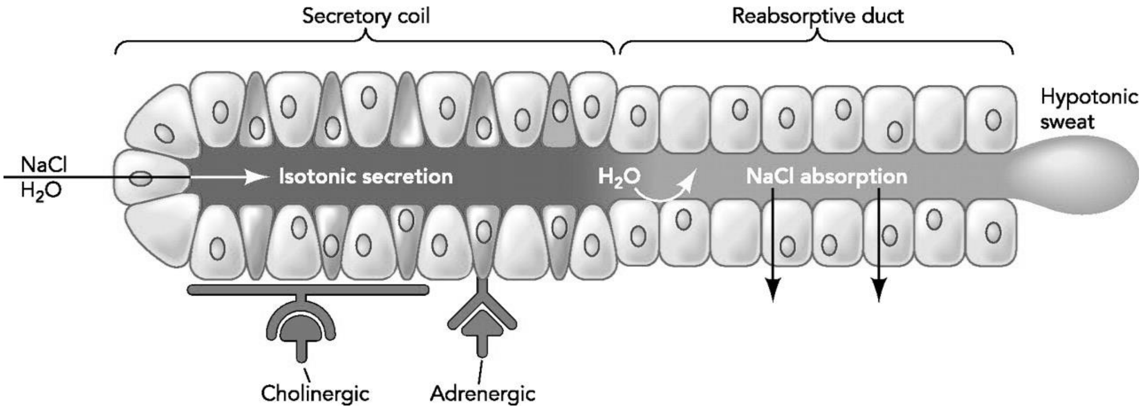

Figure 14: Mechanisms of sweat secretion

Extracted from [106]

1.13.6 Effects of heat on muscle blood flow

Given the large integrated response to exercise, the principle locations required for circulatory adjustments are the exercising muscle, cutaneous circulation and vital organs such as the brain, heart, kidneys and liver. When an athlete exercises at a high intensity in an environment that makes heat balance more difficult to achieve, for example, in a hot and humid environment compared with normal ambient conditions, this increases body heat content. The addition of this heat to the normal physiological demands of exercise places additional strain on thermoregulation.

At rest local muscle temperature is around 33 °C [107]. However this can increase to 41 °C during high-intensity exercise [108]; as a function of this increase in muscle temperature, blood temperature also increases. While there is established evidence that exercise increases muscle blood flow, data regarding the effects of increased muscle temperature during exercise on muscle blood flow is equivocal. Increased muscle and blood temperatures are associated with increases in limb blood flow during isolated leg and whole-body heat strain [109, 110]. It is unlikely that these increases are due to metabolic vasodilation as the concomitant increase in oxygen uptake is reportedly too small to account for increase in blood flow, yet the exact mechanisms responsible are currently unclear. Increases in muscle blood flow might occur as result of progressive active vasodilatory mechanisms through eNOS pathways but could also be related to an increase in arterial plasma ATP, which is a potent vasodilatory substance [88, 109]. This limited amount of evidence suggests that heat is a potentiator of increased muscle blood flow. That is, as muscle temperature increases there is a simultaneous increase in skeletal muscle vasodilation. If skeletal muscle temperature is greater than core temperature, as is typically the case during exercise in the heat [108], then muscle vasodilation will contribute to conductive and convective heat exchange from muscle to surrounding tissue and blood. However, an increase in muscle blood flow creates additional cardiovascular challenges and places greater demand on the circulatory system to maintain perfusion pressure. Further challenges are also imposed by cutaneous vasodilation.

1.13.7 Effect of heat and exercise on skin circulation

Skin circulation is under dual influence from external and internal temperature. A typical response to warm skin is increased vasodilation, whereas a typical response to a cold environment is increased vasoconstriction. Usually, if exercise is performed in a hot environment the skin will already have been warmed and be at least thermoneutral (34 °C) or close to environmental temperature. However, there are circumstances when skin temperature might be cool and environmental temperature hot, for example, transitioning from an air-conditioned room (i.e. call or changing room) to a hot outdoor environment. An understanding of the physiological responses to these circumstances and their mechanisms of action are important to evaluate the effects of interventions that aim to improve exercise capability in hot environments because skin temperature influences the threshold for cutaneous vasodilation and therefore body temperature [75]. Indeed, cooler skin temperature seems to increase the internal temperature threshold for cutaneous vasodilation, likely mediated through neural inhibition of active vasodilator activity, as blockade of the adrenergic vasoconstrictor system with Bretylium (blocks the release of noradrenaline from nerve terminals) does not appear to influence cutaneous vascular conductance of cool skin [75]. An increased threshold for skin vasodilation has consequences for the control of body temperature; when the combination of intensity and environmental conditions permit attainment of a steady-state this would be delayed by cool skin and push internal temperature closer to regulatory limits. Such physiological responses would be important to consider as a result of interventions that employ techniques to cool large surface areas before exercise in hot environments. Conversely, hot skin combined with exercise in hot environments enables the threshold for cutaneous vasodilation to be reached relatively earlier during exercise. Thus heat loss mechanisms are activated earlier, and heat balance can be achieved faster if the combination of intensity of exercise and environmental conditions permits.

Early estimates of maximal skin blood flow, imposed by whole-body passive heating of the skin surface at rest, were assumed to be in the region of 7 to 8 $L \cdot min^{-1}$ [94]. During exercise however, estimates are assumed to be related to core-to-skin temperature gradients [69] and might reach 4 to 5 $L \cdot min^{-1}$ [111]. It is noteworthy that an increase in skin temperature that decreases core-to-skin temperature gradient, also increases skin blood flow requirements to assist heat transfer to the environment. A larger core-to-skin temperature gradient can alleviate skin blood flow demands, for example an increase in core temperature from 38 °C to 39 °C that increases core-to-skin temperature gradient by 1 °C decreases skin blood flow requirements but does not compromise external heat transfer as skin temperature remains elevated and also provides a better temperature gradient for internal heat transfer [69]. Thus if skin temperature remains high but stable, an increase in core temperature that increases core-to-skin temperature gradient is favourable from a cardiovascular perspective but might have detrimental effects elicited through high body temperature that are independent of the cardiovascular system, such as thermal comfort and sensation. Nevertheless, lower skin temperatures and higher core-to-skin temperature gradients decrease skin blood flow requirements during exercise in hot environments.

1.13.8 Effect of heat and exercise on sudomotor function

The onset and rate of sweat production both determine the success of evaporative cooling. During exercise the threshold for the onset of sweat production is primarily dependent on body temperature, skin temperature and skin blood flow [112]. The rate of sweat production is dependent on the neurogenic recruitment of sweat glands and the density of sweat glands in a given body region. The largest sweat gland densities are reported to be present on the palmar surface of the hands and the soles of the feet and in theory should have the highest sweat rates [20]. However, these only account for a small proportion of body surface area (2 to 3%) thus have low absolute sweat rates. The abdomen, back and chest have much greater absolute sweat rates because they have a relatively large sweat gland density for their surface area. Subsequently these areas have the greatest potential for evaporative heat transfer and can contribute to up two-thirds of total heat loss during moderate-intensity exercise [113]

During exercise, sweat rate varies according to the demand to dissipate heat which is related to both environmental temperature and intensity of exercise. Sweat rates between 1 and 2.6 L·hour^{-1} are reported in the literature [69, 114] and sweat rates are greater in hot environments when body temperature is elevated. For example, sweat rate at 70% $\dot{V}O_{2max}$ in 31 °C (1.2 L·hour^{-1}) is double that during exercise in 4 °C (0.6 L·hour^{-1}) [115]. However, during prolonged activity it can pose a problem as sweat rate often exceeds the ingestion of fluid. For example, an athlete with a sweat rate of 3 L·hour^{-1} would be required to drink 750 ml every 15 min to match sweat rate and maintain euhydration. This is clearly difficult in some circumstances such as prolonged running or cycling or during team sports. For example, a 70 kg athlete, running for 2 hours, with a sweat rate of 3 L·hour^{-1} would in theory sweat 6 L of fluid. This amounts to body mass decrement of almost 8.5%. If the athlete was able to offset this by ingesting 1 L·hour^{-1} per hour, whereby gastric emptying is 600 to 800 ml·hour^{-1}, the decrement would still be around 7%. Fluid deficits of this magnitude have implications for internal heat dissipation, cardiovascular control, and performance.

1.13.9 Effect of heat and exercise on muscle metabolism

Heat stress and strain imposes additional demands on muscle metabolism [3]. Increases in muscle temperature augments intramuscular glycogen utilisation [116] but the cause of these metabolic alterations are not fully understood. Possible explanations include a direct temperature effect on metabolism. As muscle temperature increases, enzymatic reactions also have the potential to increase and could mediate increases in metabolism as per the collision theory. More likely, is the combination of temperature and exercise causes ATP degradation and allosteric activation of phosphofructokinase and phosphorylase increasing flux through glycolysis and upregulating glycogen utilisation [117]. Furthermore, some evidence suggests adrenaline secretion increases in response to exercise and is further augmented in response to heat stress [117]. Glycogen phosphorylase activity is enhanced by β-Adrenergic receptor stimulation thus circulating adrenaline might contribute to glycogen utilisation during exercise in the heat [117]. Reductions in skeletal muscle blood flow, and therefore additional requirements for non-oxidative energy system contribution to metabolism are unlikely, as muscle blood flow is not impaired in the heat [91].

1.13.10 Cardiovascular adjustments

Despite circulatory adjustments that limit blood flow to visceral organs, the combined estimates of the demand for maximal skin (4 L·min^{-1}) and muscle blood flow (2.5 L·min·kg^{-1} lean tissue) places strain on cardiac pumping capacity [91]. However, there is an apparent disparity between these maximal values and the potential demand during exercise at high intensity in the heat. Early research suggested that hyperthermia might limit blood flow to muscles because sympathetic nerve activity was increased during exercise but cutaneous vascular conductance was not substantially impaired [91]. Instead, current evidence suggests that increased vasodilation occurs at both sites until blood pressure regulation is impaired; at this point blood flow to active muscle and O_2 delivery decreases that limits exercise capability in the heat [118].

1.14 Limits of human exercise capability in hot environments

Exercise capacity is impaired in hot, compared to cool, environments. In 1931, Dill et al. (1931) [119] reported that cycling endurance capacity was impaired by 25% in 34 °C compared to 12 °C (45.2 ± 9.4 min and 60.0 ± 0.0, respectively) when five men cycled at a mean intensity of 250 W. Nielsen et al. [120] demonstrated that at a fixed-intensity, estimated to be close to 50% $\dot{V}O_{2peak}$, participants were able to complete 90 min of cycling exercise in a cool ambient temperature (18 to 20 °C), but when the participants were asked to exercise at the same intensity in 40 to 42 °C, 15% RH, exercise capacity was reduced by almost half, to around 47.5 ± 2 min [120]. Cycling exercise capacity at 70% $\dot{V}O_{2peak}$ was also less in 31 °C (51.6 ± 3.7 min), compared to 11 °C (93.5 ± 6.2 min) in 8 healthy males [115].

Similarly, Tatterson et al. [121] were among the first to report that self-paced cycling performance was impaired by 6.5% in hot (32 °C) (mean power over 30 min cycling time trial = 323 ± 8 W) compared to a cooler (23 °C) environment (mean power = 345 ± 9 W); and Marino et al. [86] documented a greater percentage decrement (~11%) in an 8 km running time trial in 35 °C (30.4 ± 2.9 min) compared to 15 °C (27.0 ± 1.5 min). The greater relative performance decrement in Marino et al. [86] compared to Tatterson et al. [121] is likely due to a larger temperature difference between hot and cool conditions (20 vs 9 °C). However, despite a statistically significant difference (P <0.01) in time taken to complete 20 km and mean power in 35 °C compared to 20 °C, it is unlikely that Tucker et al. [122] found any meaningful difference in performance. This opposes the conclusions drawn by Tucker et al. [122] and contrasts to similar previous studies. The participants in this study were characterised as "physically active" and had a peak minute power of 376 ± 47 W, this value is similar that maintained for 30 min in the study of Tatterson et al. [121]. Indeed, the standard deviation of participants finishing time in Tucker et al. [122] was ± 6.4% of the mean, applying confidence intervals to the data results in an unclear interpretation of the findings despite the author's conclusions that performance was significantly impaired. A larger and more homogenous sample would be required to confirm these conclusions. Nevertheless, several other studies have corroborated earlier trials including Ely et al. [123] who demonstrated that marathon finishing time is extended in hotter environments, and that the percentage decrement is greater the slower the runner; and Guy et al. [4] , who found that performance was impaired up to 3% in IAAF track events greater than 5,000 m, when they were competed in temperatures with a mean outdoor temperature of 30.4 ± 4.3 °C compared to a control of 18.5 ± 3.2 °C.

These studies manipulated (or observed) environmental temperature to investigate exercise capability. In almost all these investigations the researchers have also assessed physiological responses to observe the strain imposed by the combination of exercise and heat. The magnitude of this strain is dependent on the stress of environmental factors such as temperature, humidity and clothing; and biological characteristics such as heat acclimatisation status, hydration, fitness and morphology and the intensity of exercise. Indeed, much effort has focussed on the reasons for these limitations in exercise capacity and performance. At this point, it is important to make a clear distinction between fixed-intensity exercise trials and self-paced exercise performance, since the mechanisms that underpin exercise capacity and self-paced performance are different.

1.14.1 Critical core temperature hypothesis

Nielsen et al. [120] were among the first to detail that participants terminate exercise at a core temperature close to 40 °C and that a high core temperature *per se* is the critical factor for exercise termination in the heat. In the study of Nielsen et al. [120], participants voluntarily stopped exercising close to a rectal temperature of 40 °C on successive exercise trials (9 to 12) despite gradual heat acclimation. These findings were replicated in a subsequent heat acclimation study, whereby the authors [124] observed that participants were able to exercise for longer (pre-acclimation 44.6 ± 2.8 min; post-acclimation 52 ± 1.9 min) in hot humid environmental conditions (35 °C, 87% RH) at 45% $\dot{V}O_{2max}$ but terminated at similar rectal temperatures of 39.9 ± 0.1 °C and 39.9 ± 0.1 °C, respectively. Furthermore, González-Alonso et al. [108] also reported that voluntary fatigue occurred at an oesophageal temperature around 40 °C, irrespective of initial body temperature (36, 37, 38 °C) which was manipulated by water immersion. These studies suggest that exhaustion during exercise in hot environments coincides with the attainment of a critical core temperature that is independent of the intensity of exercise, rate of heat storage, state of acclimation, initial core temperature or skin temperature. This limited body of evidence, has led to the assertion that a high body temperature and not cardiovascular or metabolic challenges is the main factor underlying fatigue during prolonged exercise in the heat. This critical core temperature, deemed to be around 40 °C, is postulated to reduce voluntary central nervous system activation [125, 126], thus termed central fatigue. That is, a 'safety switch' or mechanism is proposed to prevent catastrophic systemic damage from hyperthermia [127].

Advancing earlier work, suggestive of a critical core temperature, Nybo and Nielsen [128] demonstrated that when participants were hyperthermic (40 °C) compared to 'normothermic' (38 °C), after 50 and 60 min cycling at 60% $\dot{V}O_{2max}$ they had less ability to produce knee extensor force over a 2-min sustained isometric action, despite an equal potential for electrically-invoked superimposed twitch force. The authors were unable to replicate this finding in a trial whereby they asked participants to produce maximal force in a 2-s effort with 5-s recovery repeated 40 times. The authors postulated that brain temperature was a key regulator of motor unit activation, but they were unable to establish whether exercise was terminated because of central fatigue *per se*, nor were they able to elucidate why sustained but not repeated muscular activity was impaired. A limitation of this study was the failure to isolate core temperature from skin temperature. That is, skin temperature was also high in these studies; thus the observed decrease in voluntary force production cannot necessarily be ascribed to a critical core temperature alone, since there were concomitant increases in skin temperature which present cardiovascular challenges. Furthermore, there are no data concerning the time-course of fatigue throughout the exercise trial since assessments of force production were only conducted immediately after reaching a threshold temperature or fatigue from a preliminary trial. Morrison et al. [129] sought to isolate core temperature independently from skin temperature and cardiovascular strain using passive heating as well as determining the time course of fatigue. Using a water-perfused suit, the investigators heated the skin surface to raise both skin and core temperature, at 0.5 °C increments from rest until 39.5 °C; at each interval they assessed voluntary activation of knee extensor force and electrically-evoked twitch force. The authors observed a progressive decline in mean maximal voluntary activation of the knee-extensors and knee extensor torque (Nm) as rectal temperature increased to 39.5 °C. At this point knee-extensor force was statistically ($P < 0.05$) less than knee extensor force at 37.5 °C; these findings were observed both with a high core temperature and high skin temperature. At a core temperature of 39.5 °C the authors cooled the participants, so that skin temperature declined rapidly while core temperature remained at 39.5 °C. Despite the reduction in skin temperature and a return of heart rate reserve to near resting levels there was not an immediate statistically significant recovery in voluntary activation or force production. The authors concluded that a high core temperature impairs force production, independent of skin temperature. However, whether a meaningful decline in knee extensor force occurred is unclear. The standardised mean difference ± 95% confidence limits for baseline (37.5 °C) and peak core temperature (39.5 °C) peak isometric knee extensor force was -0.53 (-1.19 to 0.14). As the effect size confidence interval spans positive and negative effects the interpretation of force should not be that it is significantly impaired, because there might be a beneficial (albeit trivial) effect of heating on force production.

In another study by Nybo and Nielsen [130] it was demonstrated that exercise was terminated at 40 °C oesophagal temperature and that middle cerebral artery velocity, an index of blood flow, was impaired due to hyperthermia when compared with the control trial. The authors noted that cerebral blood flow was probably impaired by a decreased cardiac output but concluded that fatigue seems to coincide with a critical core temperature that might influence central nervous system drive. However, this assertion seems secondary to cardiovascular challenges imposed by hyperthermia, i.e. a reduced cerebral artery velocity. Indeed, no study has demonstrated that a critical core temperature independently induces fatigue, in an emergency break like manner, since neuromuscular function is impaired transiently (but perhaps not meaningfully) with an increase in core temperature and skin temperature. Additionally, the choice of neuromuscular assessment is also important to consider. A maximal effort is an assessment of performance and is influenced by perceived exertion. When participants are hot and uncomfortable, their thermal perception feeds forward to perceived exertion and performance is regulated to achieve the task goal. To isolate the influence of critical core temperature on performance, researchers also need to isolate the effect of thermal perception and perceived exertion if an assessment involves the choice to produce force. A fixed-intensity protocol would likely alleviate the impact of perceptual influences.

There is insufficient evidence to suggest that there is a critical core temperature at which exercise is terminated [131]. Since it has not been clearly demonstrated that a critical core temperature alone limits exercise capacity during fixed intensity exercise, it is unlikely that a critical core temperature would limit performance in self-paced exercise. Indeed, core temperature exceeding 40 °C is observable in highly motivated athletes during performance in hot environments [132] and with dopamine reuptake inhibition, using bupropion which increases extracellular adrenergic neurotransmitters improving central nervous system function [133]. Conversely, moderately-trained participants voluntarily terminate exercise at core temperatures (38.5 °C). Thus, using a critical core temperature threshold to explain fatigue in the heat is too simple and ignores the complexity physiological processes involved in determining exercise capacity and performance.

1.14.2 Cardiovascular strain

In the studies that have suggested a high core temperature *per se* is responsible for performance impairment they have observed high skin temperature and cardiovascular strain, and principally an impairment of cardiac output. Thus, as per the Fick equation, assuming a-vO_{2diff} is fixed or at maximal capacity, any reduction in cardiac output would presumably decrease $\dot{V}O_{2peak}$. A model proposed by Cheuvront et al. [134] is an attractive opposition to that of the critical core temperature hypothesis. $\dot{V}O_{2peak}$ sets the upper limit for exercise capacity and performance and fractional utilisation of $\dot{V}O_{2peak}$ at competition intensity largely determines time to exhaustion and performance. However, $\dot{V}O_{2peak}$ is less in the heat than in temperate environments. Thus, a lower $\dot{V}O_{2peak}$ results in lower external intensity at a specified fractional utilisation or; a higher fractional utilisation at a similar external intensity, which accelerates fatigue and causes performance impairment. Nevertheless, this theory is fundamentally dependent on an impairment of $\dot{V}O_{2peak}$ in the heat. Maximal aerobic capacity, elucidated from an incremental exercise test is impaired in 35 °C compared to 22 °C (~19% impairment [135], 38 °C compared to 13 °C (~18% [136]) and when starting core temperature is increased from 37.5 to 38.5 °C using a water perfused suit (~16% [137]).

There is also evidence to suggest that a similar cardiovascular impairments occur in self-paced performance tasks. Périard et al. [138] demonstrated a very strong relationship between the decrement in external mechanical power output and stroke volume (r^2 = 0.99), cardiac output (r^2 = 0.99) and mean arterial pressure (r^2 = 0.97) and documented a statistically significant decrease in oxygen uptake from 30 to 50 min in a 40 km cycling time trial conducted in 35 °C compared to 20 °C thermoneutral trial. These cardiovascular limitations are most likely imposed by high core and skin temperatures that induce skin vasodilation, large rates of skin blood flow that decrease central blood volume and concomitantly stroke volume, cardiac output, mean arterial pressure and oxygen uptake [138, 139] (figure 15).

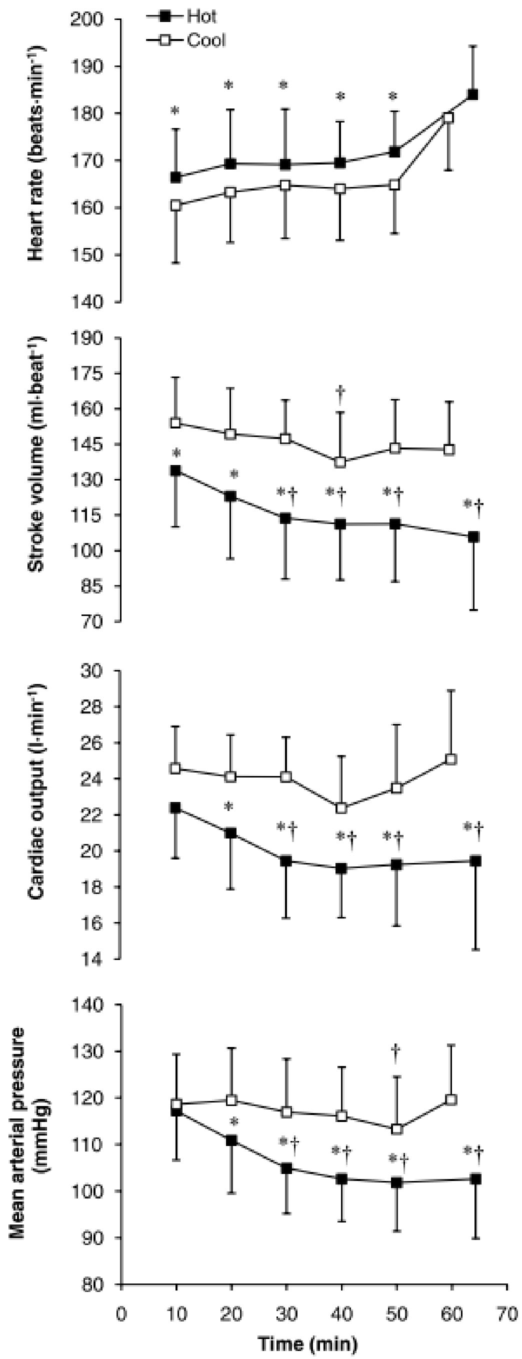

Figure 15: Heart rate, stroke volume, cardiac output and mean arterial pressure during a 40 km cycling time trial in hot and cool conditions

Note the decrease in stroke volume, cardiac output and mean arterial pressure in the hot condition compared to the control condition. Extracted from [138].

1.14.3 Psychobiological models

The Psychobiological Model of Endurance Performance [140, 141], proposes that exhaustion is caused by a conscious decision to disengage from the exercise task, rather than a decline in the muscles ability to produce force. In fixed-intensity exercise, when participants perceive their effort to be maximal they withdraw from the task (RPE 19 to 20). In self-paced exercise, participants consciously reduce external intensity to compensate for a higher than normal perception of exertion. In the psychobiological model of endurance performance, this increase in RPE is postulated to involve the anterior cingulate cortex (ACC) that regulates motor cortex activity. The model suggests that higher perception of effort is caused by an accumulation of adenosine in the ACC, which reduces activation of motor centres, a conscious drive for neuromuscular recruitment and an increase in RPE [142]. If RPE increases above a level greater than expected, then either exhaustion or a reduction in external intensity ensues until RPE returns to an expected level [140, 141].

Essentially all models such as the Central Governor [143–145], theory of Anticipatory Regulation [146], and the Somatosensory [147] model all explain the phenomena of exercise termination and self-paced exercise using perceived exertion as primary controller of the intensity of exercise, despite different afferent inputs into each model. The most well-suited theory to explain how the intensity of exercise is regulated in the heat is the model of behavioural thermoregulation [76, 148, 149]. However, the psychophysical mechanisms that integrate to control intensity of exercise in both heat and temperature conditions are not fully understood. The role of thermosensors such as TRPM8 channels and the control of thermoeffectors, afferent and efferent neural circuits involved in regulating behaviour, neuroanatomical regions and psychological influences require exploration. At present RPE and thermal perceptions are the global representations of these elements and present a simple, although blunt, examination of the effects of heat and exercise on self-paced performance.

1.15 Cooling strategies to alleviate heat strain

Alleviating heat strain and improving exercise capability in hot environments is important from occupational, military and sporting perspective. In industry, it enables safe working practice and an increase in productivity, similarly in military settings it enables personal to perform a greater volume of physically-active duties and improves athletic performance in athletes who are required to compete in hot and humid environments. This section details the cooling strategies available to applied scientists and the evidence for their effectiveness. First, pre-cooling, a well-established strategy, is reviewed and then contextualised based on the mechanistic underpinning believed to influence the effectiveness of pre-cooling. Secondly, the research surrounding cooling during exercise is examined as pre-cooling was before it. In this part, considerations for the application of cooling strategies are highlighted, specifically practical versus impractical strategies as this is a key point in translating evidence from the scientific literature and applying it in practice. Finally, this evaluation leads into study 2, a systematic review and meta-analysis of practical cooling strategies during continuous exercise in hot environments.

1.16 Pre-cooling

The increase in body temperature and implications for fatigue during exercise in the heat has led to research into acute strategies designed to alleviate heat strain and improve performance. Whilst the exact mechanisms that underpin exercise capacity and performance remain unclear ameliorating high body temperature has been a primary goal of this research. Pre-exercise cooling, that is cooling part of, or the whole body before exercise in hot conditions, has been the subject of a large body of research that stems from the treatment of exertional heat illness or post-exercise cooling. Figure 16 depicts the cooling rates associated with a range of treatments in hyperthermic athletes and individuals suffering from heat stroke [150]. Ice and cold-water immersion typically cool individuals (assessed via rectal temperature) around 2 to 3 times faster than fan cooling (figure 16). Therefore, it seems sensible that individuals suffering from a high body temperature should be treated using the fastest mode of reducing body temperature, which is cold-water immersion.

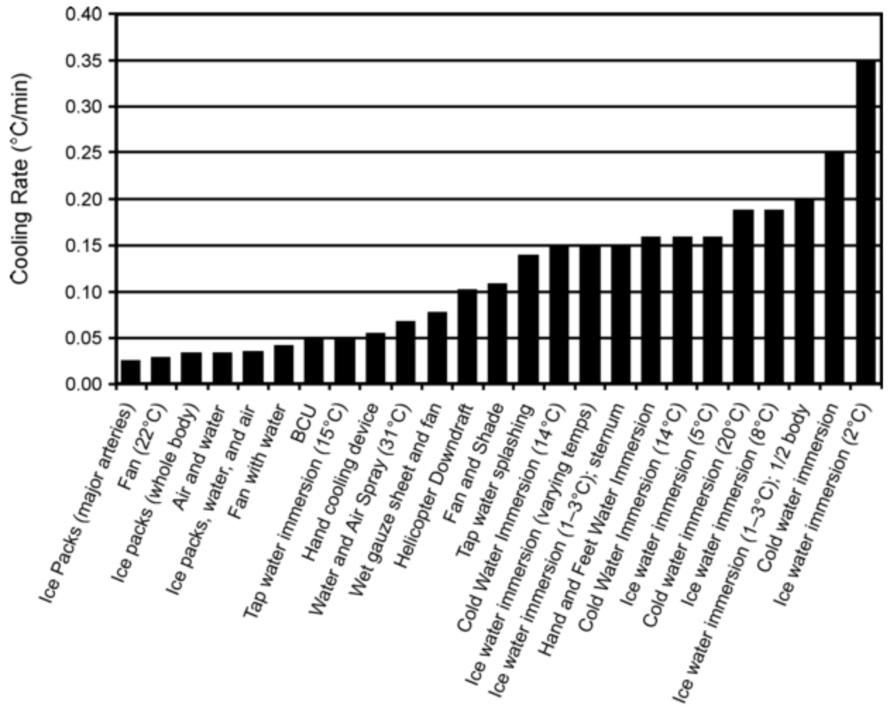

Figure 16: Cooling rates of different methods in hyperthermic athletes and heat stroke patients

Extracted from [150]

1.16.1 Physiological and perceptual benefits

The aim of pre-cooling is to decrease core temperature by around 0.5 °C before exercise in the heat [7]. Such a decrease has been suggested to be beneficial because it increases heat storage capacity, and by doing so, delays or prevents high body temperature that pre-emanates fatigue [6, 7, 108]. External pre-cooling is generally effective at decreasing skin temperature, so that even if no meaningful decrease in core temperature occurred as part of the pre-cooling strategy, there would still be a large core-to-skin temperature gradient to encourage internal heat transfer via conduction and convection from the core to the shell [151]. At a fixed-intensity, this results in observable differences in time-matched physiological variables such as core and skin temperature and heart rate compared to a control trial, especially during early stages of exercise. Furthermore, pre-cooling has also been shown to improve thermal perception [152, 153]; a regulatory variable of performance in both fixed-intensity and self-paced performance trials. The result is that participants incur less physiological strain and "feel better" resulting in an observable benefit in exercise capacity and performance. When taken as a whole body of research pre-cooling consistently improves subsequent exercise in the heat by a small to moderate magnitude (g = 0.44 [95% CI 0.31 to 0.56] [7]. The magnitude of effect, however, is exercise and strategy dependent.

1.17 Classification of pre-cooling strategies

1.17.1 Type of cooling

Pre-cooling can be broadly categorised as external, internal or a mix of the two and has typically been investigated broadly in either sprint, intermittent or endurance types of exercise. External cooling includes strategies such as cold water immersion, application of ice packs, cooling vests or ice towels. While internal pre-cooling strategies include cold water ingestion or ice slurry [154, 155]. The benefit of external cooling is that a wide range of methods are available to cool large surface areas, such as submersion of the lower limbs [153, 156] or immersion up to the neck in cold water [157]. The potential for conductive and convective heat exchange in water is much greater than in air because most of the skin surface is subject to conductive and convective heat exchange currents and the greater specific heat capacity of cold water. Water immersion generally induces the largest benefits on performance, albeit confidence intervals range from a small to very large effect. Nevertheless from a practical perspective it has some limitations [7, 151]. Cold water might lower muscle temperature and inhibit force-producing capability, induce vasoconstriction and be thermally uncomfortable [126]. To overcome these practical limitations ice vests and cooling packs have been used but with limited benefit with most studies reporting unclear effects on performance [6, 7, 158, 159]. This is unsurprising since the magnitude of cooling from these strategies is often not large enough to confer any thermoregulatory or physiological advantage when compared to no cooling. The findings from the internal pre-cooling literature are equally heterogeneous with confidence intervals ranging from unclear to very large benefits on performance [6, 7, 151]. Despite, wider confidence intervals, mixed-method pre-cooling strategies employing both internal and external strategies seems to have an additive effect and improves performance to a greater magnitude (7.0%) than cold water immersion (6.5%), ice slurry/cold water ingestion (6.3%), cooling packs (4.3%) and cooling vests (3.4%) [7].

1.17.2 Type of assessment

The effectiveness of pre-cooling is sensitive to the type of assessment method. For example, Tyler et al. [6] found that sprint performance was impaired (d = -0.26) whereas intermittent (d = 0.47) and prolonged exercise performance was improved (d = 1.91). Moreover, pre-cooling conferred more benefit to open-ended capacity tests at fixed intensities (d = 2.88 95% CI [2.02 to 3.76]) than performance tests (d = 1.06 95% CI [1.00 to 1.25]) [6]. In general, pre-cooling seems to benefit endurance performance and capacity in the heat, but the analysis of these studies is confounded by methodological heterogeneity. For instance, the magnitude of cooling differs from study to study and is often not controlled for either body surface area or somatotype when investigating external pre-cooling or body mass in internal pre-cooling studies. For example, water immersion studies need to consider the interactions of water temperature, body surface area and adiposity.

1.17.3 Considerations for the application of pre-cooling

As an example, an individual with a large body surface area and characterised as an ectomorph, with a low body fat percentage has a greater amount of surface area in contact with the skin. This would promote a greater rate of surface cooling, thus an increase in core-to-skin temperature gradient, and heat flow from the core to the periphery. To alleviate these morphological differences, researchers should investigate the relative proportion of surface area cooled and determine the individual responses to cooling to optimise pre-cooling strategies. This could be achieved in studies that cap cooling according to a threshold body temperature, rather than a time limit for immersion. In addition, researchers might consider the individual neuromuscular responses to pre-cooling since this might be dependent on morphology and thermal perception. Given that, thermal perception is a key regulator in managing external intensity, thus performance, capping thermal comfort and sensation might also prevent unnecessary decrements or at least sub-optimal responses to exercise challenges, since an athlete who feels better is likely to perform better. With this in mind, differences in the method of pre-cooling, the magnitude of thermal stimuli (absolute and relative to morphology), duration of stimulus, inclusion and exclusion of a warm-up, the mode of exercise, the type of exercise challenge (fixed-intensity or performance trial), participants and their ability to thermoregulate and the environment (compensable or uncompensable) should be considered when evaluating the literature, designing future studies and applying the research to practice.

The current body of evidence suggests that pre-cooling benefits prolonged endurance exercise in the heat to a greater extent than short duration high-intensity exercise. This is unsurprising given that endurance time and performance in the heat are impaired, principally because of increased body temperature. In theory pre-cooling should enable participants to start exercise at a lower core temperature and afford a greater magnitude of heat storage before reaching thresholds that initiate physiological and thermoregulatory responses that challenge homeostasis. Tyler et al. [6] also note that pre-cooling might attenuate the rate of core temperature increases during exercise. However, according to Newtons cooling law (heat-transfer law) the opposite must be true.

Figure 17 depicts this law using steel spheres that were pre-cooled before immersion in 38.5 °C water [5]. Irrespective of the magnitude of pre-cooling, thermal equilibrium is reached at the same time. However, the rate of change in temperature of the sphere is proportional to the size of the existing thermal gradient, such that the cooler sphere had a larger increase in the rate of temperature change. Thus, pre-cooling had no influence on the final temperature and in humans this law challenges the concept that pre-cooling prolongs the time to reach some terminal tissue temperature for fatigue (critical core temperature hypothesis) or attenuates the rate of rise in core temperature. Indeed, Booth et al. [160] observed Newton's heat-transfer law using water immersion to pre-cool and pre-heat participants before cycling exercise at 60% $\dot{V}O_{2max}$ in 34.6 ± 2.2 °C and 46.4 ± 2.6% RH.

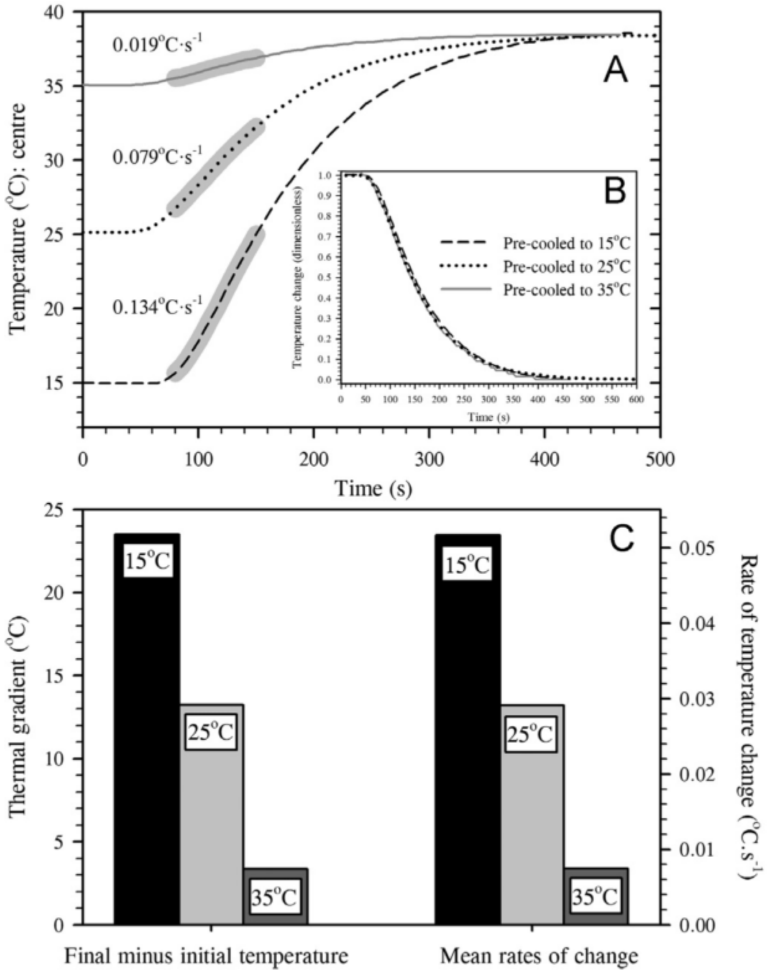

Figure 17: Depiction of Newton's Cooling Law

Extracted from [5]

Figure 18 illustrates that despite a decrease in muscle temperature achieved via pre-cooling, muscle temperature and core temperature increase at a greater rate compared to pre-heating and thermoneutral trials [160]. This indicates that core and muscle temperature increases at a greater rate as a result of pre-cooling and not an attenuated rate as suggested by Tyler et al. [6]. An after drop phenomenon has also been reported [6], whereby core temperature decreases below pre-cooling core temperature at the start of exercise. This is because previously vasoconstricted sites such as the skin, experience mild vasodilation or blood flood to adjacent cooler areas are cooled and recirculated to the core. In this respect, heat storage would presumably decrease before increasing at a faster rate than without an after drop. It seems likely that pre-cooling benefits exercise in the heat simply by lowering body temperature, which reduces cutaneous blood flow and thermal perception. Subsequently cardiovascular demands and perception of effort is reduced, enabling athletes to exercise at either a lower percentage of maximum in fixed-intensity exercise or a higher intensity in self-paced performance trials. In the latter, caution should be exerted as pre-cooling might uncouple perception-performance links. For example, pre-cooling successfully cools an athlete, they feel better in the heat because their core and skin temperature are cooler and they perceive exercise to be less hard as a result. Consequently, they exercise at a greater intensity in the early part of a challenge; however, this might be greater than their critical intensity without cooling thus risking fatigue later in the performance trial. Furthermore, as tissue temperatures increase at a faster rate because of pre-cooling, the change from being thermally cool and comfortable to hot and uncomfortable might be accelerated and result in a premature down-regulation in external intensity and thus impair performance [149]. An additional constraint regarding the use of pre-cooling in practice are logistics, for example a cold-water immersion protocol would be difficult to achieve at most venues, for most athletes, whereas a mixed-method approach of cold/ice packs, cold-wet towels and cold water/ice slurry ingestion is potentially a more practical approach to pre-cooling [161].

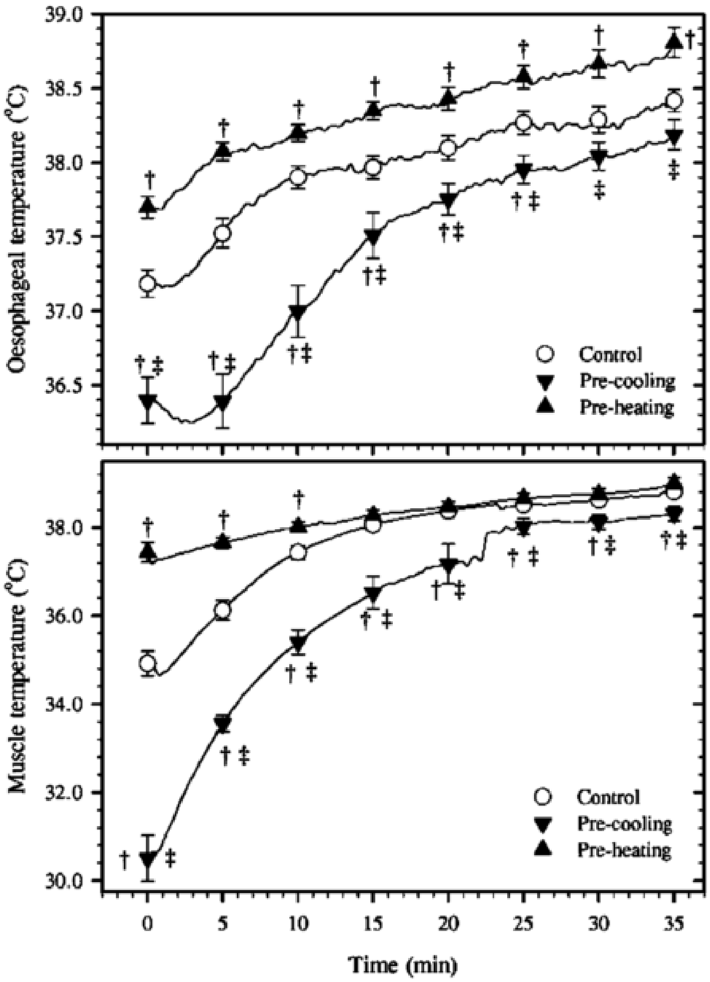

Figure 18: Changes in oesphogeal and muscle temperature during 35 min cycling in the heat

Extracted from [160]

1.18 Cooling during exercise

1.18.1 Pre-cooling combined with cooling during exercise

In addition to pre-cooling strategies, cooling can also be applied during exercise. These strategies have been used with and without pre-cooling using external and internal strategies. Hasegawa et al. [162] investigated the effects of combined external pre-cooling (water immersion in 25 °C) and internal cooling during exercise (14 to 16 °C water ingestion) on thermophysiological responses and exercise capacity in a hot environment (32 °C 80%). Pre-cooling was successful in decreasing rectal temperature by 0.3 °C compared to no water and water ingestion only trials. This difference in rectal temperature was maintained throughout exercise accompanied by a mean skin temperature that was also less than the control trial at the end of 60-min fixed-intensity cycling exercise at 60% $\dot{V}O_{2max}$. The attenuation in body temperature was likely responsible for the lower heart rate observed from 35-min onwards in the combined cooling trial and the lower thermal sensations. Exercise capacity at 80% $\dot{V}O_{2max}$ was extended by combined cooling compared to pre-cooling alone by a mean of 164-s and by 108-s compared to water ingestion alone. Four minutes separated the 60-min fixed-intensity trial and the time-to-exhaustion trial, and although thermophysiological data was not presented, it might be assumed, because of differences in rectal and skin temperature, and heart rate during the first hour of exercise, these were also meaningfully different at the start of the exercise trial to exhaustion. This assumption might explain the observed improvement in time to exhaustion in the combined cooling trial, since participants had lower heat strain, and compared to the other conditions and were able to exercise for longer. This study demonstrated that pre-cooling and cooling during exercise combined resulted in favourable thermophysiological responses during fixed-intensity exercise but comparisons for exercise capacity might be confounded by different starting body temperatures. Lee et al. [163], examined the effects of internal pre-cooling with 900 ml water ingestion (4 °C) combined with 100 ml water ingestion every 10-min throughout exercise (66% $\dot{V}O_{2peak}$). Pre-cooling successfully decreased rectal temperature by 0.5 °C, compared to the control condition (37 °C matched volume water ingestion). This lower rectal temperature was maintained throughout the trial and was accompanied by lower mean skin temperature, heart rate, thermal sensation and RPE. These findings likely explain why exercise to exhaustion was improved by 23% by pre-cooling and cooling during exercise. In addition to cold fluid ingestion, ice slurry (-1 °C) has been used as an internal cooling strategy in a combined approach with pre-cooling. Data available for the use of this method is only available from studies that have used time trial performance as their method of assessment, so the mechanistic actions cannot be fully elucidated. Nevertheless, when ice slurry is ingested during exercise it appears there is no meaningful difference in cycling performance over 40 km when external pre-cooling with ice packs and towels are used [164] or over 30 km when internal pre-cooling with cold water is used [165]. These studies suggest combined pre-cooling and cooling strategies are likely complimentary when fluid ingestion is used as a cooling strategy but perhaps there is little benefit of pre-cooling when ice slurry is used as a cooling strategy during exercise in hot environments.

1.18.2 Classification of strategies

The type of cooling strategy used during exercise can be broadly classified by the exercise trial performed, for example intermittent exercise whereby cooling is applied during recovery periods or continuous exercise where there are no breaks. Cooling strategies can also be intermittent when they are applied at pre-defined time points during exercise or continuous and applied consistently throughout the trial. Furthermore, these strategies, in the context of physical exercise and performance can be further identified as practical or impractical.

That is, could a strategy be used to enhance performance during competition?

The classification of such cooling strategies has not been considered in the scientific literature and in general, reviews and meta-analyses have collated studies that have investigated cooling during exercise into a single group. This is not particularly sensitive given the range of strategies that have investigated this topic. For example, Bongers et al. [7] and Tyler et al. [6] examined the effect of cooling during exercise on capacity and/or performance. These meta-analyses included similar studies and found cooling during exercise to have a beneficial effect on ‘performance’. The classification of these studies as cooling during exercise, however, did not differentiate between exercise capacity and performance trials, the type of cooling, or whether or not they were practical for use during competition.

1.18.3 Practical vs. Impractical strategies

Ultimately the context determines whether a strategy is practical or impractical. During continuous endurance exercise neck cooling with a cooling collar [166–168], for example, could be considered a practical cooling strategy, as it is unobtrusive, lightweight and can be easily transported and stored, thus limiting logistical constraints. These neck cooling studies were included in both Bongers et al. [7] and Tyler et al. [6] meta-analyses. They also, however, included the ice jacket study of Kenny et al. [169] both of whom reported that the ice jacket had large beneficial effects on performance. However, the ice vest used in the study should be classified as impractical for use during competition, primarily because of its added mass. Nevertheless, there is no consensus in the literature as to what constitutes a practical or impractical cooling method, and a clear definition is required. Furthermore, in the neck cooling studies [166–168] fixed-intensity exercise trials to volitional exhaustion and self-paced performance trials were used while Kenny et al. [169] used a fixed-intensity trial to volitional exhaustion. As discussed in previous chapters comparing the results of such trials is problematic since the psychophysiological mechanisms that underpin ‘performance’ in these tests are different. However, Bongers et al. [7] and Tyler et al. [6] included both types of assessment method in their analyses.

Despite the present difficulty in examining the literature as a whole, cooling during exercise, irrespective of the strategy, its application and method of assessment appears to induce beneficial effects during exercise in hot environments. One of the largest beneficial effects reported in the literature is in the study by Luomala et al. [170] that was included in the mean weighted effect size for per-cooling in the meta-analyses of Bongers et al. [7]. The authors used a continuous exercise model and reported an improvement in time to volitional exhaustion of 21.5 +/- 7.6% (*g* = 4.64 95% CI [0.96 to 0.32]); an effect much larger than that reported by others. In this study, seven trained cyclists ($\dot{V}O_{2max}$ 56 ± 3 ml·kg^{-1}·min^{-1}) undertook a protocol designed to simulate the nature of cycling competition that included 9 minutes cycling at 60% peak minute power and one-minute at 80% peak minute power in 30 °C 40% relative humidity with or without an ice vest, which was introduced at 30 min of exercise. The authors concluded that wearing an ice vest in warm, humid conditions induces multiple beneficial physiological 'adaptations' leading to reduced physiological strain and improved perception of heat strain feeding forward to 'enhanced cycling performance'. There are, however, several limitations within this study that do not fit with the observations within the author's discussion and conclusions. The authors did not find a statistically significant difference in core temperature between conditions, and this seems a valid interpretation until stage 6 (60 min). At this point the cooling vest would have been worn for 30-min and the authors note that the Flexi Cold Vest, had a cooling effect for approximately 30-min. However, the authors report that rectal temperature for the ice vest condition decreases and appears to be 0.5 °C lower than the control condition at this time point, when the reported cooling effect had in fact dimished. Moreover, mean skin temperature decreases at this time point in the control trial by approximately 0.7 °C while mean skin temperature remains stable in the cooling vest trial. These findings seem contradictory and are not addressed in the discussion. Furthermore, chest skin temperature, the site of application of the ice vest, was consistently lower throughout the control trial compared to the ice vest. These observations do not support possible mechanisms for an improvement in time to volitional exhaustion and are likely due to participant attrition, which, unfortunately, along with individual responses were not reported in the study. A likely explanation for the beneficial effects observed in the study are the reported improvements in thermal sensation and thermal comfort as a result of the application of the ice jacket which persisted until volitional exhaustion, these changes however, did not appear to induce any meaningful change in RPE, until 67 minutes, after the reported cooling effect had diminished. A major limitation of this study, and of many others, is that the authors fail to report the temperature of the cooling device and its site of application. Thus quantification of the site of cooling cannot be ascertained. Despite this study meeting criteria for inclusion in the meta-analysis of Bongers et al. [7], there are several inconsistencies in the reported data. Furthermore, contrary to the author's aims and conclusions, the ice jacket should actually be considered as an impractical strategy especially for cycling uphill. Given the drive for elite cycling teams to decrease the mass of bicycles and their components on hill and mountain stages of competition, it would be difficult to suggest that an experimental design which including an ice vest with a dry weight of almost 1 kg, with no hill climbing and intensity comparable to less than the respiratory compensation point for 60 seconds could be suggested to enhance cycling performance.

However, while the cooling vest in the Luomala et al. [170] study seemed to benefit endurance capacity, different types of cooling vest might not always offer the same benefit. For example, Eijsvogels et al. [171] did not report and meaningful difference in 5 km running performance at 25 °C 55% RH from wearing an evaporative cooling jacket (weighing approximately 500 g) compared to no ice jacket, nor were there any beneficial effects on rectal temperature. Mean skin temperature however, was statistically less when wearing the ice jacket, but this was probably because chest skin temperature was decreased substantially (~2 °C) by the jacket. The authors did report the temperature of the cooling vest and the temperature at the site of application and observed a vest-to-trunk temperature gradient of around 7 °C for most of the trial, but the lower chest skin temperature did not translate into a meaningful difference in thermal comfort or rating of perceived exertion. The differences between the three ice jackets studies and the beneficial effects reported by Kenny et al. [169] are likely due to the different type of exercise model used to investigate the effects of the cooling intervention, and the environmental conditions. For example, Kenny et al. [169] observed a large beneficial effect on endurance time to exhaustion in 35 °C 65% RH at an intensity of 4.8 km·hour^{-1}. It is possible that the metabolic heat production of participants in the Kenny et al. [169] study, who also wore heavy impermeable nuclear protection clothing, would have been much larger than that of Luomala et al. [170] (whose participants exercised at 60% for the majority of the trial) and because of the higher environmental temperature and clothing ensemble would have had less potential for evaporative cooling. Indeed, despite a potentially larger metabolic heat production, the temperature in Eijsvogels et al. [171] study was 25 °C, favouring evaporative cooling and potentially offsetting any conductive or evaporative benefit afforded by a cooling vest. Furthermore, the cooling jackets in each of these studies were all different and had different masses (4 kg Kenny et al. [169]; 1 kg Luomala et al. [170]; 500 g Eijsvogels et al. [171]) thus different cooling capacities and mechanisms of action; ice vests in the Kenny et al. [169]; and Luomala et al. [170] study functioned via conduction, and by evaporation in the Eijsvogels et al. [171] study. These methodological differences highlight the difficulty in examining the scientific literature when exploring the potential benefits of cooling during exercise.

Other methods of cooling during exercise include limb immersion [172], whole or partial body mechanical cold water or air circulation [173–183], face and head cooling with cold water and fans [184–192], large fluid bolus's [193] and fan cooling [194]. There has also been recent interest in the external application of menthol; strictly this should not be considered a cooling strategy per se, as skin temperature does not change meaningfully following its application, although 1 to 2 °C decreases and increases in skin temperature have been observed following application [148, 195]. Instead, when applied externally, menthol stimulates cold sensitive TRMP8 receptors in thermally sensitive areas such as the chest and back and because it comprises of water has presumably a small evaporative heat transfer benefit, and also potential analgesic and arousing properties [196]. The study by Schlader et al. [148] was not conducted in a hot environment (20 °C, 48% RH) but they observed that menthol application to the face skin surface improved total work done compared to a control trial by 21%, an improvement that was likely mediated by improved thermal comfort and thermal sensation. Barwood et al. [197] investigated the application of menthol to the clothing of participants running 5 km in 34 °C, but did not observe any meaningful differences in time trial performance or thermoregulatory responses despite beneficial effects on thermal comfort and sensation similar to those observed elsewhere (Schlader et al. 2011) [148]. Barwood et al. [195] observed similar responses to menthol application in a 16 km cycling time trial, whereby participants felt cooler but menthol application was unsuccessful at improving performance; the same research group observed similar trivial changes in a 40 km performance trial with menthol spray application compared to non-spray and control surfactant-water-spray conditions [198]. These findings are interesting since a reduced thermal sensation and improved thermal comfort should feed forward to an improved RPE thus selection of higher external intensity and therefore improve performance. Barwood et al. [195], however, suggest that hyperthermia might need to be more pronounced in time trials before performance is regulated by thermal perception. This line of thinking contrasts with Schlader et al. [77] who documented that changes in skin temperature initiated behavioural thermoregulation at rest, and without hyperthermia. The context to which a theory is applied is important. Indeed, it would be prudent to first investigate whether any potential cooling strategy offered a physiological, thermoregulatory or perceptual benefit to determine its efficacy before examining its effectiveness in a performance trial. This way, performance changes can be interpreted in both the context of the cooling strategy and the mechanisms underpinning performance, the strategy can then be fine-tuned to further improve the effect. A simple fixed-intensity exercise trial that forces thermophysiological and perceptual responses would achieve this and enable better context-dependent interpretations of physiological, perceptual and performance responses.

In general, external methods of cooling are also impractical methods of cooling during exercise and previous reviews have not clearly differentiated between ecologically valid strategies that athletes and coaches can apply in competition and internally valid strategies that might be used to investigate the mechanistic underpinning of thermoregulatory control during exercise. Defining these two scenarios is difficult, and there is no consensus within the scientific community. Nevertheless the second part of this thesis examines the literature concerned with improving exercise capacity and performance utilising practical cooling strategies during exercise in hot conditions.

1.19 The hands: Anatomy, physiology and cooling strategies during exercise in hot environments

The hands are a favourable site for cooling primarily because of anatomical and physiological characteristics. This section presents evidence of these characteristics and provides a rationale for why hand cooling is an effective cooling strategy and leads into an appraisal of the current body of literature that has investigated this strategy. Much like other sections the type of cooling, the manner which it is applied and the overall context should be considered distinctly, and this section provides a critical appraisal of these different approaches. Finally, based upon the work presented in previous chapters, the third and fourth studies from this programme of research are presented which focus on the application of hand cooling during continuous exercise in hot environments.

1.19.1 Morphological characteristics

The hands evolved into modern appendages from the demands to gather food, obtain sensory feedback and use tools [199] into an intricate system of neural, musculoskeletal and vascular structures capable of manipulating objects with fine and gross dexterity [10]. The human hand contains 27 bones that comprise ~20% (male) to ~30% (female) of their mass, and a similar number of muscles (30) that also contribute around 20 to 30% of mass [10]. These structures are relatively inactive, have limited heat production and are poorly insulated, which is problematic in cold environmental conditions, as neural control can be impaired which challenges dexterity and the completion of basic survival tasks. Moreover, when tissue temperature decreases there is greater chance of cold-related injuries such as frostbite. When body temperature is elevated, however, this can be an advantage as the morphological characteristics of the hand suit heat transfer to the environment. The surface area of both hands represents around 4.5% of total body surface area but they have a surface to mass ratio relative to 4 to 5 times larger than the rest of the body as a whole [10].

1.19.2 Neurological characteristics

The hand is innervated by the three nerves (figure 19). The Ulnar and Median nerve primarily control dexterity but also play key roles in sensory feedback, and the superficial branch of the radial nerve which senses cutaneous innervation from the dorsolateral surface of the hand, thumb and first two fingers [10]. Seven to 9 cold-sensitive thermoreceptors per cm^2 have been located in the dorsal aspects of the fingers and hands and respond to temperatures from -5 to 43 °C [79]. Whereas warm-sensitive thermoreceptors range from 0.5 to 1.7 cm^2 and function over a smaller range of 28 to 48 °C. Thermoafferent signals travel to the spinal cord, where neurons enter the sensory (dorsal) roots of 6th, 7th and 8th cervical nerves, ascend the spinal cord via the lateral spinothalamic tract to the somatosensory cortex and hypothalamus where sensory neurons synapse with warm-and-cold sensitive hypothalamic neurons [72, 200]. The neural pathways involved in sensory activity from the hands carry important thermosensitive information and represent a relatively large volume of the somatosensory cortex. It appears the thermoeffectors of the hands, as with most cutaneous circulations are controlled by the preoptic anterior hypothalamus. The dorsal surface of the hand is under control of the active vasoconstriction system whereas the ventral (glabrous) aspect of the hand is under the control of active vasodilatory mechanisms [10, 75].

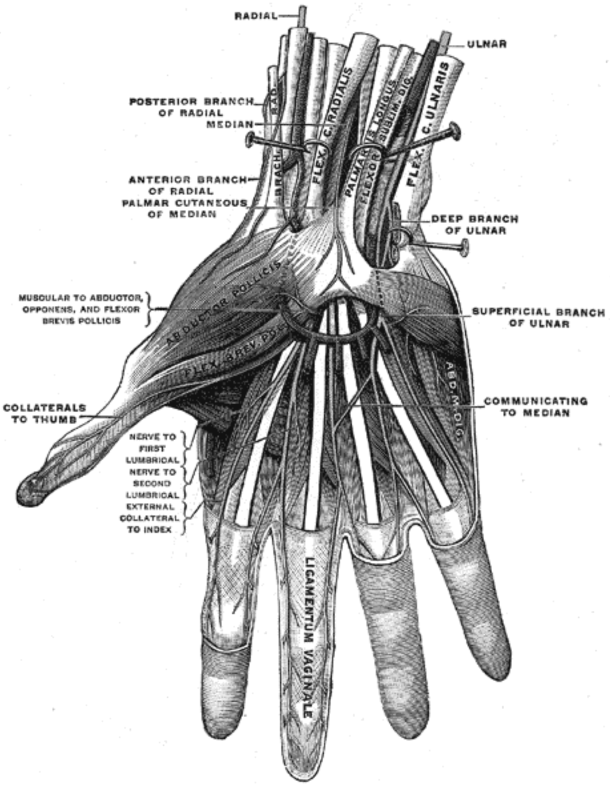

Figure 19: Neuromuscular and vascular structures of the hands

Extracted from [201]

1.19.3 Vascular characteristics

Blood is delivered to the hands by the brachial artery, which divides into the radial and ulnar arteries, forming the deep palmar arch, before dividing into the common palmar digital branches. Blood vessels for the fingers run down both sides of each digit where capillaries in the papillary region loop upwards to the surface before descending to the superficial venous plexus. These capillaries align perpendicularly to arterial and venous structures which optimise heat transfer gradients [10]. This ability is enhanced by arteriovenous anastomoses which behave as capillary bypass vessels. These structures are suggested to have a radius ten times larger than a capillary, thus, when blood flow increases, arteriovenous anastomoses dilate and increase cutaneous blood flow. These conduits also deliver more blood to the slower flowing regions of the deep venous plexus. In a thermoneutral state, blood flow to the hands is also responsive to cold and constriction of the aforementioned vessels which reduces blood flow to conserve heat, but is often accompanied by loss of dexterity, pain and cold-injury. Anastomoses, however, do intermittently dilate (cold-induced vasodilation) which helps to protect surrounding tissues from excessive decreases in digit temperature [99, 202, 203].

Figure’s 20 and 21 were obtained using a corrosion casting technique, using resin to carefully conserve vasculature structures before being scanned in 3 dimensions using an electron microscope [11, 12]

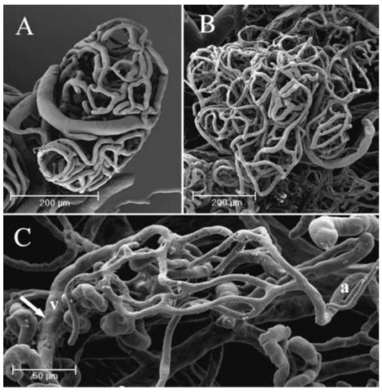

Figure 20: Hypodermal layer of the palmar surface

A = vessels supplying the sweat glands; B = capillaries surrounding thermoreceptorial corpuscles; C = arteriovenous anastomoses [12]

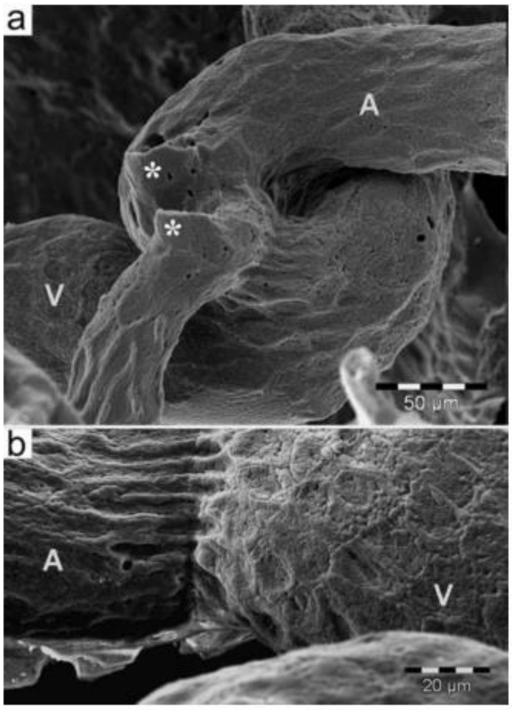

Figure 21: Arteriovenous connections

a = side-to-side; b = end-to-end. A = artery; V = vein [11]

Venous blood is drained via three routes: the deep and superficial palmar venous arches, which drain into the radial and ulnar veins, respectively) and superficial venous plexus that feeds the antebrachial vein [10]. The close proximity of veins and arteries within the hands enables effective counter-current heat exchange, which is useful in both heat conservation and dissipation. Blood flow to the skin of the hands is modified centrally, with deep body temperature controlling these responses seemingly irrespective of local tissue temperature [204]. Caldwell et al. [205] demonstrated that hand blood flow could be modified with local application of hot and cold water, but was most responsive when deep body temperature was considered mildly hyperthermic (38 to 38.5 °C). Conversely, when participants were hypothermic (oesophageal temperature 36 °C) local application of heat failed to increase hand blood flow. Vascular sensitivity of the hands is therefore influenced by the thermal state of the whole body, so that even when colder temperatures are introduced to the skin surface during whole body heating, relatively large rates of blood flow are still achieved. The hands are therefore a favourable site for cooling since they have a large surface area to mass ratio, low metabolic heat production, specialised structures that enable large rates of blood flow and remain well perfused during hyperthermia even when local cooling is applied to the skin surface.

1.20 Hand cooling research

Table 1 provides an overview of the research detailing the effects of hand cooling versus a control trial (no cooling) on body temperature, cardiovascular, perceptual responses and exercise capability. All but one [183] was conducted in environmental temperatures exceeding 30 °C, whereby the aim of each study was primarily to limit or reduce the deleterious effects of a high body temperature. The majority of studies used males as participants, however, a total of 9 females were included in group analyses. Most studies used firefighters or military personnel as participants, and these were often dressed in firefighting, military combat or protective clothing during exercise and in recovery periods. A large proportion of the research studies detailed in table 1 was designed to assess the effect of hand or palm cooling on recovery from exercise in the heat, whereby a period of exercise was followed by a single period of cooling; or multiple periods of exercise interspersed with cooling (for example, exercise-cooling-exercise). The aim of the exercise period was to increase core temperature to around 38.5 °C. There appears to be a lack of rationale for this figure and there are inconsistencies in the assessment of deep body temperature as oesophageal, tympanic, intestinal and rectal temperatures were all used for determining exercise termination temperature. None of the studies used an increase from resting core temperature as a termination point (for example an increase of 1.5 °C from baseline) or considered mean body temperature as an assessment of whole-body thermal state.

Moreover there is a lack of consideration for the assessment of mean skin temperature, which is surprising given the crucial role of skin temperature and cutaneous blood flow in determining exercise capability, particularly at the low intensities used in these studies [206]. Relative intensity of exercise was low ranging from 50 to 75% $\dot{V}O_{2peak}$, however, intensity was not always controlled according to internal demands ($\dot{V}O_2$, HR, the intensity corresponding to a physiological threshold (W at VT1), metabolic heat production) and was often fixed according to an external demand for every participant irrespective of fitness or body mass or surface area. The deep body temperature chosen as a termination temperature is an example of the overemphasis placed on a single tissue temperature to determine the success of an intervention. It is more likely that the combination of exercise intensity, permeability of protective clothing and cutaneous blood flow would induce considerable cardiovascular strain and present a serious challenge to mean arterial pressure, and it is this that would determine exercise capability, rather than a fixed body temperature *per se* [206]. However, few studies considered these integrative effects as key variables of interest. Nevertheless, studies that used water immersion or the ‘rapid thermal exchange (RTX)’ device (full details below), were largely successful in their attainment of their aim of decreasing core temperature, however, there were instances when no effect (all defined as $P > 0.05$ in these studies) was observed. Yet, there was not always a concomitant improvement in mean skin temperature or cardiovascular responses.

The studies which did not use protective clothing, reported both no effect and beneficial effects, but differences in experimental protocols make direct comparisons between studies difficult. The temperature of the cooling method ranged between 10 and 25 °C, however, although it is reasonable to assume there is a temperature gradient between the cooling temperature and the site of application, confirmation of this gradient was consistently overlooked. Failing to report this, and where logistically possible, cutaneous vascular conductance, makes the interpretation of vasoconstriction at the site of cooling difficult. Although, it is possible that an elevated thermal-state might drive palmar vasodilation and increase blood flow to enable heat extraction, quantification of this would be useful to interpret findings. In general, studies that induced greater deep body temperature, or were conducted under greater thermal stress reported larger beneficial effects of hand cooling. Studies that used cooler temperatures as an intervention in combination with relatively larger thermal stress were also consistently successful in achieving their aims. This was highlighted in the analyses of Goosey-Tolfrey et al. [207] and Grahn et al. [13] using linear regression to demonstrate that individuals who experienced greater heat strain benefitted the most from cooling. This is likely because of a greater temperature gradient between skin temperature and the cooling surface. Three studies used a combination of hand and forearm immersion in water; these were all successful, and this is likely because of the larger surface area being cooled. These interventions were only logistically feasible during static rest periods, so although effective, have limited applicability during continuous exercise. Three studies investigated the continuous application of cooling during exercise, two that used a cooled water circulation device reported improvements in all key variables, whilst the palm gel pack used in Scheadler et al. [208] had no effect and a possible impairment in exercise capacity.

Despite the potential for hand cooling as a practical cooling strategy during exercise in hot environments, few studies have investigated exercise capability without an emphasis on occupational or military function. The optimal temperature for hand cooling during continuous exercise and the combined effects of exercise and cooling on vasomotion is also currently unclear. Moreover, the research conducted so far has a lack of focus on integrative thermophysiological responses, which includes ratings of thermal perception and perceived exertion which are key drivers of exercise capability.

Therefore, the final two studies were designed to address the above gaps in knowledge and application by studying the mechanistic effects of hand cooling during exercise in a hot environment. The main purpose of these studies was to elucidate the thermophysiological responses to fixed-intensity exercise using cycle ergometry as a mode of exercise. Such an understanding is critical to the development and refinement of practical cooling strategies and translation of knowledge and are required to form the basis for future research.

Table 1: Overview of hand cooling research.

NR = not recorded. NA = not applicable. ↔ = no difference. ↓ = impaired. ↑ = improved. ± = Standard deviation. T_{rec} = rectal temperature. T_{es} = oesophageal temperture.

Cooling method	**Type of application**	**Overview**	**Temperature of cooling method** (°C)	**Confirmed temperature gradient at cooling site?**	**Core body temperature at time of application** (°C)	**Core body temperature response**	**Mean skin temperature response**	**Heart rate response**	**Perceptual responses (RPE/Thermal perception)**	**Effect on exercise capability**
Palm Cooling	Continuous Palm gel pack	12 males TTE 75% V̇O2max 30 °C, 50% RH [208]	Unknown	NR	NA	↔	NR	↔	↔	↓
		Intermittent cooling								
Water immersion	Hand and forearm immersion	15 males Walking firefighter clothing 4.5 kph^{-1} for 50 min, 30 min recovery, 2nd bout of exercise until T_{rec} reached 39.5 °C, 90% HRmax or exhaustion. 35 °C 50% RH [209]	17.4 ± 0.2 °C	NR	38.2	↑	↑	↑	↑	↑

Cooling method	Type of application	Overview	Temperature of cooling method (°C)	Confirmed temperature gradient at cooling site?	Core body temperature at time of application (°C)	Core body temperature response	Mean skin temperature response	Heart rate response	Perceptual responses (RPE/Thermal perception)	Effect on exercise capability
	Hand immersion	9 males Exercised until T_{rec} reached 38.5 °C, rested for 15 min and repeated once more 31 °C 70% RH [210]	16.4 ± 0.5	NR	38.5	↔	↔	↔	↔	↑
	Hand immersion	9 males 20 min intermittent running. Simulated half-time cooling. [211]	19.1 ± 1.0	NR	38.3	↔	NR	↔	↔	NA
	Hand and forearm immersion	7 males Two bouts of 20 min walking (5 kph^{-1}, 7.5% gradient) wearing firefighting clothing, 15 min recovery 49.6 °C, 13% RH [212]	19	NR	38.2	↑	↑	↑	↑	NA

Cooling method	Type of application	Overview	Temperature of cooling method (°C)	Confirmed temperature gradient at cooling site?	Core body temperature at time of application (°C)	Core body temperature response	Mean skin temperature response	Heart rate response	Perceptual responses (RPE/Thermal perception)	Effect on exercise capability
Hand immersion	6 Males Dressed in firefighting clothing Three 20 min stepping-based exercise bouts, with 20 min cooling between exercise 40 °C, 40% RH [213]	10 20	NR NR	37.8 ± 0.1	↑ ↔	NR NR	↔ ↔	NR NR	NR NR	
Hand immersion	17 males Military protective clothing Two 50 walking bouts at 5 kph, 5% gradient, 10 min rest 35 °C, 50% RH [214]	10	NR	37.8	↑	↑	↑	↔	↑	
	6 males Stepping exercise wearing Navy protective clothing Exercise until 37.5 °C, 20 min rest period, exercise until	10 25	Yes	37.5, 38 and 38.5	↑ ↑	↑ ↑	↑ ↑	NR	↑ ↑	

		38 °C, rest 20 min, exercise until 38.5 °C, rest 20 min 30 °C, 50% RH [215]								

After exercise

Cooling method	**Type of application**	**Overview**	**Temperature of cooling method (°C)**	**Confirmed temperature gradient at cooling site?**	**Core body temperature at time of application (°C)**	**Core body temperature response**	**Mean skin temperature response**	**Heart rate response**	**Perceptual responses (RPE/Thermal perception)**	**Effect on exercise capability**
	Hand immersion	10 males Stepping exercise wearing Navy protective clothing until deep body temperature of 38.5 °C followed by 40 min seated rest 40 °C, 50% RH [216]	11.9 ± 0.8	NR	38.5	↑	NR	↑	NR	NA
	Hand and forearm immersion	49 males 20 min simulated firefighting 20 min rest 33.3 to 36.9 °C, 33 to 61% RH [217]	24.9	NR	38.5	↑	NR	NR	NR	NA

Cooling method	Type of application	Overview	Temperature of cooling method (°C)	Confirmed temperature gradient at cooling site?	Core body temperature at time of application (°C)	Core body temperature response	Mean skin temperature response	Heart rate response	Perceptual responses (RPE/Thermal perception)	Effect on exercise capability
	Hand immersion	7 Males 60 min exercise at 50% W_{peak} 10 min rest 3 km time trial 30.8 ± 0.2 °C, 60.6 ± 0.2% RH [207]	10	NR	38.5	↑	↑	↑	NR	↑
	Hand immersion	4 males Stepping exercise wearing firefighter clothing until T_{rec} reached 38.5 °C, then rested for 30 min. 40 °C, 50% RH [218]	10 and 20	NR	38.5	↑	NR	NR	NR	NA

Cooling method	Type of application	Overview	Temperature of cooling method (°C)	Confirmed temperature gradient at cooling site?	Core body temperature at time of application (°C)	Core body temperature response	Mean skin temperature response	Heart rate response	Perceptual responses (RPE/Thermal perception)	Effect on exercise capability
Rapid Thermal Exchanger										
Continuous application during exercise										
	Single palm	6 Males, 2 females Walking at 5.6 kph^{-1} until 90% HRmax. 40 ± 0.5 °C, 25% RH [13]	18 to 22	NR	NA	↑	NR	NR	NR	↑
	Single palm	8 males 60% $\dot{V}O_{2peak}$ for 60 min 31.9 ± 0.1 °C, 24% RH [14]	22	NR	NA	↑	NR	↔	NR	↑
Intermittent application										
	Single palm	5 males, 5 females 30 s very hard self-selected running, 1.5 min recovery x 8 reps 21 to 23 °C, 30 to 50% RH [183]	15	NR	NA	↔	↔	↔	↔	↔

Cooling method	**Type of application**	**Overview**	**Temperature of cooling method (°C)**	**Confirmed temperature gradient at cooling site?**	**Core body temperature at time of application (°C)**	**Core body temperature response**	**Mean skin temperature response**	**Heart rate response**	**Perceptual responses (RPE/Thermal perception)**	**Effect on exercise capability**
		8 Males, 2 females Walking 50% VO_{2peak} until T_{rec} reached 38.5 °C, rested for 40 min, walked at same intensity until T_{rec} reached 39 °C. 42 °C, 30% RH [219]	15, 18 and 22	NR	38.5	↔	NR	↔	NR	↔
					After					
	Single palm	10 males Wearing military protective clothing walked at 6.1 kph, 2 to 4% gradient until Tes reached 38.8 °C then rested for 50 min. 42 ± 0.5 °C, 36.5 ±	10	NR	38.8	↑	↑	↔	↑	NA

1% RH
[220]

Cooling method	Type of application	Overview	Temperature of cooling method (°C)	Confirmed temperature gradient at cooling site?	Core body temperature at time of application (°C)	Core body temperature response	Mean skin temperature response	Heart rate response	Perceptual responses (RPE/Thermal perception)	Effect on exercise capability
	Two palms	17 males Walking 5.6 kph until T_{es} reached 39 °C, 95% HRmax or exhaustion then rested for 60 min in protective clothing. 41.5 ± 0.5 °C, 20 to 35% RH [221]	10 to 11	NR	39.0	↑	NR	↔	NR	NA
		8 Males Walked on a treadmill wearing firefighting clothing for 40 min, then rested for 40 min. 33.7 °C, 40 to 45% RH [222]	21 ± 1.9	NR	39.1 ± 0.4	↑	NR	NR	NR	NA

1.21 Chapter 2 conclusions

The quantification of temperature is essential to life and the understanding of the effects of temperature has driven social, industrial, military and medical advances. To quantify temperature it is important to understand the general considerations of thermometry, the types of assessment and appraise the local influences of temperature at the site of assessment. Moreover, examination of the error surrounding the assessment is crucial to the interpretation of temperature and is especially important in hot environments. As such, study 1 investigated the day-to-day reliability of gastrointestinal temperature and demonstrated that an intestinal telemetry pill system had low day-to-day error. This is important from a safety perspective for monitoring athletes within hot environments, when determining the effectiveness of treatments designed to alleviate heat strain and investigating how body temperature is controlled during thermal stress and strain.

It is also important to make a clear distinction between the mechanisms limiting exercise capability in fixed-intensity exercise and self-paced exercise. In fixed-intensity exercise to exhaustion, heat strain leads to peripheral vasodilation and increases in skin blood flow this accelerates cardiovascular strain and precedes any decrease in neuromuscular function. In self-paced endurance exercise behaviour is primarily regulated by RPE, where key inputs include thermal perception and cardiovascular strain. The body responds to exercise and heat stress utilising a complex and integrative approach of local and central control. Several theories have been proposed to suggest *what* controls body temperature, some are simple others are more complex but from a practical perspective *how* body temperature is regulated by physiological responses is crucial for applied scientists. These physiological responses have a local origin, for example, changes in blood flow at the muscle at the onset of exercise, and are an important starting point to understanding what limits exercise capability in hot environments. As are the fundamentals of attaining heat balance because ultimately the combination of metabolic heat production and the potential for heat transfer to the environment determines heat strain. The challenge for the exercising athlete is to maintain a balance between performance intensity and magnitude of heat strain, which have also been presented as models or theories. The most prominent of these being the critical core temperature hypothesis, which has been used extensively to suggest that a temperature *per se* is the primary factor that constrains exercise capability in the heat. However, understanding what limits performance and how this is context dependent is important for the applied practitioner, as this will influence the strategy and the evaluation of strategies designed to alleviate heat strain, mainly heat acclimation and cooling methods.

The two main types of acute strategy designed to alleviate heat strain are pre-cooling and cooling during exercise. Cooling before exercise is generally effective, but the success of an intervention is dependent on the proceeding task, individual responses and whether the cooling strategy is applied externally or internally. Moreover, the interpretation of *why* a pre-cooling strategy is successful is dependent on the understanding of *what* limits exercise capability in the heat, mainly cardiovascular limitations or a critical core temperature. This is important since the conclusions drawn from a study that has interpreted the mechanistic basis for the effect leads to future research applied in context. Cooling during exercise, has also been investigated both with and without pre-cooling and the type of cooling seems to be important factor in these situations. Cold fluid ingestion is required before and during exercise to have beneficial effects, whereas pre-cooling with ice slurry does not appear to be required when ice slurry is consumed during exercise. This distinction is important from a practical perspective as is the classification of the type of exercise trial performed to investigate the efficacy of a treatment and whether or not cooling during exercise is practical or impractical.

The hands, which comprise intricate neural, musculoskeletal and vascular structures, are capable of manipulating objects with fine and gross dexterity and can initiate rapid vasoconstriction and vasodilation, the latter of which induces large rates of blood flow. The hands also have low rates of metabolic heat production and a large surface to mass ratio making them and ideal site for cooling. Most studies investigating the effectiveness of hand cooling have used military personnel as participants in studies of recovery from exercise in the heat, and although effective have limited application for use during continuous endurance exercise.

1.22 Thesis research questions

1.22.1 Study 1

In healthy participants, does practical cooling during continuous exercise in a hot environment, attenuate mean and final core temperature responses compared to a thermoneutral or no cooling condition in randomised cross-over trials?

In healthy participants, does practical cooling during continuous exercise in a hot environment, improve self-paced endurance performance and exercise capacity compared to a thermoneutral or no cooling condition in randomised cross-over trials?

Secondary research questions sought to investigate the effects of cooling during exercise on mean skin temperature, heart rate, whole body sweat production, RPE and thermal perception, all of which have been implicated in the regulation of performance during exercise in the heat.

1.22.2 Study 2

What is the inter-day reliability of intestinal core temperature using an ingestible telemetry pill system during exercise within a hot environment?

1.22.3 Study 3

Does continuous hand immersion in cold water during exercise in a hot environment alleviate increases in body temperature, cardiovascular and perceptual strain?

1.22.4 Study 4

Can a pair of novel hand cooling gloves worn during exercise in a hot environment alleviate increases in body temperature, cardiovascular and perceptual strain?

Chapter 2: Practical cooling strategies during continuous exercise in hot environments: A systematic review and meta-analysis

2.1 Abstract

Introduction: Performing exercise in thermally-stressful environments impairs exercise capacity and performance. Cooling during exercise has potential to aid thermoregulation, attenuate detrimental increases in body temperature and improve exercise capacity and performance. The objective of this systematic review and meta-analysis was to assess the effect of practical cooling strategies applied during continuous exercise in hot environments on body temperature, heart rate, whole-body sweat production, rating of perceived exertion (RPE), thermal perception and exercise performance. **Methods:** Electronic database searches of MEDLINE, SPORTDiscus, Scopus and PEDro were conducted using medical subject headings, indexing terms and key words. Studies were eligible if participants were defined as 'healthy', the exercise task was conducted in an environment ≥25 °C, used a cooling strategy that would be practical for athletes to use during competition, cooling was applied during a self-paced or fixed-intensity trial, participants exercised continuously, the study was a randomised controlled trial with the comparator either a thermoneutral equivalent or no cooling. Data for experimental and comparator groups were meta-analysed and expressed as a standardised mean difference and 95% confidence interval. **Results:** Fourteen studies including 125 participants met the eligibility criteria. Confidence intervals for meta-analysed data included beneficial and detrimental effects for cooling during exercise on core-temperature, mean skin temperature, heart rate and sweat production during fixed-intensity exercise. Cooling benefited RPE and thermal perception during fixed-intensity exercise and improved self-paced exercise performance. **Conclusions:** Cooling during fixed-intensity exercise, particularly before a self-paced exercise trial, improves endurance performance in hot environments by benefiting RPE and thermal perception but does not appear to attenuate increases in body temperature.

2.2 Introduction

Sporting events are frequently scheduled in hot and humid environments (e.g., stages of the Tour de France, summer-month marathons) thus evidence-based practical strategies that can alleviate thermal demand, reduce the risk of heat illness and improve performance are of interest to scientists and applied practitioners. During cellular respiration heat produced in active muscle is transferred by conduction and convection to blood and surrounding tissues [30, 149]. At the skin surface heat must be transferred via dry and evaporative mechanisms to the environment to limit heat storage and increases in body temperature. When the rate of metabolic heat production exceeds the rate of external heat transfer, which frequently occurs when exercise is combined with high ambient temperature (>25 °C) and water vapour pressure, heat is stored and body temperature increases [30].

Performing exercise in thermally-stressful environments increases the risk of exercise-associated muscle cramps, heat syncope, exhaustion, heat injury and exertional heat stroke [223] and also impairs exercise capacity and performance [4, 108, 115, 121–123, 224, 225]. During fixed-intensity exercise the attainment of high brain [35] and body temperature [108] and subsequent cardiovascular demands limit exercise capability [118]. Whereas during self-paced exercise performance, external force production is limited so that the task can be completed, possibly mediated through rating of perceived exertion [149] skin temperature [226, 227], skin wettedness [78] and thermal sensation [149, 228].

Cooling the body has been the subject of several reviews [6, 7, 154, 155, 229] [18–22], two of which [6, 7] investigated the effects of cooling *during* exercise and suggested that cooling improved endurance performance in the heat. Siegel and Laursen [154] , however, noted that most cooling methods are largely impractical for use during competition, a view supported by Tyler et al. [6] who recognised that some cooling methods would be unsuitable for use during performance because of their mass, potential for irritability and sports regulations. Nevertheless, previous reviews [6, 7] included strategies that would be impractical to use during continuous exercise performance (for example, heavy ice vests, mechanically-circulated cool water and fan-assisted head cooling), although these might be useful during intermittent exercise, care needs to be taken when contextualising analyses.

Tyler et al. [6] noted that the largest improvements in performance were observed when core temperature and heart rate were both reduced by cooling but acknowledged that further research is required to ascertain the mechanisms that explain these performance improvements. This mechanistic underpinning of performance has been identified as an important step in translational physiology [230].

Accordingly, the primary research questions were:

- In healthy participants, does practical cooling during continuous exercise in a hot environment, attenuate mean and final core temperature responses compared to a thermoneutral or no cooling condition in randomised cross-over trials?
- In healthy participants, does practical cooling during continuous exercise in a hot environment, improve self-paced endurance performance and exercise capacity compared to a thermoneutral or no cooling condition in randomised cross-over trials?

Secondary research questions sought to investigate the effects of cooling during exercise on mean skin temperature, heart rate, whole body sweat production, RPE and thermal perception, all of which have been implicated in the regulation of performance during exercise in the heat.

2.3 Methods

This review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [231].

2.3.1 Inclusion and exclusion criteria

Studies were included if;

- the participants were defined as 'healthy' or 'able-bodied' and without disability or disease that influenced exercise capability or thermoregulation;
- the study was conducted in an environment where the temperature ≥ 25 °C;
- the study used a cooling strategy that would be practical for athletes to apply during competition;
- cooling was applied during the self-paced performance trial or fixed-intensity task;
- the participants exercised continuously;
- the study was a randomised controlled trial with a comparator being either administered at a temperature from 30 to 40 °C, or no cooling trial;
- studies assessed either core body temperature, skin temperature, heart rate, sweat loss, rating of perceived exertion, thermal comfort/perception, exercise capacity or self-paced performance as an outcome;
- the study was original research published, in the English language, in peer-reviewed journals (including ahead of press/online first)

We did not exclude studies based upon exercise mode or sex but did exclude studies that were designed exclusively to investigate fluid balance. We received no funding for translation services so only research published in English language was included within the review.

2.3.2 Information sources and search strategy

Electronic database searches were performed up to 10th March 2015 using MEDLINE, SPORTDiscus, Scopus and PEDro. Medical subject headings (MeSH), database indexing terms, key words and Boolean operators (AND/OR) were used in the search strategy. Terms were grouped into themes related to cooling, exercise and body temperature regulation. For SPORTDiscus search terms included "Cool*", "Cold*", "Cold temperature", "Cryotherapy", "Exercise", "Physical fitness", "Exercise therapy", "Physical exertion", "Sports", "Exercise movement techniques", "Core temperature", "rectal or oesophageal or oesophageal or intest* or tympanic AND temperature", "Body temperature", "Body temperature regulation", "thermosen*", "thermor*", "Hypothermia", "Hyperthermia". All searches were conducted by the same author (AR). Search results were collated using Endnote software (Thomson Reuters, New York) and duplicates were removed. The title and abstract of the remaining studies were screened for relevance (AR). Full texts of potentially appropriate studies were obtained and independently assessed for eligibility by two authors (AR/BR) according to the inclusion criteria. Reference lists and citations (via Google Scholar search) of manuscripts and relevant review articles were examined for potentially eligible studies (AR).

2.3.3 Data extraction process

Study characteristics including sample size, age, body mass, stature, aerobic capacity, health status, exercise mode, intensity of exercise, duration of exercise, ambient temperature and humidity, air/wind speed and description of the intervention were extracted for selected studies (AR). Mean and standard deviations of the primary outcomes (core temperature and self-paced performance) and secondary outcomes (mean skin temperature, heart rate, whole body sweat production, RPE and thermal perception) for experimental and comparator groups were extracted for outcomes of interest (AR). When relevant data was not reported in the text it was extracted from figures using GetGraph Graph Digitizer (http://www.getdata-graph-digitizer.com/index.php) by one author (AR). Validity of data extraction was verified by another author (BR). When there were reference to, but no pertinent data available from the manuscript the authors were contacted (AR). Reviewers (AR/BR) were not blinded to authors or institutions at any stage of the selection or data collection process.

2.3.4 Data items

Core temperature (°C) was a primary outcome and defined as an assessment at either rectal, intestinal, oesophageal or tympanic sites. Mean skin temperature (°C) was defined as at least a four-site weighted assessment using skin surface thermometry. Heart rate (beats·min^{-1}) was defined as an assessment using electrocardiography or short-range telemetry. Whole body sweat loss (L) was defined as the difference in body mass pre to post assessment taking into account fluid ingestion and urine output. Rating of perceived exertion and thermal comfort were defined as choices made by participants from a perception scale. Exercise capacity tests were defined as those that had a fixed external or internal intensity applied until volitional exhaustion. Self-paced exercise performance was defined as tests whereby the participant was free to choose external intensity over a pre-determined duration, distance or set amount of external mechanical work.

2.3.5 Risk of bias in individual studies

Risk of bias was assessed using the 6-point Cochrane Risk of Bias assessment tool [232]. Two authors (AR/BR) independently assessed risk of bias. Appraisal of study quality was performed according to subject expertise (led by AR) and guided by the risk of bias assessment tool.

2.3.6 Summary measures

The mean and standard deviation of participant physical characteristics, health status, intensity and duration of exercise and exercise mode were used to subjectively determine methodological heterogeneity prior to meta-analysis (AR/BR). Data for experimental and comparator groups was analysed using Cochrane Collaboration's Review Manager 5.3 (Cochrane IMS, Melbourne, Australia). Data was expressed as a standardised mean difference (adjusted Hedges '*g*') and 95% confidence interval. Statistical heterogeneity was assessed using the I^2 statistic to determine the percentage of the variability in effect estimates due to heterogeneity rather than sampling error (chance). Pooled intervention effect estimates and 95% confidence intervals were calculated as a weighted average of the standardised mean difference estimated in individual studies. When I^2 exceeded 40% (moderate heterogeneity) a random-effects model was used to calculate the pooled intervention effect, otherwise it was calculated using fixed-effect inverse variance. We performed a sensitivity analysis on self-paced performance trials after we found that studies had either; 1) performed fixed intensity exercise before performance trials (e.g. 60% $\dot{V}O_{2max}$ for 60-min followed immediately by a time-trial); or 2) used self-paced performance trials only. Exercise to exhaustion, however, was considered to have large methodological heterogeneity for intensity and duration of exercise and was not meta-analysed.

2.4 Results

2.4.1 Participants and included studies

Figure 22 details the PRISMA [231] flow chart. Participant characteristics are detailed in table 2 and study details in table 3. Mean fixed intensity was 63 ± 7% $\dot{V}O_{2max}$, mean duration of exercise 74 ± 23 min, consisting of running (*n* = 7 studies) and cycling (*n* = 7) as modes of exercise. Mean ambient temperature, relative humidity and wind speed was 31 ± 2 °C, 52 ± 17% and 2.9 ± 3.5 $m{\cdot}s^{-1}$, respectively. Participant characteristics, intensity, duration and mode of exercise and environmental conditions were considered to have small between-study methodological heterogeneity, thus meta-analysis was performed on outcomes assessed using fixed intensity exercise. Self-paced performance trials consisted of cycling (*n* = 4 studies) and running (*n* = 2 studies), the mean duration of these trials was 32.6 ± 36.3 min (range from 15 to 97.4 min).

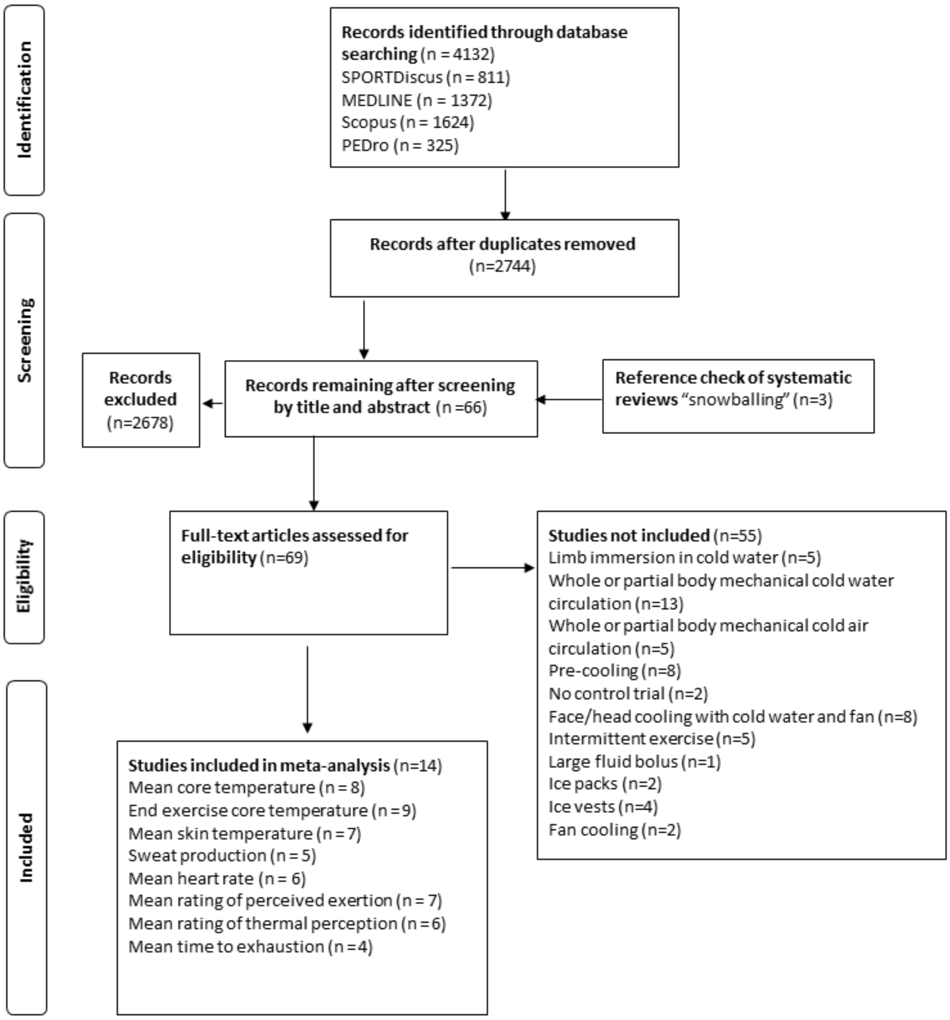

Figure 22: PRISMA flow diagram

PEDro Physiotherapy Evidence Database, PRISMA Preferred Reporting Items for Systematic Reviews and Meta-Analyses

Table 2: Characteristics of participants in included studies

Study	Number of participants	Age ± SD (years)	Body mass (kg)	Stature (cm)	$\dot{V}O_{2max}$ (ml·kg^{-1}·min^{-1})	Characterisation
Burdon et al. (2010) [155]	7	33 ± 6	81.1 ± 11.1	183 ± 9	59.4 ± 6.6	Non-acclimated males
Burdon et al. (2013) [233]	10	30 ± 7	75.1 ± 9.4		61.8 ± 5.6	Healthy, naturally acclimatized male endurance cyclists
Burdon et al. (2015) [234]	10	30 ± 7	75.1 ± 9.4	175 ± 7	61.8 ± 5.6	Healthy, naturally acclimatized male endurance cyclists and triathletes
Lee et al. (2008) [235]	8	27 ± 4	70.9 ± 7.9	174 ± 5	53.8 ± 6.2	Non-heat acclimated males
Lee et al. (2014) [236]	12	24 ± 2	61.6 ± 8.1	172 ± 5	59.4 ± 5.3	Healthy males
Minniti et al. (2011) [237]	8	25 ± 5	77.4 ± 5.6	181 ± 8	53.7 ± 4.7	Healthy males
Morris et al. (2015) [238]	9	25 ± 5	75.9 ± 12.2	177 ± 7	50.9 ± 8.5	Healthy males
Scheadler et al. (2013) [208]	12	23 ± 4	76.1 ± 8.7	179 ± 6	53.8 ± 5.2	Healthy males
Schulze et al. (2015) [164]	7	33 ± 8	73.1 ± 3.3	179 ± 5	61.7 ± 3.0	Well trained male triathletes
Tyler et al. (2010) [167]	9	25 ± 4	76.5 ± 5.9	181 ± 7	54.2 ± 4.6	Healthy males
Tyler et al. (2010) [167]	8	25 ± 3	75.5 ± 7.0	180 ± 5	54.9 ± 3.1	Healthy males
Tyler and Sunderland (2011) [168]	8	26 ± 2	77 ± 6.2	177 ± 6	56.2 ± 9.2	Endurance trained athletes
Tyler and Sunderland (2011) [166]	7	25 ± 2	75.3 ± 8.4	179 ± 5	55.3 ± 3.6	Healthy males
Bulbulian et al. (1999) [239]	10	27 ± 6	80.5 ± 6.7	181 ± 4	38.6 ± 6.3	Healthy active males
Carvalho et al. (2014) [240]	10	25 ± 6	69 ± 2.7	170 ± 10	67.2 ± 1.8	Well trained male athletes (cyclists, mountain bikers, triathletes)

Table 3: Details of included studies that used fixed-intensity exercise

Study	Exercise mode	Intensity (% $\dot{V}O_{2max}$)	Duration (min)	Ambient temperature (°C)	Relative humidity (%)	Air speed (m/s)	Intervention
Burdon et al. (2010) [155]	Cycling	65	90	28.0	70.0	1.0	2.3 ml·kg^{-1} (185 ml) every 10 minutes of 4 °C 7.4% carbohydrate-electrolyte solution. 37 °C 7.4% carbohydrate-electrolyte solution. 37 °C 7.4% carbohydrate-electrolyte solution + 30 ml ice slurry (-1°C) every 5 min
Burdon et al. (2013) [233]	Cycling	62	90	32.1	40.0	1.0	260 ± 38 g of 7.4% carbohydrate-electrolyte solution every ten 10 minutes as either ice slurry (-1°C) or thermoneutral (37 °C)
Burdon et al. (2015) [234]	Cycling	62	90	32.0	40.0	1.0	260 ± 38 g of 7.4% carbohydrate-electrolyte solution every ten 10 minutes as either ice slurry (-1°C) or thermoneutral (37 °C)
Lee et al. (2008) [235]	Cycling	50	90	25.3	60.0		400 ml of 10 °C or 37 °C water ingested at 30, 45, 60 and 75 min of exercise.
Lee et al. (2014) [236]	Running	70	75	30.2	71.0		155 g neck cooling collar worn throughout. No neck cooling collar.
Minniti et al. (2011) [237]	Running	60	75	30.4	53.0		155 g neck cooling collar worn throughout. Uncooled collar.
Morris et al. (2015) [238]	Cycling	55	75	33.5	23.7	2.25	3.2 mg·kg^{-1} (240 ml) or 37 °C of ice slurry ingested at 15 min intervals for first 45 min of exercise
Scheadler et al. (2013) [208]	Running	75	53	30.0	50.0		Refrigerated gel pack on single palm. No refrigerated gel pack
Schulze et al. (2015) [164]	Cycling		60	30.0	80.0	9.1	Ad libitum ingestion of either carbohydrate-electrolyte solution ice slurry (-1°C) or thermoneutral beverage (30 °C)
Tyler et al. (2010) Tyler et al. (2010) [167]	Running	60	75	30.4	53.0		155 g neck cooling collar worn throughout. Uncooled collar.

Tyler and Sunderland (2011) [168]	Running	70	41	32.2	53.0		155 g neck cooling collar worn throughout. No cooling collar.
Tyler and Sunderland (2011) [166]	Running	60	75	30.4	53		155 g neck cooling collar worn throughout. Neck cooling collar replaced at 30 and 60 min. No cooling collar.
Bulbulian et al. (1999) [239]	Cycling	60	30	30	25	8.9	Headband and neck cooling collar soaked in ice water. No cooling.

2.4.2 Mean and end-exercise core temperature

Ten outcomes from 8 studies [155, 164, 208, 233–236, 238] were included in the meta-analysis for mean core temperature. Six studies used rectal temperature to assess core temperature and two studies used gastrointestinal pills. Studies used ice slurry (n = 5), cold fluid (n = 2), ice slurry mouthwash (n = 1), neck cooling (n = 1) and palm cold pack (n = 1) as interventions. There was no effect of cooling on mean core temperature during exercise (g = -0.08 [95% CI = -0.37 to 0.22]) (Figure 23).

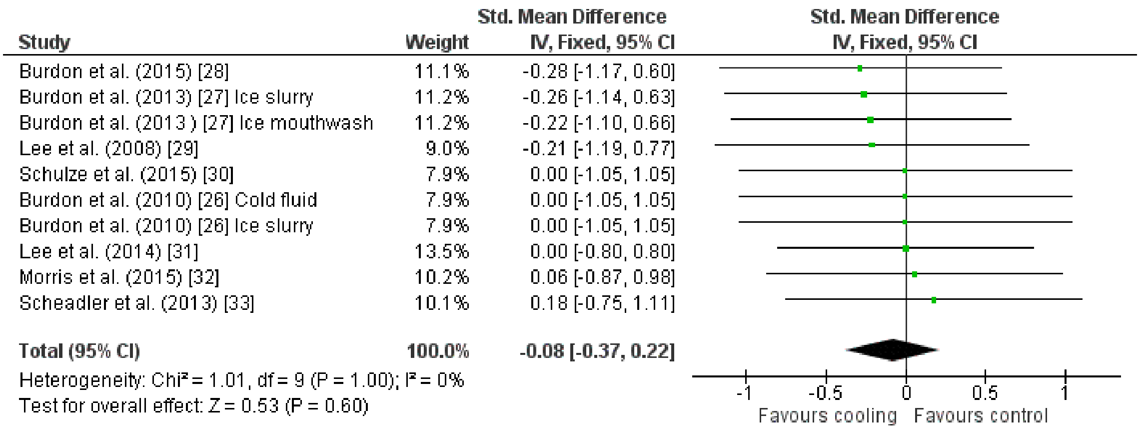

Figure 23: Intervention effect estimates, 95% CIs and weighted average of the Std for mean core temperature.
CI confidence interval, IV inverse variance, SD standard deviation, Std standardised mean difference.
Figure extracted from [8]. Values in [ ] do not represent reference numbers within the thesis.

Thirteen outcomes from 10 studies [155, 166–168, 233, 234, 236, 238, 239] were included in the meta-analysis for end-exercise core temperature. Nine studies used rectal temperature to assess core temperature and one study used gastrointestinal pills. Studies used neck cooling (n = 5), ice slurry (n = 4), cold fluid (n = 2) and ice slurry mouthwash (both n = 1) as interventions. There was no effect of cooling on core temperature at the end of exercise (g = -0.21 [-0.47 to 0.04]) (figure 24).

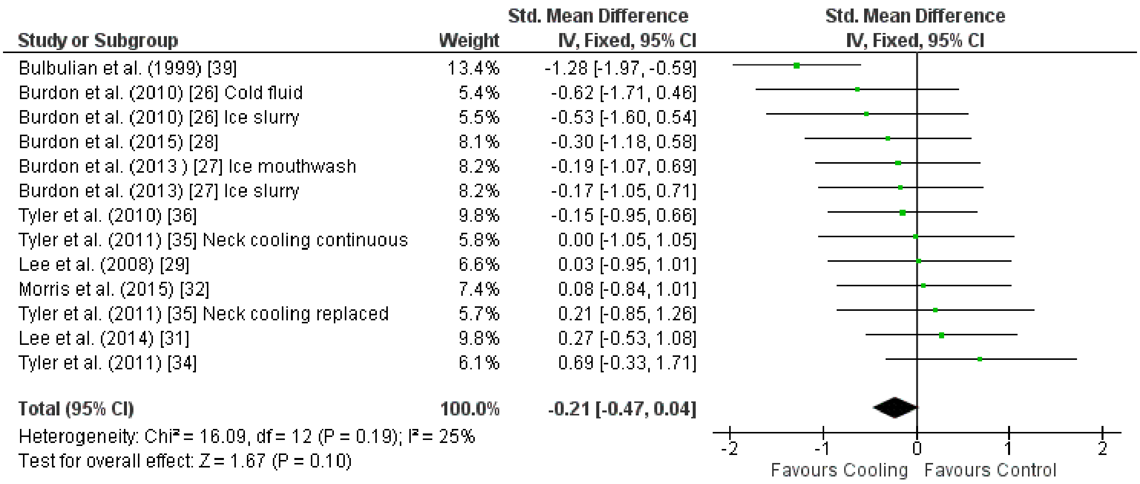

Figure 24: Intervention effect estimates, 95 % CIs and weighted average of the Std for end-exercise core temperature.

CI confidence interval, IV inverse variance, SD standard deviation, Std standardised mean difference. Figure extracted from [8]. Values in [ ] do not represent reference numbers within the thesis.

2.4.3 Mean skin temperature

Ten outcomes from 8 studies [155, 164, 233–236, 238, 239] were included in the meta-analysis for mean skin temperature. All assessments were made using weighted 4-site mean calculation [241] via skin surface thermometry. Studies used ice slurry (*n* = 5), cold fluid (*n* = 2), ice slurry mouthwash (*n* = 1) and head/neck cooling (both *n* = 1) as interventions. There was no effect of cooling on mean skin temperature (*g* = -0.28 [-0.56 to 0.00]) (figure 25).

Study	Weight	Std. Mean Difference IV, Fixed, 95% CI
Burdon et al. (2010) [26] Cold fluid	5.4%	-1.40 [-2.62, -0.19]
Burdon et al. (2015) [28]	9.2%	-0.88 [-1.81, 0.05]
Burdon et al. (2010) [26] Ice slurry	7.0%	-0.47 [-1.54, 0.60]
Bulbulian et al. (1999) [39]	20.5%	-0.29 [-0.91, 0.34]
Schulze et al. (2015) [30]	7.2%	-0.17 [-1.22, 0.88]
Morris et al. (2015) [32]	9.3%	-0.17 [-1.09, 0.76]
Burdon et al. (2013) [27] Ice slurry	10.3%	-0.13 [-1.00, 0.75]
Lee et al. (2014) [31]	12.4%	0.02 [-0.78, 0.82]
Burdon et al. (2013) [27] Ice mouthwash	10.4%	0.05 [-0.83, 0.92]
Lee et al. (2008) [29]	8.3%	0.05 [-0.93, 1.03]
Total (95% CI)	**100.0%**	**-0.28 [-0.56, 0.00]**

Heterogeneity: Chi² = 6.73, df = 9 (P = 0.67); I² = 0%
Test for overall effect: Z = 1.93 (P = 0.05)

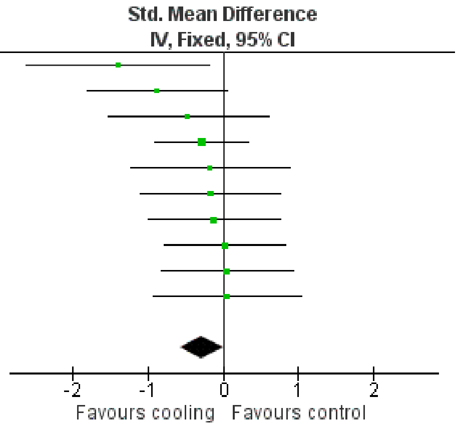

Figure 25: Intervention effect estimates, 95 % CIs and weighted average of the Std for mean skin temperature.

CI confidence interval, IV inverse variance, SD standard deviation, Std standardised mean difference. Figure extracted from [8]. Values in [ ] do not represent reference numbers within the thesis.

2.4.4 Mean heart rate

Seven outcomes from 6 studies [164, 208, 233, 235, 236, 238] were included in the meta-analysis for mean heart rate. Studies used ice slurry (n = 3), cold fluid, palm cold pack, neck cooling and ice slurry mouthwash (all n = 1) as interventions. There was no effect of cooling on mean heart rate (g = -0.03 [-0.37 to 0.32]) (figure 26).

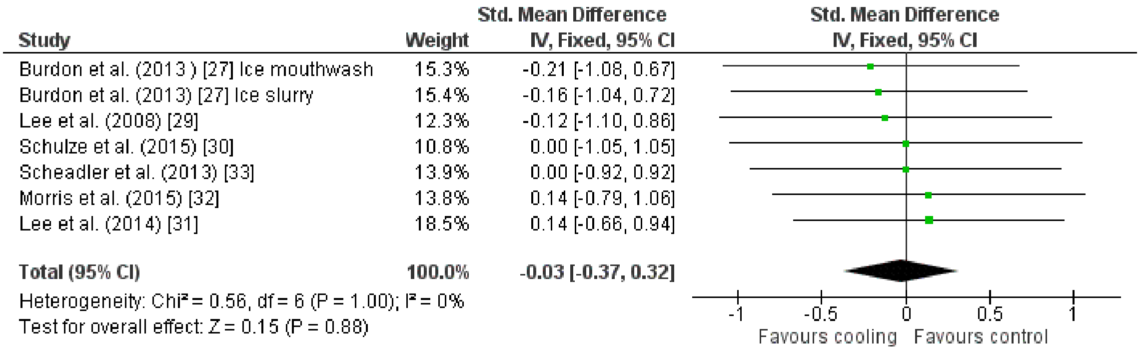

Figure 26: Intervention effect estimates, 95 % CIs and weighted average of the Std for mean heart rate. CI confidence interval, IV inverse variance, SD standard deviation, Std standardised mean difference. Figure extracted from [8]. Values in [ ] do not represent reference numbers within the thesis.

2.4.5 Rating of perceived exertion and thermal perception

Eight outcomes from 7 studies [167, 168, 208, 233, 236, 237, 239] were included in the meta-analysis for mean rating of perceived exertion. All studies used the Borg 6 to 20 RPE scale. Studies used neck cooling (*n* = 4), palm cold pack, ice slurry, ice slurry mouthwash and combined forehead and neck cooling (all *n* = 1) as interventions. Cooling during exercise improved rating of perceived exertion (g = -0.49 [-0.81 to -0.17]) (figure 27).

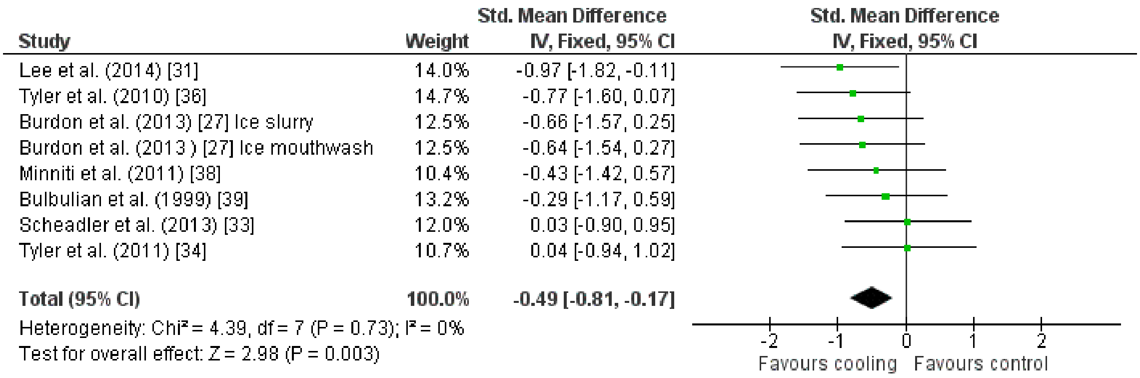

Figure 27: Intervention effect estimates, 95 % CIs and weighted average of the Std for mean rating of perceived exertion.

CI confidence interval, IV inverse variance, SD standard deviation, Std standardised mean difference.

Figure extracted from [8]. Values in [ ] do not represent reference numbers within the thesis.

Six outcomes from 6 studies [164, 167, 168, 233, 235, 236] were included in the meta-analysis for mean thermal perception. Studies used three different scales [67, 80, 242] one investigation did not report the scale used [236]. Studies used, neck cooling (n = 3), ice slurry (n = 2) and cold fluid (n = 1) as interventions. Cooling during exercise improved thermal perception (g = -0.67 [-1.06 to -0.29]) (figure 28).

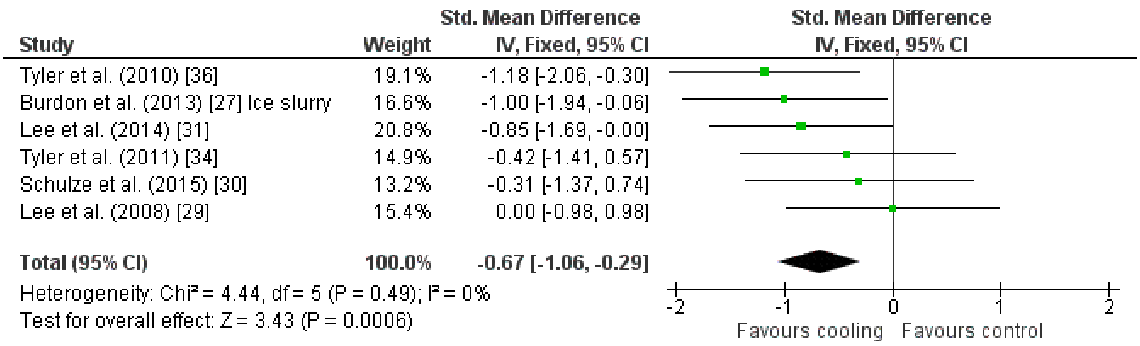

Figure 28: Intervention effect estimates, 95 % CIs and weighted average of the Std for mean thermal perception.

CI confidence interval, IV inverse variance, SD standard deviation, Std standardised mean difference

Figure extracted from [8]. Values in [ ] do not represent reference numbers within the thesis.

2.4.6 Whole body sweat production

Six outcomes from 5 studies [166–168, 238] were included in the meta-analysis for whole body sweat production. Studies used neck cooling (n = 4) and ice slurry and head and neck cooling (both n = 1) as interventions. There was no effect of cooling during exercise on whole-body sweat production (g = -0.13 [-0.50 to 0.23]) (figure 29).

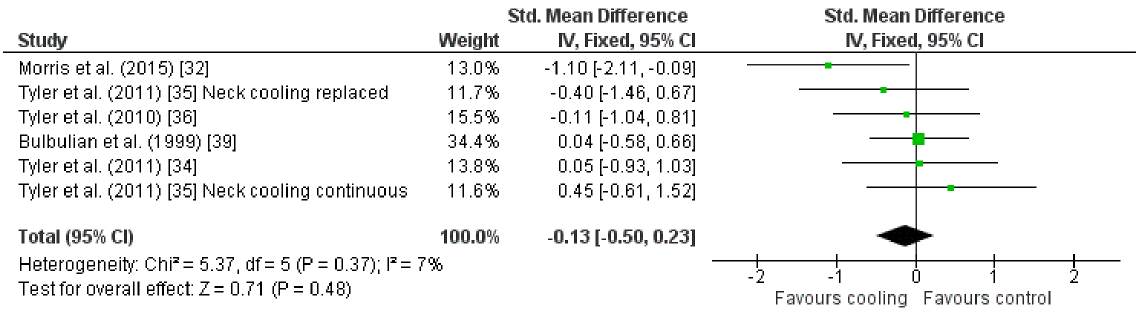

Figure 29: Intervention effect estimates, 95 % CIs and weighted average of the Std for mean sweat rate. CI confidence interval, IV inverse variance, SD standard deviation, Std standardised mean difference

Figure extracted from [8]. Values in [ ] do not represent reference numbers within the thesis.

2.4.7 Exercise duration

Four studies assessed time to exhaustion at a fixed intensity. Two studies reported mean improvements in time to exhaustion using neck cooling however confidence intervals suggested no effect was observed; (*g* = -0.38 [-1.37 to 0.61]; *g* = -0.58 [-1.40 to 0.24], respectively) [168, 236]. One study used a palm cold pack [208] and reported no effect on time to exhaustion during running (*g* = -0.07 [-0.87 to 0.73]) and another used cold fluid [235] and documented no effect on time to exhaustion during cycling (*g* = -0.09 [-1.07 to 0.89]).

2.4.8 Self-paced performance

Eleven outcomes from 6 studies [155, 164, 166, 167, 233, 240] were included in the meta-analysis for self-paced performance. Studies used neck cooling (*n* = 4), cold fluid ingestion (*n* = 3), ice slurry (*n* = 3) and ice slurry mouthwash (*n* = 1) as interventions. There was a beneficial effect of cooling during exercise on self-paced performance (*g* = -0.48 [-0.78 to -0.18]) (figure 30). Sensitivity analysis demonstrated that self-paced performance was improved after fixed intensity exercise (*g* = -0.47 [-0.83 to -0.12]) (figure 30) but the effect was no effect for self-paced performance trials only.

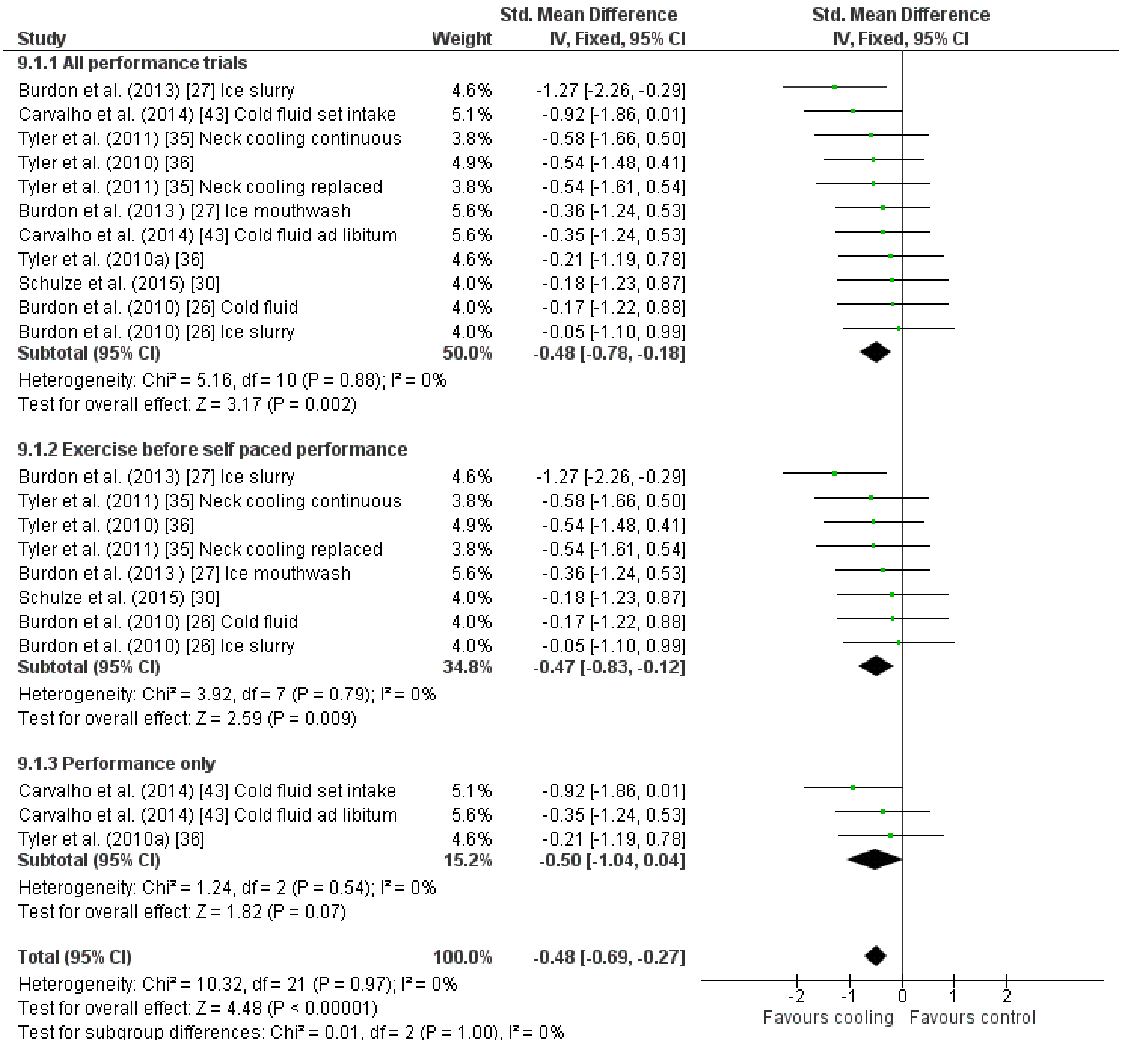

Figure 30: Intervention effect estimates, 95% CIs and weighted average of the Std for self-paced performance.

CI confidence interval, IV inverse variance, SD standard deviation, Std standardised mean difference.

Figure extracted from [8]. Values in [ ] do not represent reference numbers within the thesis.

2.5 Discussion

The purpose of this study was to investigate the effects of practical cooling strategies used during continuous exercise in hot environments. Meta-analyses revealed no effect for cooling during exercise on mean core temperature, end-exercise core temperature, mean skin temperature, mean heart rate, whole body sweat production and stand-alone self-paced performance; although confidence intervals for these estimates overlapped beneficial and detrimental effects suggesting uncertainty in the point estimate, we interpret these findings as being unclear and that more data is required to improve confidence in the interpretation of these outcomes. Cooling during exercise, however, was beneficial for self-paced exercise performance when cooling was applied during a period of fixed-intensity exercise before the trial; rating of perceived exertion and thermal perception were also improved by cooling. The unclear effects on stand-alone self-paced performance and improved RPE and thermal perception oppose findings from previous meta-analysis [6, 7]. These studies found clear improvements in performance but unclear findings for perceptual responses. These contradictions are likely due to differences in study selection.

Our systematic search strategy identified 14 studies that met our inclusion criteria, whereas previous meta-analysis included up to 9 studies [6]. Tyler et al. [6] noted that some cooling methods might have issues regarding practicality (e.g. excess mass, skin irritation and sport-rule constraints), thus we only included studies that were deemed to be practically applicable during continuous exercise. Specifically, only studies that were considered practical to use during continuous exercise were included in the systematic review. We excluded studies that used "face/head fan or water cooling", "liquid/air cooling garments", "partial limb water immersion", "ice cooling vests", and "fluid bolus >400 ml"; these strategies were deemed to be impractical, especially during competition. Studies utilising these methods, however, were included in the two previous meta-analysis on cooling during exercise [6, 7]. Bongers et al. [7] and Tyler et al. [6] found that ice jackets had the greatest effect on performance; Tyler et al. [6] recognised this and subsequently offered an alternative mean-weighted standardised difference estimate with the ice jacket study [169] excluded from their analysis; but this was because the study was conducted in an uncompensable environment, not because the suitability of ice jackets.

Tyler et al. [6] did not include cold water or ice slurry ingestion in their analysis, however, we choose to include these methods because they are practical methods during continuous exercise in the heat. Bongers et al. [7] included one cold water ingestion study in their analysis [192], but the comparator to the experimental trial (4 °C) was also cold fluid (19 °C) and not thermoneutral, thus it was not included in the present meta-analysis. Moreover, it is unclear whether a criterion for inclusion in the previous meta-analyses required a thermoneutral or no cooling comparator trial. Whilst we recognise that studies might be investigating 'applied' practices, using a thermoneutral trial as a comparator is preferable to understand the true effect of cooling during exercise, particularly the mechanisms of action, which is an important component of translational physiology [230].

To understand the mechanistic actions of cooling during exercise, we discriminated between studies that used fixed-intensity exercise and self-paced performance trials. During self-paced exercise participants are free to choose external intensity and regulate performance; but between-trial differences in intensity makes interpretations of thermophysiological data difficult. During fixed-intensity exercise, however, thermophysiological effector responses are forced [69]. Such responses (e.g. core temperature) are typically reliable [63, 64, 243] and enable valid comparisons between interventions. Bongers et al. [7] did not discriminate between fixed intensity exercise or self-paced performance and it was not the aim of Tyler et al. [6] to do so, but both studies reported thermophysiological responses. This distinction between study design is a possible explanation for the differences reported in perceptual responses between the present study and that of Tyler et al. [6]. Our analysis indicates that RPE and thermal perception are improved with cooling during fixed intensity exercise, however, Tyler et al. [6] reported unclear findings.

We discriminated between time-to-exhaustion trials and self-paced performance trials which the two previous meta-analysis did not. These types of test are suggested to be regulated by different mechanisms; in self-paced trials participants are free to choose external intensity and whilst this choice might have a physiological origin, behaviour is regulated by RPE within acceptable limits for the task [149] to avoid excessive physiological strain. In fixed-intensity exercise participants cannot freely choose external intensity and the increasing demands on cardiovascular, neuromuscular and central nervous system as a result of metabolic heat production and heat storage [244] integrate with psychological factors to determine time-to-exhaustion. Therefore, these types of tests should be analysed separately to avoid confusion in interpretation. Furthermore, it is well established that time to exhaustion tests have a greater magnitude of test-re-test error than time trials [50] and such variance might contribute to wider confidence intervals resulting in an unclear effect. Indeed, we found unclear effects of neck cooling [168] and a palm cold gel pack [208] on exercise time to exhaustion.

2.5.1 Core temperature

Bongers et al. [7] suggested that cooling during exercise might attenuate the increase in core temperature, increase heat storage capacity and improve exercise capacity based on theory for a single terminal tissue temperature ('critical core temperature') for cessation of exercise. This assertion was based upon the purported effectiveness of an 'aggressive' cooling strategy using an ice vest [170]. Ice vests, however, are not practical for use during continuous exercise performance and the mechanistic theory (critical core temperature hypothesis) underpinning this recommendation is likely too simple to explain human behavioural thermoregulation [131, 244]. Nevertheless, we investigated this hypothesis using fixed intensity exercise trials. None of the practical cooling methods demonstrated clear reductions in either mean or end-exercise core temperature. A possible explanation is that the enthalpy of cooling methods were insufficient or the site at which cooling was applied had limited tissue perfusion (required for effective heat transfer). This might have been the case in cold water and slurry ingestion given the documented reduction in splanchnic blood flow during exercise in the heat [94] and also for neck cooling. Continuous cooling at a site with potential for high rates of perfusion would seem to be an ideal method for attenuating increases in body temperature.

2.5.2 Perceptual responses

Flouris and Schlader [149] suggested that thermal perception is an important mediator of behavioural thermoregulation that integrates with RPE in its role as the predominant controller of exercise intensity. We found that RPE and thermal perception were improved by cooling during fixed-intensity exercise and is a key finding from our analysis. Prior to increases in core temperature, self-selected intensity of exercise is likely mediated by thermal perception and its influence on RPE, whereas when core and skin temperature are elevated cardiovascular strain is a key RPE input [149]. Studies included in the present meta-analysis used neck cooling, ice slurry and fluid ingestion. Cooling the neck during heat exposure elicits feelings of thermal comfort at rest [81], a finding extended to 2 [167, 236] of 3 neck cooling during exercise studies. We found an unclear effect for one study [168]; the reason for this is unknown as the neck cooling collar was the same and participants and environmental conditions were similar in all three investigations. The study, however, was designed to investigate time to exhaustion and final core temperature was >39 °C, therefore cardiovascular strain might have been the key RPE mediator rather than thermal perception, however, it is worth noting that RPE was similar between conditions. There was also a clear beneficial effect of ice slurry ingestion on thermal perception in one study [233] but not in another [164]. These differences might be attributed to the study design, specifically, a beneficial effect of set-planned [233] rather than *ad libitum* [164] ingestion of slurry. Lee et al. [235] reported similar between-trial responses for thermal perception (400 ml of 10°C fluid versus 37 °C fluid ingested at 15 min intervals), although the mean ambient temperature of 25.3 °C combined with an intensity of 50% $\dot{V}O_{2max}$ was among the least thermally stressful of included studies, indeed final core temperature was 38.11 °C, less than the mean of included studies which was 38.48 ± 0.58 °C.

Six out of eight studies reported mean improvements for RPE. Standardised mean differences for neck cooling [168] and palm cold pack [208] were similar for experimental and comparator trials. In the latter whether palm cooling occurred is unclear as palm skin temperature was not reported, thus absence of cooling might be an explanation for the similar between trial RPE. Nevertheless, the weighted standardised mean difference and 95% confidence interval indicate that cooling during exercise has the potential to improve RPE; possibly mediated via beneficial effects of cooling on thermal perception.

2.5.3 Performance

Our findings indicate that cooling during fixed intensity exercise, before a self-paced time trial improves performance (figure 30). Strictly, this could be considered cooling before performance, but we included these studies in our analysis because of the number of studies that have classified this type of design as cooling during exercise. This data is informative for those sports whereby 'sub-maximal' intensities precede an intense period of activity, such as in team road cycling. In these circumstances tactical efforts are used to position a rider (or group) for an 'attack' at key points within a race. Cooling during the sub-maximal phase of the race, whereby fluid ingestion and external cooling aids are less constrained by logistics, might benefit performance in a subsequent 'attack'. In stand-alone self-paced performance trials there are usually observable 'end-spurts' which prior cooling might also benefit, however, we did not investigate pacing profiles in these studies. Furthermore, we found unclear effects of cooling during stand-alone self-paced performance trials, but the three trials included in the meta-analysis all reported mean improvements; a larger sample size would improve the precision of the effect.

2.5.4 Skin temperature and heart rate

We observed unclear effects of cooling during exercise on mean skin temperature and heart rate during fixed intensity exercise. Burdon et al. [234] investigated a potential link between ice slurry ingestion, decreased skin temperature and heart rate during exercise. Although Burdon et al. [234] reported a statistically significant difference ($P < 0.05$) between ice slurry and thermoneutral trials for mean skin temperature towards the end of 90 min cycling at 62% $\dot{V}O_{2max}$ in 30 °C we report an unclear effect on mean skin temperature (g = -0.88 [-1.81 to 0.05]) for this study. These unclear effects were replicated across all included studies apart from Burdon et al. [155] where there was a beneficial effect of cold fluid ingestion (4 °C, ~185 ml every 10 min for 90 min) on mean skin temperature (g = 1.40 [2.62 to -0.19]. There were no beneficial effects on heart rate across the range of included studies (figure 26) in the present meta-analysis. This does not, however, indicate there were no beneficial effects on skin blood flow or stroke volume, as skin temperature and heart rate are only indexes of these variables in this context.

The effect of cooling during exercise on whole body sweat rate was unclear (figure 29), although one study [238] reported a clear decrease in whole body sweat rate after ingesting 3.2 $ml \cdot kg^{-1}$ of ice slurry (~240 ml) at three, 15 min intervals (15, 30 and 45 min) during the first 45 min of 75 min exercise. The authors suggested that intra-abdominal thermoreceptors integrate with the central nervous system to elicit strong thermoeffector responses at the skin surface, in particular sudomotor function. Therefore, despite an internal heat sink caused by slurry ingestion, the decreased evaporative heat loss impaired net heat loss and increased heat storage. It should be noted that this was the only study included in the meta-analysis that used ice slurry during exercise to investigate whole body sweat rate responses; more research is required to corroborate these findings.

2.5.5 Study methods and reporting

All studies included in the present investigation were randomised cross-over trials; however, it was unclear as to how randomisation and allocation concealment occurred (table 4). Researchers should report this information to facilitate appraisal of bias and study quality. Some studies (for example [166]) reported changes in local temperature as a result of cooling, however, most studies did not. Tyler et al. [6] recognised that such information is required to confirm whether local cooling occurred as a result of the intervention and is particularly relevant for external cooling methods. In addition, researchers should indicate the practicality of the method and report feelings of uncomfortableness, irritations, adverse effects and general appraisals from participants. This information would be helpful to scientists, coaches and athletes who are in the process of evaluating the suitability of a particular cooling method for their own specific use.

Table 4: Risk of bias assessment

Study	Random sequence generation	Allocation concealment	Blinding of participants and personnel	Blinding of outcome assessment	Incomplete outcome data	Selective reporting
Burdon et al. (2010) [155]	?	?	-	?	+	+
Burdon et al. (2013) [233]	?	?	-	?	+	+
Burdon et al. (2015) [234]	?	?	-	?	?	+
Lee et al. (2008) [235]	?	?	-	?	?	+
Lee et al. (2014) [236]	?	?	-	?	?	+
Minniti et al. (2011) [237]	?	?	-	?	?	+
Morris et al. (2015) [238]	?	?	-	?	?	+
Scheadler et al. (2013) [208]	?	?	-	?	+	+
Schulze et al. (2015) [164]	?	?	-	?	+	+
Tyler et al. (2010) [167]	?	?	-	?	?	+
Tyler et al. (2010) [167]	?	?	-	?	?	+
Tyler and Sunderland (2011) [168]	?	?	-	?	?	+
Tyler and Sunderland (2011) [166]	?	?	-	?	?	+
Bulbulian et al. (1999) [239]	?	?	-	?	?	+

? = not reported; - = low risk; + = high risk

2.5.6 Limitations

A potential limiter to the application of all cooling studies is that is no consensus as to what constitutes a practical or impractical cooling strategy. The suitability of a particular technique is ultimately based upon complex interplay between the logistical constraints of the situation, coaching philosophy and athlete perceptions. Nevertheless, researchers have investigated strategies that might not be feasible for use during continuous exercise, a problem that has been previously identified in the scientific literature [6, 154]. In the absence of such consensus we have excluded strategies that we deem to be impractical for use during actual competition. This might have introduced selection bias within our included studies but we are confident that we have captured strategies that are useful for athletes, coaches and scientists. Including studies that used impractical strategies would have limited the ecological validity of the present review and thus its applied impact.

2.5.7 Recommendations

Our analysis provides evidence that self-paced performance is improved when the cooling method is administered during continuous exercise before the performance trial. Ice slurry ingestion and neck cooling are the most studied practical cooling interventions and are both associated with beneficial effects on thermal perception, RPE and performance. We suggest that improvements in self-paced performance are mediated via the beneficial effects of cooling on thermal perception and RPE. This is consistent with human behavioural thermoregulatory theory [149], that states that self-selected intensity of exercise increases or decreases dependent on the magnitude of thermal or cardiovascular strain which integrate with the predominant intensity controller, RPE. In principle, participants felt cooler during exercise and perceived the intensity of exercise to be less. Consequently, participants chose to increase external intensity resulting in a performance improvement. This is clearly beneficial for high-performance athletes, however, is associated with a risk of heat-related illness, particularly for novice and youth athletes as an increased intensity causes a greater magnitude of metabolic heat production, heat storage and body temperature. This combination is of particular concern if the environment is uncompensable or the thermoregulatory responses of the participant are inadequate to equilibrate the basic heat balance equation [30].

Practitioners should also be aware, relatively large volumes of ice slurry (240 ml) or cold-water ingestion (>400 ml) might decrease sweat gland activity and limit the potential for evaporative heat loss resulting in heat storage and high body temperature. This is another concern for underprepared novice and youth populations whose whole body sweat responses and evaporative heat transfer potential are likely inadequate to match that required to attain heat balance. Such a bolus, however, is associated with discomfort [238] and an ingestion of this magnitude would likely be avoided *ad libitum*. We are not aware of any meaningful detriments on whole body sweat rate occurring due to neck cooling; however, neck cooling is associated with the attainment of a high body temperature. Indeed, none of the practical cooling methods were sufficient to attenuate an increase in body temperature. Therefore, we suggest practitioners undertake a thorough evaluation of the environment where competition or training will take place and that metabolic heat production and evaporative heat loss requirements are estimated prior to activity. Adequate body temperature, fluid balance and perceptual monitoring procedures [223, 245] should be in place, especially for highly motivated novice and youth athletes. Such an approach will improve the likelihood that appropriate cooling strategies are implemented during exercise. To date no studies have investigated a combination of neck cooling, ice slurry and cold fluid ingestion; these strategies might have additive effects and be more beneficial than administering a single method alone. Future research should also consider exploiting sites, such as the hands, that have potential to attenuate increases in body temperature [10, 14]. In addition, opinions of coaches, athletes and support staff regarding the practicality of cooling methods should be evaluated to guide scientists towards research that has high ecological validity and sound mechanistic underpinning.

2.6 Conclusion

We found that practical cooling strategies administered during exercise before a self-paced endurance trial improve performance in hot environments, but not by decreasing core temperature as previously thought [7]. Instead we suggest that current methods improve performance by benefiting thermal perception and RPE, resulting in greater self-selected external intensities compared to a thermoneutral or no cooling trial thus improving endurance performance. We encourage practitioners and to explore the use of cold fluid, ice slurry ingestion and neck cooling for endurance performance enhancement after examining the thermal constraints of the environment. Future research should investigate a combination of approaches to cooling during continuous exercise as well additional sites, such as the hands, that have the potential to attenuate increases in body temperature.

Chapter 3: Reliability of intestinal temperature using an ingestible telemetry pill system during exercise in a hot environment

3.1 Abstract

Introduction: Ingestible telemetry pill systems are being increasingly used to assess intestinal temperature during exercise in hot environments. The purpose of this investigation was to assess the inter-day reliability of intestinal temperature during an exercise-heat challenge. **Methods:** Intestinal temperature was recorded as twelve physically active males (25 ± 4 yrs, stature 181.7 ± 7.0 cm, body mass 81.1 ± 10.6 kg) performed two 60-min bouts of recumbent cycling (50% of maximum aerobic power (W)) in an environmental chamber set at 35 °C 50% relative humidity 3 to 10 days apart. A range of statistics were used to calculate reliability including a paired t-test, 95% limits of agreement (LOA), coefficient of variation (CV), technical error of measurement (TEM), Pearson's correlation coefficient (*r*), intraclass correlation coefficient (ICC) and Cohen's *d*. Statistical significance was set at $P \leq 0.05$. **Results:** Analysis revealed a statistically significant (P = 0.02) mean systematic bias of −0.07 ± 0.31°C (trial 1 temperature lower than trial 2). Investigation of the Bland-Altman plot indicated that systematic and random error components were proportional to the magnitude of intestinal temperature and suggested the presence of heteroscedasticity. The method indicated good overall reliability (LOA = ±0.61 °C, CV = 0.58%, TEM = 0.22 °C, *r* = 0.84, ICC = 0.91, Cohen's *d* = 0.12). Further analysis revealed the error free change and minimum likelihood of a probable change in intestinal temperature to be ≈0.32 °C. **Conclusions:** Although this method demonstrates good reliability, researchers should be aware of potential heteroscedasticity whereby error increases as the magnitude of the

assessed variable increases. Practitioners can be confident that observed changes in intestinal temperature greater than 0.32 °C as a result of exercise or an intervention in hot environment are true and unlikely due to error associated with the method.

3.2 Introduction

Exercise in a hot environment challenges the function of cardiovascular [118], metabolic [115] and thermoregulatory systems [75]; thus exposure to prolonged, intense exercise that raises body temperature increases the risk of heat illness and impairs athletic performance [246]. Subsequently, strategies have been designed to help athletes perform in hot environments, all of which are designed to regulate body temperature. A heat tolerance test is useful for assessing the ability to regulate body temperature and measurements of body temperature responses are integral to interpretation. Where improved heat tolerance is required, decisions regarding the most appropriate method and their specific derivatives are determined; these are usually grouped into 1) heat acclimation or acclimatisation protocols and; 2) cooling methods. The most appropriate method is context specific but the choice is driven by whether body temperature responses to a strategy are sufficient to improve safety and performance. Consequently, it is important that practitioners use valid and reliable methods to monitor body temperature [32] to make well-informed and clear decisions about the success of the chosen method. Oesophageal and rectal sites are most commonly used for assessing core body temperature [19, 32]; however, ingestible telemetry pill systems that assess intestinal temperature are being increasingly used to overcome the impracticalities associated with these methods [37]. Several studies provide evidence to suggest that telemetry pill systems are valid tools for assessment of core temperature [33, 247–249] however, there are little data regarding the reliability of intestinal temperature measurement during exercise in a hot environment.

Ingestible telemetry pills are often used when environmental temperature is high (≥ 25 °C) to monitor core body temperature or detect treatment effects following the application of an intervention (e.g. cooling). For example, the reported magnitude of intestinal temperature change following a treatment in a hot environment ranges from 0.30 to 1.8 °C [250, 251]. As such, ingestible telemetry pill systems must demonstrate small test re-test error for practitioners to be confident that these changes are true and unlikely due to measurement error. Incorrect interpretation of intestinal temperature due to measurement error or failing to understand the limits of the system could place athletes at an increased risk of heat illness and impair athletic performance. To improve confidence when interpreting a change in a dependent variable it is important to identify the magnitude of measurement error within repeated measurements. Performing such an assessment assists in interpreting whether a change has occurred due to a treatment or because of inherent measurement error (biological or technical).

To date only two studies have published data regarding the inter-day test re-test reliability of intestinal pill telemetry systems. Goosey-Tolfrey et al. [207]conducted a small reliability study (*n* = 5) using ingestible telemetry pills (CorTemp, HQinc, USA) in wheelchair athletes exercising at submaximal intensities (50% peak power output (W_{peak}) for 60 min in a hot environment (30.8 °C, 60.1% RH). The authors reported a mean test-retest error of 0.30 °C (95% CI 0.20 to 0.40) and limits of agreement (LOA 95%) of ± 1.2 °C. In a cooler environment (15.0 °C, 60% RH), Gant et al. [248] investigated the reliability of telemetry pills (CorTemp, HQinc, USA) during intermittent shuttle running and reported excellent reliability with a near absent test-retest error of 0.01 °C (95% CI -0.02 - 0.05 °C) and LOA 95% of ± 0.23 °C.

Given that ingestible telemetry pill systems are increasingly being used to monitor core body temperature responses and that important health, treatment-effect and performance decisions are made upon these assessments, it is important to establish the test-re-test reliability of this method. The purpose of this study was to investigate the inter-day reliability of intestinal core temperature using an ingestible telemetry pill system during exercise within a hot environment.

3.3 Methods

3.3.1 Experimental approach to the problem

Participants were asked to visit the exercise physiology laboratory on three separate occasions. Each visit was separated by a minimum of 3 days and maximum of 10 days. During visit 1, participants performed an incremental exercise test to maximal volitional exhaustion for assessment of peak oxygen uptake ($\dot{V}O_{2peak}$) and associated power output (W_{peak}) at room temperature; (20 °C, 40% RH) followed by a 30-min exercise heat stress accustomisation trial within an environmental chamber (35 °C, 50% RH). During visits 2 and 3, participants rested for 60-min in a temperature-controlled environmental chamber set at 35 °C, 50% RH before cycling at a power output equivalent to 50% W_{peak} for 60-min. The combination of environmental conditions and intensity of exercise was chosen to induce moderate-to-high heat strain within an ethically-acceptable limit of intestinal temperature (39.5 °C). All exercise trials were performed at the same time of day and at least 3 hours after waking and 3 hours before sleep to minimise the circadian rhythm impact on body temperature and gastrointestinal function [252]. All exercise trials were conducted using an externally-verified, electromagnetically-braked arm crank ergometer (Lode Angio, Groningen, The Netherlands) positioned for recumbent cycling.

3.3.2 Participants

Twelve non-heat-acclimated physically-active males (age 25 ± 4 yrs, stature 181.7 ± 7.0 cm, body mass 81.1 ± 10.6 kg) volunteered for the study which was approved by the Ethics Committee of Sheffield Hallam University and conducted according to the principles of the Declaration of Helsinki (7th revision, 2013). The risks and experimental procedures were fully explained and all participants provided written informed consent before the study. Participants were instructed to refrain from strenuous exercise, caffeine and alcohol 24 h before each trial and food 3 h before each trial. Each participant recorded their diet 24 h prior to the first heat stress trial and replicated their diet for the re-test. Adherence to the standardised diet was verified by the investigator prior to each trial. All experimental trials were conducted between the months of October and January in the UK, where mean maximum ambient temperatures ranged from 14 to 7 °C.

3.3.3 Procedures: $\dot{V}O_{2peak}$ test and accustomisation trial

Participants undertook a 10-min warm-up period prior to physiological testing. Peak oxygen uptake ($\dot{V}O_{2peak}$) and associated power output (W_{peak}) were assessed using a continuous incremental exercise test to maximal volitional exertion. The initial intensity of exercise was set at 50 W and was increased by 25 $W \cdot min^{-1}$ in a stepped manner. Pedalling frequency was self-selected in the range of 60-80 $rev \cdot min^{-1}$, and participants were encouraged to continue to maximal volitional exertion. Breath-by-breath pulmonary oxygen uptake was measured continuously using a calibrated low dead space (20 ml) bi-directional differential pressure pneumotach and rapid response galvanic O_2 and non-dispersive infrared CO_2 analysers (Ultima, CardiO_2, Medgraphics, USA). Peak oxygen uptake was calculated as the highest 30-s mean value recorded before termination of the test. The power output at the last completed stage was used to determine W_{peak}. Heart rate was recorded continuously during exercise using short range telemetry (RS400, Polar OY, Finland).

After 60 min of rest in a temperate environment, participants undertook 30 min of recumbent cycling within the environmental chamber (35 °C, 50% RH) at an intensity of 50% W_{peak} to accustomise with the experimental procedures. Nude body mass (kg) was recorded before and after the accustomisation trial along with volume of water ingested *ad libitum* during the trial. Sweat rate ($ml \cdot min^{-1}$) was estimated from the change in body mass adjusted for fluid intake and urine output. Fluid requirements (which matched sweat rate) were calculated for each subject and were closely adhered to in the main experimental trials. During the exercise session heart rate, rating of perceived exertion (RPE) and thermal perception (TP) [253] were assessed every 5 min.

3.3.4 Heat stress trials 1 and 2

These sessions were used to assess the reliability of intestinal temperature measurements. Participants were instructed to replicate their diet 24 hours before each trial and consume 500 ml of non-caffeinated fluid in the preceding 2 hours to promote euhydration [246]. On arrival participant's nude body mass (kg) and urine osmolality ($mOsmol \cdot kg^{-1}$ H_2O) (Advanced Model 3320 Micro-Osmometer, Advanced Instruments, Inc., USA) were assessed. A urine osmolality of $\leq$ 700 $mOsmol \cdot kg^{-1}$ H_2O was used to verify pre and post-trial euhydration status [114]. Participants drank 100 ml of cold water (4 °C) to verify the positioning of the telemetry pill in the gastrointestinal tract.

We observed changes in pill temperature greater than 0.1 °C for two participants; in these instances tests were rescheduled. For all trials there was no change in pill temperature greater than 0.03 °C. After these initial measures, participants rested for 60-min in the environmental chamber, which was set at 35 °C, 50% RH to stabilise intestinal and skin temperature before commencing exercise. At rest and during exercise, participants were encouraged to drink room-temperature water (35 °C) to meet their individual fluid requirements. Measures of heart rate (HR), skin temperature (T_{sk}), intestinal temperature (T_{int}), RPE and thermal perception were recorded immediately prior to exercise (0-min) and at 5-min intervals throughout the exercise trial. The exercise test was terminated when one of the following criteria was met: 1) participants voluntarily stopped exercising, 2) when intestinal core temperature reached 39.5 °C or 3) participants completed 60-min of exercise.

3.3.5 Intestinal temperature

Intestinal temperature was assessed using a telemetric monitoring system consisting of an ingestible temperature sensor and a data logger (CorTemp, HQinc, USA) (figure 31). The sensor comprises a silicone coated outer shell and within it a quartz crystal, communication coils, circuit board and silver oxide battery. When activated the quartz crystal oscillates and creates a magnetic flux, which is communicated via low-frequency telemetry to the data logger. The signal frequency is then converted to a relative temperature by the data logger and displayed on the unit.

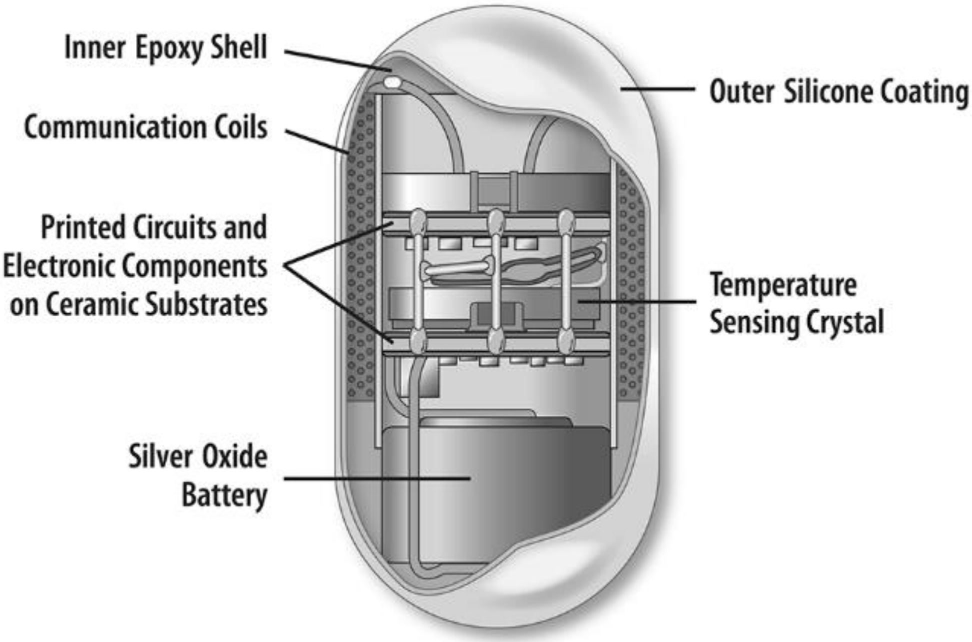

***Figure 31**:* The ingestible telemetry pill

Prior to ingestion the temperature measurement of each pill was verified by immersion in a water bath at 4 temperatures (37, 38, 39 and 40 °C) according to recommended guidelines [254]. Water temperature was verified using a calibrated thermometer. A linear regression relationship between measured (pill temperature) and actual (water bath) temperatures was derived and the resulting regression equation used to convert measured temperature during exercise to actual temperature. The coefficient of determination of this relationship was $r^2 = 0.99$ and the two methods demonstrated excellent agreement LOA 95% (-0.01 ± 0.09 °C). Participants ingested pills at the same time of day, 6 h prior to each visit as recommended [37]. This ingestion time has been reported to be sufficient to allow the telemetry pill to pass into the gastrointestinal tract and produce valid intestinal temperature measurements [247].

3.3.6 Skin temperature

Four skin thermistors (Grant Instruments, Cambridge, UK) were attached to the left side of the body at the medial calf, anterior mid-thigh, anterior mid-forearm and chest using acrylic dressing (Tegaderm, 3M Healthcare, USA) and secured in place using hypoallergenic surgical tape (Transpore, 3M Healthcare, USA). Weighted mean skin temperature ($\bar{T}_{sk}$) was calculated using the equation of Ramanathan [241]. Mean body temperature ($\bar{T}_{body}$) was calculated as $\bar{T}_{body} = 0.66(T_{int}) + 0.34(\bar{T}_{sk})$ at rest and $\bar{T}_{body} = 0.79(T_{int}) + 0.21(\bar{T}_{sk})$ during exercise [255].

3.3.7 Statistical analysis

Reliability of gastrointestinal temperature, which in this study refers to the reproducibility of day-to-day measurements at identical time-points during exercise, was assessed through several statistical analyses following the guidelines of Atkinson and Nevill [44]. Bland-Altman plots [53] were generated to investigate systematic and random error trends. The presence or absence of heteroscedasticity was formally investigated by plotting a regression line through the data points of the Bland-Altman plots. A paired *t*-test was used to assess systematic bias between trials, with statistical significance set at $P \leq 0.05$. Coefficient of variation (CV), standard error of measurement and 95% limits of agreement (LOA) were utilised to assess absolute reliability. Relative reliability was assessed using Pearson's correlation coefficients and Intraclass correlation coefficients (ICC). Cohen's *d* was used as a measure of effect size (ES) and data were evaluated according to small (0.2), medium (0.5) and large (0.8) effects [55]. A paired *t*-test was used to assess between trial differences in environmental conditions, urine osmolality, skin temperature, sweat rate, fluid intake and heart rate. Statistical significance was set at $P \leq 0.05$. Gaussian distribution of data was assessed using Kolmogorov-Smirnov test and was accepted when $P \geq 0.05$.

We acknowledge that practitioners prefer to use different approaches when assessing reliability and that the acceptable levels of error may differ between researchers. Therefore, we have presented a range of reliability statistics and avoided using stringent and pre-defined acceptable levels of error. To provide real-world practical context to reliability data we present hypothetical changes in intestinal temperature (when used in a comparison study is an approach used to determine the effectiveness of a treatment) and used the approach of Hopkins [256] to interpret magnitudes of change. This analysis determined the chance (probability) that a change was harmful, trivial or beneficial in context to the error (reliability) of the test and smallest worthwhile change. It also enabled identification of the minimum change in intestinal temperature that is deemed to be a likely-beneficial change (76% probability), which in the example was a decrease in intestinal temperature.

3.3.8 Research Hypotheses

There will not be statistically significant differences between trials for environmental temperature and relative humidity, urine osmolality, intestinal temperature at the of exercise, sweat rate between trials, changes in body mass between trials and mean intestinal temperature between trials

3.4 Results

Participant's mean $\dot{V}O_{2peak}$ elicited during the incremental exercise test was 36.5 ± 5.2 ml·kg^{-1}·min^{-1} corresponding to a mean peak power of 293 ± 36 W. The mean duration of heat stress trials was 55.4 ± 9.4 min completed at 147 ± 18 W. There were no statistically significant differences for environmental temperature (P = 0.38) and relative humidity (P = 0.74) between trial 1 (35.0 ± 0.2 °C, 49 ± 3% RH) and trial 2 (35.1 ± 0.4 °C, 49 ± 5% RH). Urine osmolality at the start of trial 1 (317 ± 179 mOsmol·kg^{-1}H_2O) was not significantly different (P = 0.95) from the start of trial 2 (313 ± 194 mOsmol·kg^{-1}H_2O). Intestinal temperature at the start of trial 1 was similar to the start of trial 2 (37.26 ± 0.23 °C vs. 37.26 ± 0.25 °C; P = 0.99). However, skin temperature was marginally lower at the start of trial 1 (35.43 ± 0.35 °C vs. 35.70 ± 0.37 °C, P = 0.01). Sweat rate did not differ markedly between trials 1 and 2 (29 ± 5 ml·min^{-1} vs. 28 ± 5 ml·min^{-1}; P = 0.63). *Ad libitum* fluid intake helped restrict body mass deficits in trial 1 to 0.82 ± 0.58% and trial 2 to 0.84 ± 0.52%, which were not significantly different (P = 0.87). Heart rate and skin and body temperatures progressively increased throughout the heat trials reaching peak values at the end of exercise as evidenced in table 5. There was no statistically significant difference in mean heart rate between trial 1 and trial 2 (P = 0.97).

Mean intestinal temperature after 60-min of exercise (table 6) indicates that the intensity and duration of exercise was sufficient to induce moderate-to-high levels of heat stress in both trials. The mean intestinal temperature bias between trial 1 and 2 was -0.07 ± 0.31 °C indicating a small but statistically significant systematic bias (P = 0.02). Visual inspection of figure 32 illustrates that intestinal temperature in trial 1 was consistently higher than trial 2 from 10 min onwards until termination of exercise.

Limits of agreement for intestinal temperature are presented in figure 33. The scattering of data points indicated a degree of both systematic and random error proportional to the measurement range of intestinal temperature. Although the slope of the relationship was close to zero (-0.16) a statistically significant ($P < 0.01$) small correlation coefficient ($r = 0.26$) confirmed the presence of heteroscedasticity.

Reliability data for the entire trial and each 10-min segment of the trial can be found in table 7. Using data from the entire set indicates good overall reliability for all statistical methods. However, when data was grouped by time (table 7) small changes in error were evident over the exercise duration. The error displays a trend that increases from the onset of exercise, before peaking mid-exercise and decreasing towards the end of exercise.

As the Bland-Altman plot suggested the presence of heteroscedasticity, the coefficient of variation (which assumes the largest test-retest error occur at higher values) was used to determine probabilities of a change in intestinal temperature in relation to the smallest worthwhile change [256] (Table 8). This analysis suggests that a change in intestinal temperature as a result of a treatment or intervention (e.g. cooling) of 0.34 °C is required to be interpreted as a likely beneficial change (≥76% chance).

Table 5: *Physiological and perceptual responses during exercise averaged over 10 min (mean* ± SD*)*

Time (min)	% HR_{peak}	RPE	$\bar{T}_{sk}$ (°C)	$\bar{T}_{b}$ (°C)	Thermal perception
10	75 ± 7	13 ± 1	35.85 ± 0.51	36.71 ± 0.47	7 ± 1
20	82 ± 6	14 ± 2	36.06 ± 0.56	36.96 ± 0.53	7 ± 1
30	85 ± 7	15 ± 2	36.19 ± 0.61	37.17 ± 0.62	8 ± 1
40	88 ± 7	16 ± 2	36.21 ± 0.54	37.31 ± 0.68	8 ± 1
50	90 ± 8	17 ± 2	36.29 ± 0.59	37.43 ± 0.73	8 ± 1
60	94 ± 7	17 ± 2	36.36 ± 0.62	37.48 ± 0.78	8 ± 1

%HR_{peak} = percentage of peak heart rate; RPE = Rating of perceived exertion; $\bar{T}_{sk}$ = Weighted mean skin temperature**;** $\bar{T}_{b}$ = Mean body temperature

Table 6: *Mean intestinal temperature (± SD) (°C) data for the entire trial and 10-min blocks of exercise.*

	Intestinal temperature trial 1 (°C)	Intestinal temperature trial 2 (°C)	Mean Difference (Bias ± SD)
Entire	37.93 ± 0.50	38.00 ± 0.58	-0.07 ± 0.31
Time (min)			
10	37.43 ± 0.20	37.40 ± 0.27	0.03 ± 0.20
20	37.69 ± 0.22	37.73 ± 0.32	-0.04 ± 0.35
30	37.97 ± 0.30	38.00 ± 0.32	-0.03 ± 0.40
40	38.15 ± 0.31	38.28 ± 0.32	-0.13 ± 0.35
50	38.41 ± 0.32	38.50 ± 0.35	-0.09 ± 0.30
60	38.56 ± 0.35	38.71 ± 0.44	-0.15 ± 0.24
CI bias			-0.10 to -0.02

CI = 90% confidence interval

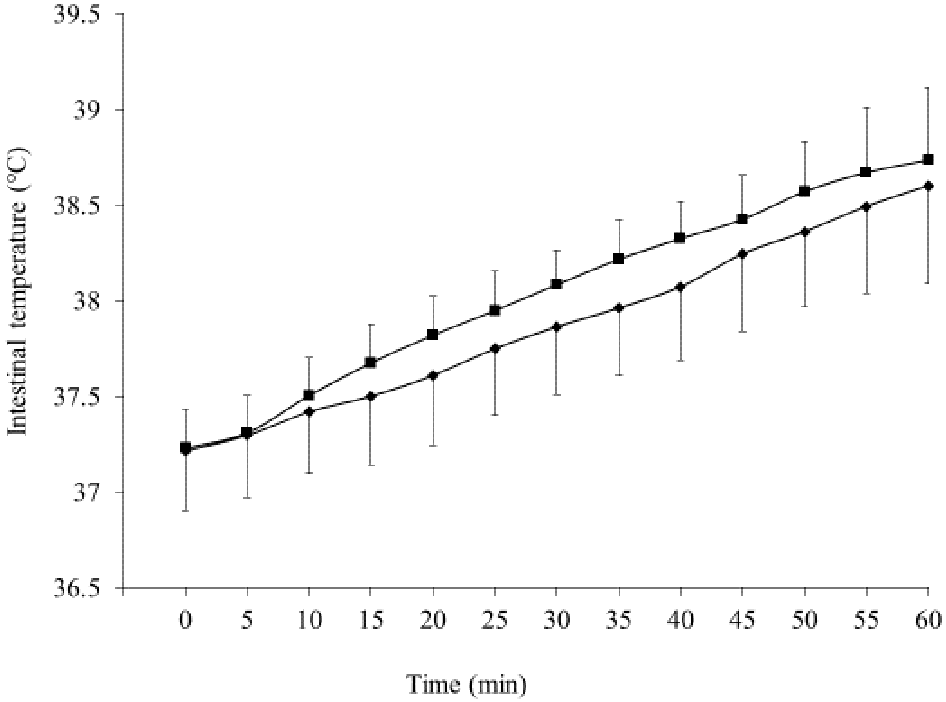

Figure 32: Mean intestinal temperature responses during exercise

Error bars represent standard deviation. Solid black square = trial 1; solid black diamond = trial 2.

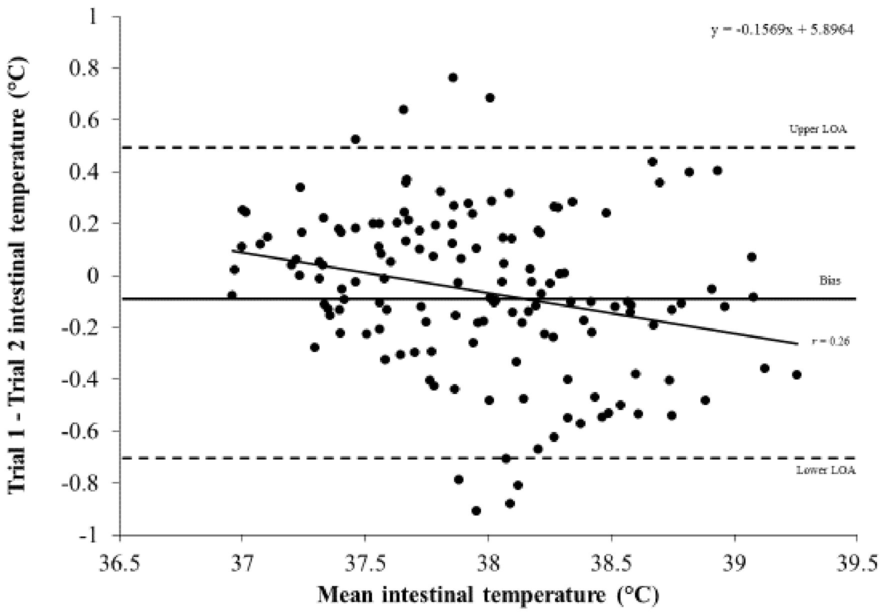

Figure 33: Bland-Altman plot exhibiting variations in intestinal temperature assessment recorded every 5 min during exercise

Solid line represents mean intestinal temperature bias. Dashed lines represent 95% limits of agreement (n = 145).

***Table 7*:** Reliability statistics for entire trial and 10-min blocks of exercise

	95% LOA (±)	CV (%)	SEM (°C)	Cohens *d*	*r*	ICC
Entire	0.61	0.58	0.12	0.12	0.84	0.84
Time (min)						
10	0.39	0.29	0.11	0.19	0.82	0.71
20	0.69	0.64	0.24	0.65	0.46	0.17
30	0.78	0.71	0.28	0.72	0.32	0.18
40	0.68	0.68	0.26	0.81	0.31	0.35
50	0.59	0.57	0.22	0.59	0.67	0.57
60	0.46	0.52	0.18	0.38	0.81	0.80

95% LOA = Limits of agreement; CV = Coefficient of variation; SEM = Standard error of measurement; *r* = Pearson moment correlation coefficient; ICC = intraclass correlation coefficient;

Table 8: Probabilities of hypothetical changes in intestinal temperature

Change in intestinal Temperature (°C)	Probability of decrease (%)	Probability of no change (%)	Probability of increase (%)
-0.1	49	25	26
	Possibly, may not	Unlikely, probably not	Possibly, may not
-0.25	67	19	14
	Possibly, may not	Unlikely, probably not	Unlikely, probably not
-0.5	88	8	4
	Likely, probable	Unlikely, probably not	Very unlikely

Smallest worthwhile change = 0.5% coefficient of variation in intestinal temperature at 38.6 °C = 0.11 °C

3.5 Discussion

The main finding of this study is that the measurement of intestinal temperature using intestinal telemetry pills demonstrated good test-retest reliability during submaximal recumbent cycling exercise in the heat. In accordance with recommendations suggested by [44], we used a range of reliability statistics to assess intestinal temperature. Inspection of Bland-Altman plots identified a small degree of systematic and random error proportional to the measured range of intestinal temperature and suggested the presence of heteroscedasticity. Assessment of intestinal temperature is often used to determine the success of an intervention (e.g. prevent increases in ‘core’ temperature). To provide practical context to the reliability data and investigate whether hypothetical changes in intestinal temperature were likely greater than a smallest worthwhile change we utilised the approach of Hopkins [256]. We identified that the smallest magnitude of change in intestinal temperature required to detect a likely beneficial change (76% chance) to be 0.34 °C. Changes less than 0.34 °C decrease confidence in interpretation and augment the uncertainty of the true effect of an intervention. This information might be useful for scientists interpreting changes in intestinal temperature due to an intervention and should be considered when decisions regarding body temperature need to be made from health, treatment-effect and performance perspectives. For example, a decrease in intestinal temperature of 0.25 °C as a result of an intervention has a 67% chance that it is a beneficial change, 19% chance trivial and 14% chance harmful (table 8). When the decrease in intestinal temperature is 0.5 °C there is an 88%, likely probable chance that this is a beneficial change and a 4%, very unlikely chance it is a harmful change. In this example, a decrease in core temperature may not always be a true decrease when considering the magnitude of change in context to the error of the system and smallest worthwhile change. It should be noted that to improve confidence in interpretation a smaller error (better reliability) would be required.

We observed a systematic error of -0.07 °C and LOA (95%) ± 0.61 °C which is lower than the mean bias of 0.30 °C and LOA (95%) of ± 1.2 °C reported by Goosey-Tolfrey et al. [207] despite a similar intensity of exercise, duration and environmental conditions in both studies. The differences may be explained by a smaller sample size (n = 5) and a large variation in intestinal temperature of one subject in the Goosey-Tolfrey et al. [207] investigation. The mean bias in the present study is greater than that reported by Gant et al. [248] who observed a near absent test-retest systematic error of 0.01 °C and LOA of ± 0.23 °C during intermittent running in a cool environment. Furthermore, the values reported for correlation coefficients, ICC and CV indicate better reliability in the study by Gant et al. [248]. This observation of larger systematic and random errors in intestinal temperature during exercise in hot environments is in agreement with data from Jette et al. [257] who studied the reliability of rectal temperature during exercise in two different conditions in males wearing chemical protective clothing. At 20 °C, no statistically significant difference in mean rectal temperature change between trials was observed (-0.01°C). However, at 40 °C the authors reported a statistically significant mean difference of -0.05 °C which is similar to the mean bias observed within the current investigation.

A potential explanation for the increased variation in intestinal temperature might be gastrointestinal (GI) function. The GI tract is a complex organ and the many potential interactions within it could serve to increase the variability observed in GI pill temperature in heat stressed humans. The recommended pill ingestion time of 6 hours prior to intestinal temperature assessment reflects a balance between sensor gastric emptying and expulsion time [37]. We observed no changes in pill temperature greater than 0.03 °C when participants ingested 100 ml of cold water 1 hour prior to exercise, confirming that the pill ingestion time of 6 hours provided sufficient time for gastric emptying. However, 2 tests out of 24 were rescheduled due to a change in observed pill temperature of greater than 0.1 °C. Wilkinson et al. [39] demonstrated that drinking cold water (5 - 8 °C) influenced pill temperature by up to 2 °C 8 hours after pill ingestion. The authors suggested that this temperature variation may be due to the pill residing in areas of the GI tract in close proximity to the stomach (e.g. duodenum and transverse colon). To reduce the potential for pill temperature fluctuations in the present study, participants ingested room temperature water (35 °C) at frequent intervals throughout the trial and as a result we observed no large variations in intestinal temperature.

In a further attempt to standardise GI function the subjects refrained from food three hours prior to each test and their diet was replicated in the preceding 24 hours. However, exercise speeds intestinal peristaltic velocity [258] and it is conceivable that peristaltic velocity might have been different between trials. Subsequently, this variation could have changed the position of the pill within the GI tract. Indeed, we observed an increase in temperature variability mid-exercise. As eluded to by Gant et al. [248], this mid-exercise variability may have been caused by peristalsis advancing the pill along the GI tract before reaching more compact faecal matter towards the end of exercise, thereby reducing temperature variability.

Several human studies provide indirect evidence to support the notion of a temperature gradient along the GI tract as GI pill temperature is consistently higher than rectal temperature [5]. Further evidence is available from animal studies which demonstrate a temperature gradient along with GI tract as duodenum and ilium temperatures were significantly higher than stomach, large intestine and rectum [259]. As a result, one possible explanation for the observed variation in intestinal temperature is that variability in intestinal peristaltic velocity advances the pill to areas of the GI tract which may exhibit different temperatures. This interpretation suggests that although a pill ingestion time of 6 hours prior to exercise is sufficient for gastric emptying, perhaps a longer period is required to limit the effects of peristaltic velocity.

Numerous studies have presented data indicating that each pill has a bias from certified thermometry; as such it is recommended that each pill is individually calibrated. Following recommendations [254], we noted excellent agreement (-0.01 ± 0.09 °C) between a verified electronic thermometer and intestinal pills. This agreement was similar to that reported within previous studies [39, 254, 260] and within the guidelines that suggest random errors between thermometers should not be greater than ± 0.1 °C [19]. To reduce potential systematic and random bias we applied a linear regression equation to each pill determined following verification. Therefore, it is unlikely that the variation in intestinal temperature during exercise was due to invalid temperature measurement by the pills. Furthermore, the variation in intestinal temperature was not likely caused by a difference in total work between the two trials as there was no statistically significant difference between trials for mean HR (P = 0.97).

Our findings are only applicable to pill ingestion times of 6 hours. It is likely that different ingestion times will change pill location in the GI tract and influence reliability of the method. Although skin temperature, thermal perception and RPE were high, mean end-exercise intestinal temperature was ≈38.60 ± 0.4 °C, which is around 1-1.5 °C lower than reported voluntary exercise termination core temperature. As such our results should be applied with caution to temperatures exceeding 39 °C; however, during self-paced exercise, which is common in most sports, intestinal temperature may be regulated around 39 °C [261]. We also applied pill-specific regression equations to account for bias, and as such our findings might only be applicable after corrections have been employed. We recommend following the verification guidelines of Hunt and Stewart [254] prior to dispensing telemetry pills for ingestion as conducted in the present study. Recumbent cycling was chosen as the mode of exercise as laser-Doppler flowmetry, which requires a stable upper body, was used to assess forearm skin blood flow (data not presented). Generalisations to other modes of exercise should be applied with caution; however, it is likely that our results are applicable to other modes of exercise that produce similar energetic and thermoregulatory demands.

3.5.1 Practical Applications

We have assessed the reliability of intestinal temperature sensors using a range of statistical approaches and practitioners are encouraged to interpret these results using their preferred method. Using hypothetical data we have demonstrated that practitioners can be confident that observed changes in intestinal temperature greater than 0.34 °C as a result of an intervention in hot environment are likely beneficial and less influenced by error associated with the method. This interpretation is important from a safety perspective for monitoring athletes within hot environments, when determining the effect of a treatment on intestinal temperature responses, and when making performance-based decisions. For example, understanding the reliability of a method and obtaining reliable temperature measurements are important for prescription of appropriate training intensities in hot environments, especially at high intensities where body temperature can rise to induce considerable strain on cardiovascular, metabolic and thermoregulatory systems and place athletes at risk of heat illness. Heat tolerance tests are often used to determine whether athletes can regulate body temperature in hot environments or require acclimation/acclimatisation prior to competition. Reliable body temperature measurements are needed to ensure that athletes who are heat intolerant are not considered tolerant and vice versa as incorrect decisions because of measurement error can place athletes at risk of heat illness and waste vital training and adaptation time as well as financial resources. In instances where athletes require acclimation, intestinal temperature is often used to determine the effectiveness of the intervention. It is important that practitioners can be confident that changes in body temperature are the result of an adaptation to heat and not due to measurement error. Similarly where cooling methods are required to lower core temperature prior to, during or after exercise, scientists require reliable measurements of core temperature to elucidate the most appropriate method and monitor the health of athletes. We have demonstrated that intestinal temperature measurement assessed using an ingestible telemetry pill system is capable of providing scientists with reliable temperature measurements so that health, treatment-effect and performance decisions can be made with confidence when accounting for the error within the method.

Chapter 4: Effect of hand cooling on body temperature, cardiovascular and perceptual responses during recumbent cycling in a hot environment

4.1 Abstract

The purpose of this study was to quantify physiological and perceptual responses to hand immersion in water during recumbent cycling in a hot environment. Seven physically-active males (body mass 79.8 ± 6.3 kg; stature 182 ± 5 cm; age 23 ± 3 years) immersed their hands in 8, 14 and 34 °C water whilst cycling at an intensity (W) equivalent to 50% peak aerobic capacity ($\dot{V}O_{2peak}$) for 60 min in an environmental chamber (35 °C 50% relative humidity). 8 and 14 °C water attenuated an increase in body temperature and lowered cardiorespiratory and skin blood flow demands. These effects were considered to be practically beneficial (standardised effect size > 0.20). There was a tendency for 8 and 14 °C to extend exercise duration versus 34 °C (> 7%). Heart rate, intestinal, mean skin and mean body temperature were less in 8 °C compared to 14 °C; these differences were considered practically beneficial. Augmented heat loss at the palm-water surface might enable cooler blood to return to the body and limit physiological strain. These findings provide a mechanistic basis for continuous hand cooling and indicate that endurance exercise in hot environments could be improved using this method. Future research should investigate its effectiveness during cycling and running performance.

4.2 Introduction

During fixed-intensity and self-paced exercise athletes benefit from artificial heat transfer through protocols that cool the body. These protocols are grouped into pre and-per cooling. Pre-exercise cooling includes cold water immersion [153], iced towels [262], ice vests [263] and ice slurry ingestion [264]. A reduction in body temperature prior to exercise is thought to increase heat storage capacity, core-to-skin gradient and reduce thermal perception enabling exercise at a higher intensity, or for longer before reaching a regulatory limit for performance and body temperature [265]. Neck [167], head [187], torso [169] and palm cooling [13, 14] have been used as per-cooling techniques. These might be applied continuously throughout exercise or at intervals between bouts to attenuate a rise in body temperature, reduce body temperature between bouts and lower perception of heat strain. In a meta-analysis on cooling methods [6] the majority of per-cooling studies were shown to improve exercise performance with similar beneficial effects compared to pre-cooling ($d = 0.76$; $d = 0.73$ respectively). These findings were supported by Bongers et al. [7] who found pre-cooling and per-cooling also had similar beneficial effects on exercise performance ($d = 0.44$; $d = 0.40$, respectively).

Hand or palm cooling has been used as a per-cooling method to attenuate a rise in body temperature [266], extend low-intensity cycling, stepping and walking exercise capacity [13, 213–215, 218], improve short-term high intensity wheelchair ergometer (1 km) and cycling performance (3 km) [207] and improve endurance cycling performance (30 km) [14] in environmental temperatures greater than 30 °C.

The hands have a large surface to mass ratio [10] and low metabolic heat production that suit high rates of conductive heat transfer. Additionally, the glabrous skin of the palms contain dense proportions of arteriovenous anastomoses and retia venosa [11, 12] enabling blood flow. A large volume of blood flow through the palm is conducive to heat transfer between warm arterial blood, the palmar surface and cooler contacting media such that heat is conducted and cooler blood returns to the body through venous networks. In most hand or palm cooling studies the treatment has been applied between bouts of exercise [207, 209, 213, 214, 220, 267] or after exercise [218, 266] in hot environments. However, Hsu et al. [14] demonstrated that continuous hand cooling alleviated an increase in tympanic temperature during 60-min of fixed intensity cycling exercise at 60% $\dot{V}O_{2peak}$ in 32 °C 25% relative humidity (1.2 ± 0.2 °C; 1.8 ± 0.2 °C with and without hand cooling respectively). Similarly, Grahn et al. [13] reported that hand cooling attenuated a rise in oesophageal temperature during walking at 5.7 km·hour^{-1} in 40 °C 25% relative humidity (2.1 ± 0.4 °C; 2.8 ± 0.5 °C (with and without hand cooling respectively). However, only a single-palm was used and the results are only applicable to the vacuum assisted heat extraction device used (RTX CoreControl, AVAcore Inc., CA, USA) which is impractical to use during competition. Moreover, Amorim et al. [219] did not report any benefit of the vacuum assisted heat extraction device whilst walking at 6.7 km·hour^{-1} 4% gradient, in 42 ± 1 °C, 30 ± 5% relative humidity whilst wearing military uniform and body armour. However, this study is limited by several methodological issues. A practical approach to hand cooling was addressed by Scheadler et al. [208] who secured a gel pack to the non-dominant hand during a running time-trial to exhaustion task at 75% $\dot{V}O_{2peak}$. The rate of change in intestinal temperature was similar between control and gel pack trials and participants ran for longer in the control trial than the gel pack trial (46.7 ± 32.1 min; 41.3 ± 26.3

min respectively). However, the authors only applied the gel to a single palm and did not report its temperature or palm skin temperature, raising doubts as to whether sufficient palm cooling occurred. Furthermore, given the large standard deviation in time to exhaustion it is difficult to make confident interpretations regarding the effectiveness of continuous application of a gel pack during exercise from this study. Given that the physical properties of the hands are conducive to heat exchange and previous research has identified the potential effectiveness of continuous hand cooling during exercise, alternative methods should be investigated. Indeed, the ergogenic mechanisms, optimal cooling temperature and whole body physiological and perceptual responses when cooling both hands continuously during exercise are unclear. Therefore, the aim of this study was to provide a mechanistic basis for the development of practical hand cooling techniques by assessing body temperature, cardiovascular and perceptual responses to continuous hand immersion in water during exercise in a hot environment.

4.3 Methods

4.3.1 Pilot work

The choice of exercise mode for the first two studies was important because it needed to enable hand cooling, limit extraneous movement to ensure measurement signal quality (e.g. laser-Doppler flowmetry (LDF) for assessment of skin blood flow) and be tolerable for the participants.

Initial pilot testing centred on the exercise mode of upright cycling. It was believed that assessments should replicate actual performance as closely as possible and therefore upright cycling adopting a ‘tucked’ time trial position was considered the most appropriate position. However, after pilot trials it was apparent that this position was uncomfortable, induced lateral torso movement (which could potentially interfere with signal quality of LDF) and it was difficult to cool the hands.

Table 9: Relationship between intensity of exercise and time to exhaustion during recumbent cycling in 35 °C, 50% relative humidity from a sample of 3 physically active male's representative of sampling population

Relative exercise intensity (% power at $\dot{V}O_{2peak}$)	Exercise time limit (min)
70	30 – 40
60	40 – 50
50	50 - 60

An alternative mode of exercise was recumbent cycling which offered good stability of the forearm when supported, limited lateral movement from the upper body and offered a practical way to cool the hands during exercise (using water buckets).

The negative of recumbent cycling was that the potential for intensity of exercise/ mechanical work done, and therefore liberation of metabolic heat would be lower than upright cycling and thus induce less heat strain. In pilot testing it was found that there was a trade-off between intensity of exercise and tolerable duration (table 9); such that an increase in intensity of 10% from 50% power at $\dot{V}O2_{peak}$ would decrease duration of exercise by 10 to 15 min. Although not investigated, it is postulated that a 10% increase in intensity accelerated locomotor muscle fatigue which contributed to the local discomfort of the lower back, gluteal muscles and quadriceps thereby causing voluntary exercise termination. This 'pain' was likely a contributor to overall RPE and a key contributor in determining exercise time limit. Despite these inferences from the small sample in pilot work there appears to be no research that has reported differences in RPE between upright, recumbent or supine cycling exercise, there are however, a small number of studies that have investigated physiological responses.

Upright cycling is characterised as a traditional cycling position, supine cycling is typically associated with a horizontal body position (laying down on the back) and recumbent cycling at angles between the two. Fully horizontal, compared to upright cycling is associated with a slower rate of oxygen kinetics, higher blood lactate concentrations and impaired exercise capacity [268]. Hydrostatic pressure is practically absent during supine cycling which reduces arterial pressure and arterio-venous pressure gradient compared to upright cycling which might impact the delivery and perfusion of oxygen at the muscle level and is one possible mechanism for the impairment in oxygen uptake kinetics.

In a recumbent position (30 to 65 degs), perfusion pressure is less than an upright but greater than a supine position and might presumably decrease exercise capability due to the aforementioned impairments [268]. Egana et al. [268], however, report that neither 30 or 65 °C recumbent position impairs exercise capability despite a decrease in perfusion pressure. In a time to exhaustion trial at a mean external intensity of 202 ± 26 W. The mean exercise duration for upright was however greater than the recumbent cycling positions, however there was a large variation in time to exhaustion and more data would improve the uncertainty in these capacity tests (which have large associated error). Nevertheless, the authors report that none of the physiological assessments of oxygen uptake or associated kinetic variables were different between the 3 conditions. There was, however, an increase in stroke volume and concomitant cardiac output in both recumbent conditions compared to upright cycling. The authors suggest that these cardiovascular adjustments offset the decrease in perfusion pressure imposed in the recumbent position.

Moreover, there appears to be an increase in motor unit recruitment as assessed through normalised electromyography (NEMG) as cycling position transitions from upright to fully supine [269] possibly attributed to an increase in motor unit recruitment or/and rate coding due to fatigue imposed by supine cycling. However, the authors express concern with their EMG data as some fatigue indices were not significantly correlated with NEMG and there were other non-significant interactions when the data was associated with physiological maximum EMG.

This data suggests that from a physiological perspective recumbent cycling is not physiologically different from upright cycling. Thus, from pilot work it was decided that using an intensity of 50% would enable most participants to cycle for 60-min. This duration has been suggested to be the maximum time limit that pre-cooling procedures can have an effect on physiology and performance [263].

Rational heat stress equations [84] were useful to determine the combination of intensity, duration and ambient temperature that would produce moderate to high level of heat strain within ethically acceptable limits. Assuming a body mass of 75 kg, body surface area of 1.93 m^2 , gross cycling 'efficiency' (exercising in hot conditions) of 20% [270], mean intensity of exercise 150 W, metabolic heat production of 750 W, air temperature of 35 °C, relative humidity of 50%, mean skin temperature of 36.5 °C and a clothing factor of 0.92 (light t-shirt and shorts) [84]; it was estimated that the rate of rise in body core temperature would be 1.9 °C over 60-min and within the ethical safety limit of 39.5 °C (37.2 + 1.9 = 39.1).

A full experimental trial was performed as a pilot test prior to any data collection using ingestible telemetry pills (which are costly). This section details interesting findings from this pilot trial.

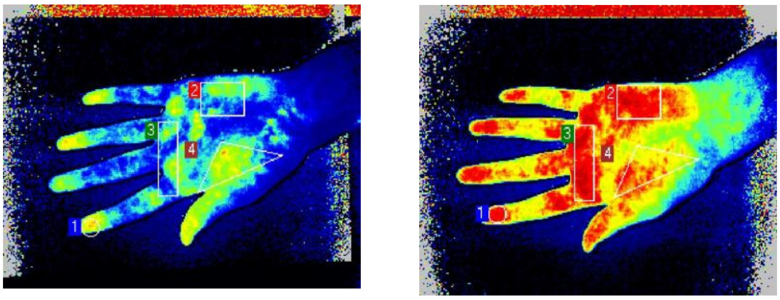

Figure 34: Laser-speckle contrast image of blood flow before (upper) and after (below) exercise. Blue = regions of low blood flow; Red = regions of high blood flow.

Figure 34 depicts blood flow to different areas of the hand after 15 min of exercise at an RPE of 13 (150 W) from a single participant. The increase in blood flow to the hands can be observed after short duration moderate intensity exercise.

Figure 35 depicts tympanic temperature over time across the three conditions. Evident from figure 35 is that hand cooling appears to attenuate a rise in tympanic temperature across the exercise trial. Interestingly the initial rise in tympanic temperature is similar between conditions. After 15 min of exercise the rate of rise in tympanic temperature is around 0.4 - 0.5 °C in all three conditions. Thereafter, tympanic temperature in the 34 °C condition continues to increase progressively throughout the trial, in the 14 °C condition the rise tympanic temperature is attenuated and a cooling effect is observed in the 8 °C condition. The similar rise in tympanic temperature during the first 15 min of exercise may be related to the combined effects of water temperature and exercise-induced vasoconstriction [75, 203]. In the environmental conditions (35 °C, 50% RH) the potential for dry heat loss (radiative and convective) is low; evaporative heat loss is slow to respond and vasoconstriction at the fingertip means that hand cooling is redundant too. That is, until either the rate of increase in body temperature or body temperature itself reaches a threshold for vasodilation [271] which causes an autonomic sympathetic withdrawal at the fingertip thus increase in blood flow – enabling hand cooling. In the hand cooling conditions tympanic temperature plateaus after around 15 min at the same time that fingertip CVC also starts to plateau (figure 36).

Forearm skin blood flow (figure 37) demonstrates similar initial responses as the fingertip blood flow. A slow response or slight reduction in blood flow is followed by a rapid increase. The onset of this increase in blood flow occurs at an earlier time point at the forearm, this difference may be because the forearm was not cooled locally, unlike the hand whereby local cooling plus exercise caused a decrease in blood flow. Unlike fingertip blood flow, forearm skin blood flow is lower in the 8 °C condition compared to the 14 and 34 °C conditions. A simple explanation for this finding is that as tympanic temperature is lower, the demand for skin blood flow to aid cooling is less. This explanation is supported by a lower forearm skin temperature in the 8 °C condition.

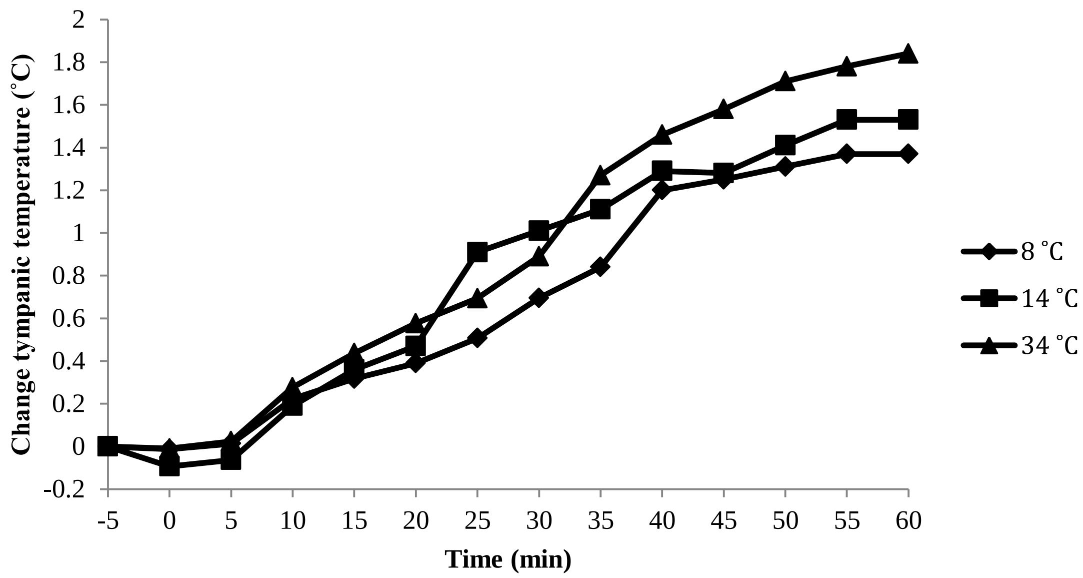

Figure 35: Tympanic temperature in response to hand immersion in three different water temperatures

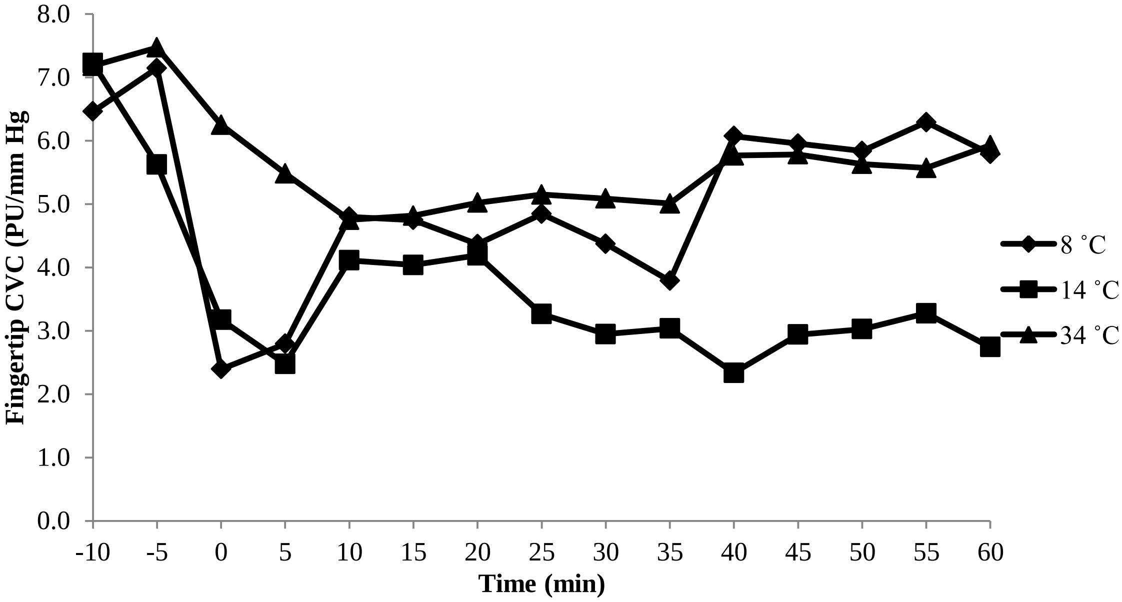

Figure 36: Cutaneous vascular conductance of the fingertip in response to hand immersion in three different water temperatures

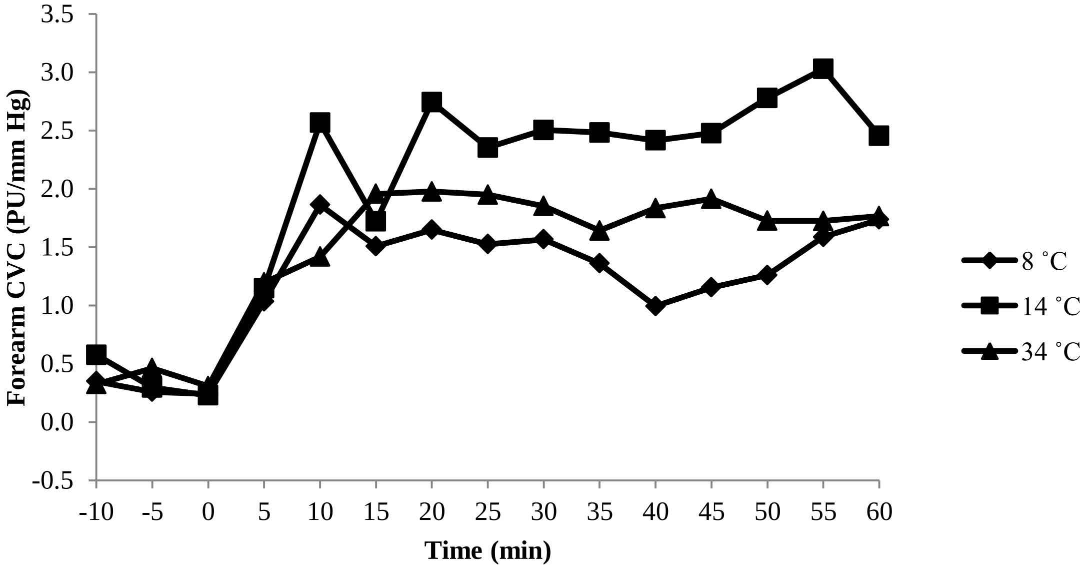

Figure 37: Cutaneous vascular conductance of the forearm in response to hand immersion in three different water temperatures

Table 10: Magnitude-based interpretations of changes in tympanic temperature from pilot study

Condition	End exercise T_{temp} (˚C)		Condition	90 % CI	Probability of change (%)	Description
34 ˚C	38.3	Vs	14 ˚C	-1.01 to 0.22 ˚C	78	Likely probable
14 ˚C	37.9	Vs	8 ˚C	-1.10 to 0.11	86	Likely probable
8 ˚C	37.4	Vs	34 ˚C	-1.50 to -0.29	98	Very likely

T_{temp} = tympanic temperature; 90% CI = 90% confidence interval

It is possible to interpret these initial findings using a magnitude based statistical approach, which combines reliability data and changes observed in the pilot trial (table 10). When compared to the control trial of 34 °C, it is 'likely/probable' that tympanic temperature at the end of the 14 °C condition was lower and that 8 °C was 'very likely lower'. The 90% confidence intervals support these assertions.

There was no 'probably not' any difference between 34 °C and 14°C conditions for the plateau in forearm skin blood flow. However, the 8 °C condition elicited 'likely probable' differences in forearm skin blood flow (table 11). The lower skin blood flow in the 8 ˚C condition is mirrored by a lower mean skin temperature (figure 38) from 10 min onwards and coincides with an increase in fingertip CVC which suggests that as blood passes through the hand it is cooled and re-circulated around the body. The lower demand for skin blood flow also reduces cardiovascular strain as observed by lower heart rates in both the cooling trials (figure 39).

Table 11: Magnitude-based interpretations of changes in CVC from pilot study

Condition	Forearm CVC (APU/mmHg)		Condition	90 % CI	Probability of change (%)	Description
34 ˚C	2.12	Vs	14 ˚C	-0.94 to 1.48	40	Probably not
14 ˚C	2.17	Vs	8 ˚C	-1.25 to 0.46	81	Likely, probable
8 ˚C	1.50	Vs	34 ˚C	-1.30 to 0.40	83	Likely, probable

CVC = cutaneous vascular conductance; 90% CI = 90% confidence interval

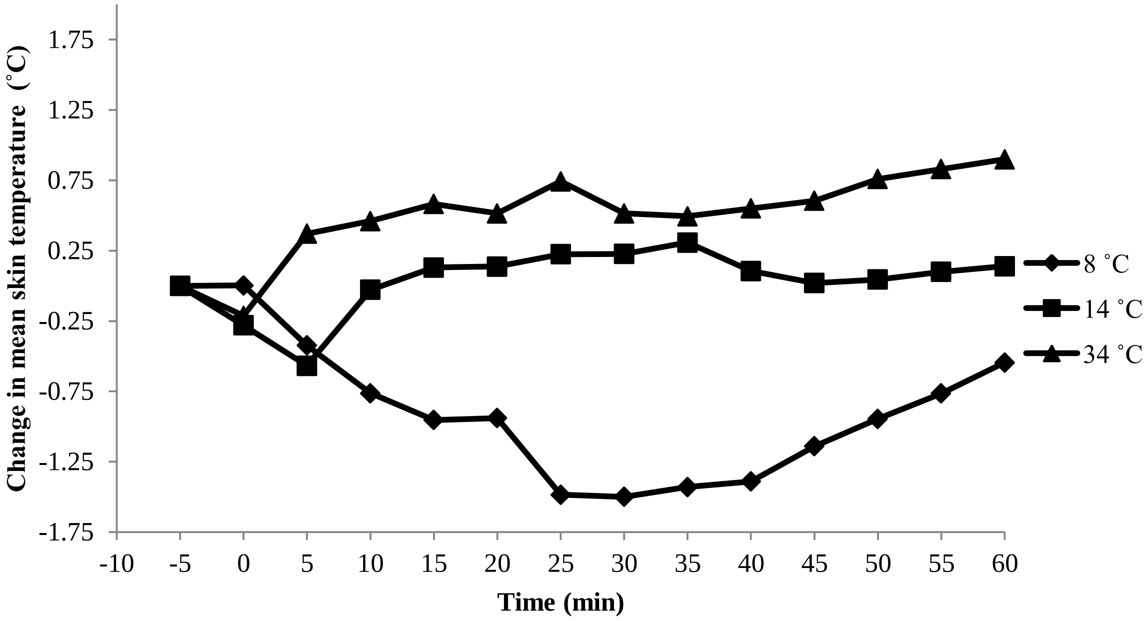

Figure 38: Changes in mean skin temperature (˚C) in response to exercise and hand immersion in three different water temperatures

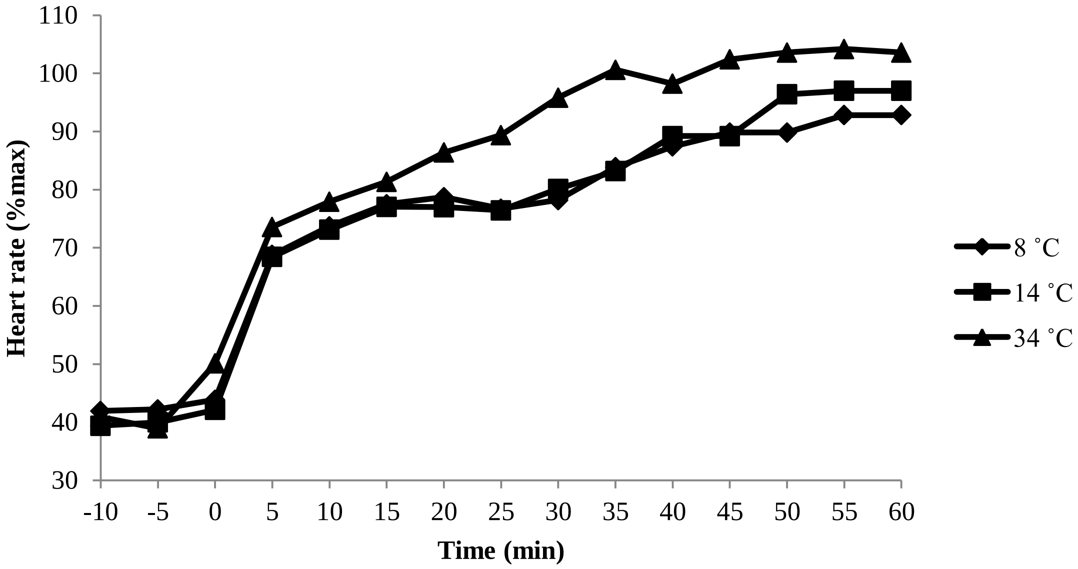

Figure 39: Heart rate responses to hand immersion in three different water temperatures

4.3.2 Participants

A priori sample size calculation based upon finding a 0.20 °C intestinal temperature difference between experimental and control conditions at the end of exercise, a standard deviation of 0.40 °C, $\beta = 0.20$ and $\alpha = 0.05$ suggested a sample size of 6 participants would be adequate. This data was based on findings from a previous study [14]. Nine non-heat-acclimated physically active males volunteered for the study that was approved by the local ethics committee and conducted according to the principles of the Declaration of Helsinki. All experimental trials were conducted between the months of August and October where mean ambient temperatures ranged 12 - 22°C. Seven participants (age 24 ± 3 years; body mass 78.3 ± 7.2 kg; stature 180 ± 7 cm) completed all trials; drop-outs were due to illness and one participant being unable to tolerate hand immersion in cold water. All participants provided written informed consent before the study. Participants were told that they were required to place their hands in three different water temperatures whilst exercising but were not told the temperatures or the true purpose of the study. Participants were asked to refrain from strenuous exercise, caffeine and alcohol 24 h before each trial and food 3 h before each trial. Each participant recorded their diet 24 h prior to the first trial and replicated their diet for the remaining trials. Adherence to the standardised diet was verified by the investigator before each trial.

Participants visited the laboratory 4 times, each visit separated by 3 days to 7 days. Trials were performed at least 3 hours after waking and 3 hours before sleep to minimise the circadian rhythm impact on body temperature and gastrointestinal function [252]. Exercise trials were conducted on an externally-validated, electromagnetically-braked ergometer (Lode Angio, Groningen, The Netherlands) positioned for recumbent cyling.

4.3.3 Visit 1: Pre-experimental trial testing and accustomisation

In a temperature controlled laboratory (18 °C 60% relative humidity) a continuous 25 $W{\cdot}min^{-1}$ incremental exercise test to maximal volitional exhaustion was used to determine peak oxygen uptake ($\dot{V}O_{2peak}$) (Ultima, CardiO$_2$, Medgraphics, USA) and peak minute power (W_{peak}). Heart rate was recorded continuously during exercise (RS400, Polar OY, Finland).

After 60 min of rest in a temperate environment, nude body mass (kg) was recorded using beam balance scales (Weylux, UK) before the accustomisation trial. Participants performed 30 min of recumbent cycling within the environmental chamber (28.5 °C Wet bulb globe temperature [35 °C, 50% relative humidity]) at an intensity of 50% W_{peak} to accustomise to the experimental procedures. During the exercise session heart rate, rating of perceived exertion (RPE) [272] and thermal perception (9 point scale) [253] were assessed every 5 min. Whole body sweat rate ($L{\cdot}hour^{-1}$) was estimated from the change in body mass adjusted for fluid intake and urine output.

4.3.4 Experimental trials

An ingestible temperature pill was used to assess intestinal core temperature (CorTemp, HQinc, USA). The validity of temperature measurement of each pill was verified according to recommended guidelines [254]. Participants ingested the pill at the same time of day, 6 h prior to each visit [37], a procedure demonstrated to provide reliable responses under similar conditions [243].

On arrival, participants voided and nude body mass (kg) and urine osmolality (mOsmol·kg^{-1} H_2O) (Advanced Model 3320 Micro-Osmometer, Advanced Instruments, Inc., USA) were assessed. A urine osmolality of ≤700 mOsmol·kg^{-1} H_2O was used to verify pre-and post-trial euhydration status [114]. Participants rested for 60 min in the environmental chamber set at 28.5°C WBGT. Participants wore the same clothing (shorts, socks and running shoes) for all trials. Air currents from the environmental chamber fans were ≈0.5 m·s^{-1}, no cooling fans were used.

Thirty minutes before the start of exercise, participants were fitted with a chest strap for the measurement of heart rate, and skin thermistors (Grant Instruments, Cambridge, UK) were attached to the left side of the body at the medial calf, anterior mid-thigh, anterior mid-forearm, chest and index finger using acrylic dressing (Tegaderm, 3M Healthcare, USA), secured in place using hypoallergenic surgical tape (Transpore, 3M Healthcare, USA). A 7-point integrating laser Doppler flowmeter probe (Probe 413, Perimed AB) was positioned on the volar aspect of the upper left forearm and on the left middle fingertip within a housing disc surrounding the probe (Model 455, Perimed AB) for measurement of arbitrary perfusion units (APU). The position of the site was standardised for each participant. Blood pressure (mmHg) was assessed using auscultation and an aneroid sphygmomanometer.

APU (mean of last 60 s for each 5 min period), rating of perceived exertion and whole body, right hand and left hand thermal perception were recorded at -10, -5 min and immediately before exercise (0 min) and then at 5-min intervals throughout the exercise trial. Expired air was assessed breath-by-breath every 15 min for 3 min. Participants were asked to cycle for 60 min within the environmental chamber (28.5 °C Wet bulb globe temperature [35 °C, 50% relative humidity]) at an intensity of 50% $W_{peak.}$ This intensity and duration was chosen to balance muscular fatigue, due to recumbent cycling, with an ethically acceptable magnitude of heat strain. The exercise test was terminated when one of the following criteria was met: 1) participants voluntarily stopped exercising, 2) when intestinal core temperature reached 39.5 °C or 3) participants completed 60 min of exercise.

Ten minutes before exercise (-10 min) participants immersed their hands up to the ulna head in buckets filled with water controlled at 8, 14 or 34 ± 2 °C. Hands remained immersed in water until the exercise trial was complete. These temperatures were chosen because of the similarity to previous hand cooling research.

4.3.5 Calculations

Weighted mean skin temperature (T_{sk}) was calculated using the equation of Ramanathan [241]. Mean body temperature ($\bar{T}_{body}$) was calculated using the equation of Colin et al. [255]. Mean arterial pressure (MAP) was calculated as using the equation of Razminia et al. [273]. Raw cutaneous vascular conductance (CVC), an index of skin blood flow was calculated as: CVC = APU ÷ MAP.

4.3.6 Statistical analysis

Normal distribution was assessed using Kolmogorov-Smirnov test and homogeneity of variance using Levene's test in IBM SPSS statistics version 20 (IBM Armonk, NY, USA). Data were assessed for meaningful between-trial differences using a magnitude-based approach [57]. The analysis was performed using a statistical spreadsheet [61] that calculates trial means, standard deviations, standardised effect sizes (Cohen's *d*) using the pooled standard deviation and confidence intervals. Cohen's *d* was assessed according to accepted thresholds; $\leq$ 0.2 (trivial), > 0.2 - 0.59 (small), 0.60 - 1.19 (moderate), 1.20 - 1.99 (large), > 2.0 - 3.99 (very large) and > 4.0 (extremely large) [57]. 90% confidence intervals were calculated for *d*. The probability (% chance) that the between-trial differences were less than, similar to or greater than the smallest worthwhile difference (calculated as 0.2 × between-trial pooled standard deviation) was assessed using a statistical spreadsheet [61]. When data violated assumptions of normality the Wilcoxon Signed Rank Test was used to assess between-group differences. Statistical significance was set at $P < 0.05$.

4.3.7 Reliability of physiological assessments

Reliability data for measurements in the study are presented in table 9. Data were collected from 12 non-heat-acclimated physically-active males (age 25 ± 4 yrs, stature 181.7 ± 7.0 cm, body mass 81.1 ± 10.6 kg) who took part in study 1. The same methodological procedures, equipment and environmental conditions were used to assess thermophysiological variables. Data were paired at identical time-points and assessed as a whole group. The data collected for all variables with the exception of forearm and fingertip CVC were considered small enough to make confident interpretations of subsequently collected data. Whereas, data collected for CVC should be interpreted with caution, especially when observed differences between conditions are small.

Table 12: Reliability data for measurements used in the investigation

Variable	Mean 1	Mean 2	± 95% LOA	CV (%)	TEM	Error free change	Minimum, likely probable change
Intestinal temperature (˚C)	37.93	38.00	0.61	0.58	0.22	0.32	0.34
Tympanic temperature (˚C)	37.54	37.55	0.67	0.64	0.24	0.35	0.37
Mean skin temperature (˚C)	36.00	36.13	0.75	0.79	0.29	0.41	0.44
Mean body temperature (˚C)	37.51	37.58	0.57	0.56	0.21	0.31	0.33
Fingertip CVC (APU/mmHg)	3.65	4.04	1.72	21.46	0.67	0.95	1.45
Forearm CVC (APU/mmHg)	1.54	1.90	0.74	19.70	0.36	0.52	0.66
Heart rate (bpm)	143	142	10	2.61	4	6	7
RPE	15	15	2	4.62	1	1	2
Thermal perception	7.7	7.62	1.07	5.08	0.36	0.52	0.62

All data presented in absolute units except CV. LOA = limits of agreement; CV = coefficient of variation (root mean square method; TEM = technical error of measurement [58].

4.3.8 Research hypotheses

There will not be a statistically significant difference for mean RPE, thermal perception, fingertip temperature or fingertip CVC between trials.

4.6 Results

4.6.1 Pre-trial measures

Mean $\dot{V}O_{2peak}$ for the recumbent cycling incremental exercise test was 41 ± 5 mL·kg^{-1}·min^{-1}. Wet bulb globe temperature was similar between 8 (28.6 ± 0.4 °C) and 34 °C (28.5 ± 0.2 °C) trials; *d* = 0.16 [0.07 to 0.25], there was a moderate difference between 8 and 14 °C (28.3 ± 0.2 °C); *d* = 0.70 [0.42 to 0.97] and a moderate difference between 14 and 34 °C trials; *d* = 0.72 [0.16 to 1.29]. Pre-trial urine osmolality was 257 ± 255; 291 ± 225; 387 ± 259 mOsmol·kg^{-1} H_2O for 8, 14 and 34 °C trials respectively and within the limit for euhydration.

4.6.2 Initial physiological responses to hand immersion

Hand immersion at rest had no influence on physiological variables (table 13). Whole body rating of thermal perception was lower after hand immersion (-5 min), irrespective of water temperature, compared to -10 min (difference in thermal perception -0.4 units; *d* = 0.52 [0.00 to 1.04]). Rating of right and left hand thermal perception was lower than whole body thermal perception when immersed in water at all temperatures (difference in thermal perception -3.6 units; *d* = 1.48 [1.06 to 1.98] and corresponded to the qualitative descriptor “cool”.

Table 13: Initial physiological responses to hand immersion.

Data presented as mean ± standard deviation and 90% confidence intervals

Time (min)		**VCOLD (8 °C)**	**COLD (14 °C)**	**NEUT (34 °C)**
-10	T_{int} (°C) ± SD	37.44 ± 0.33	37.29 ± 0.38	37.29 ± 0.21
	(90% CI)	(37.20 to 37.69)	(37.01 to 37.57)	(37.13 to 37.44)
-5		-0.02 ± 0.03	0.00 ± 0.10	0.00 ± 0.02
	ΔT_{int} (°C) ± SD	(-0.05 to 0.00)	(-0.06 to 0.07)	(-0.02 to 0.02)
0	(90% CI)	-0.02 ± 0.08	-0.02 ± 0.08	0.05 ± 0.13
		(-0.08 to -0.02)	(-0.08 to 0.05)	(-0.05 to 0.15)

Time (min)		VCOLD (8 °C)	COLD (14 °C)	NEUT (34 °C)
-10	T_{sk} (°C) ± SD	35.31 ± 0.52	35.33 ± 0.50	35.42 ± 0.50
	(90% CI)	(34.92 to 35.70)	(34.96 to 35.7)	(35.05 to 35.78)
-5		-0.01 ± 0.05	0.01 ± 0.39	0.00 ± 0.03
	ΔT_{sk} (°C) ± SD	(-0.05 to 0.02)	(-0.07 to 0.08)	(-0.03 to 0.02)
0	(90% CI)	-0.03 ± 0.04	-0.05 ± 0.05	0.01 ± 0.05
		(-0.10 to 0.04)	(-0.14 to 0.05)	(-0.03 to 0.05)
-10		42 ± 4	42 ± 6	45 ± 9
		(39 to 44)	(37 to 46)	(38 to 51)
-5	Heart rate (% HR_{max}) ± SD	41 ± 3	43 ± 8	44 ± 8
	(90% CI)	(39 to 43)	(37 to 49)	(39 to 50)
0		42 ± 3	44 ± 7	43 ± 6
		(35 to 48)	(38 to 49)	(40 to 47)

4.6.3 Exercise duration and cardiorespiratory responses

Mean intensity of exercise was 148 ± 17 W and the duration was 50:48 ± 16:18 min, 51:30 ± 15:00 min and 47:24 ± 14:24 min for 8, 14 and 34 °C conditions. Exercise duration in 14 °C was 1.3% longer than 8 °C and 8.7% longer than 34 °C. Exercise duration in 8 °C was 7.3% longer than 34 °C. However, there were no statistically significant differences between conditions. Five participants completed 60 min of exercise in 8 and 14 °C and 3 participants completed 60 min of exercise in 34 °C. Exercise trials were self-terminated by participants due to volitional exhaustion. None of participants reached ethical limit of intestinal temperature and there were no instances of heat illness. Percentage of peak heart rate (figure 40A) was likely (94%) lower in 8 °C versus 34 °C from 25 min onwards (87 ± 4% and 90 ± 5% respectively); d = 0.69 [0.18 to 1.20]. Percentage of peak heart rate during 8 °C was also likely (77%) lower than 14 °C (89 ± 10%) from 25 min onwards; d = 0.28 [0.10 to 0.46]. Peak percentage heart rate in 14 °C and 34 °C were similar (68%) from 25 min onwards; d = 0.13 [-0.09 to 0.36]. Mean $\dot{V}O_2$ during 8 °C was possibly (62%) less than 34 °C (27.1 ± 3.1 $ml \cdot kg^{-1} \cdot min^{-1}$ and 28.0 ± 1.9 $ml \cdot kg^{-1} \cdot min^{-1}$ respectively); d = 0.37 [-0.55 to 1.28]. Mean $\dot{V}O_2$ during 8 °C (27.5 ± 3.7 $ml \cdot kg^{-1} \cdot min^{-1}$) was possibly (50%) less than 34 °C; d = 0.18 [-2.62 to 2.99] and possibly similar (49%) to 8 °C; d = 0.12 [-0.33 to 0.58].

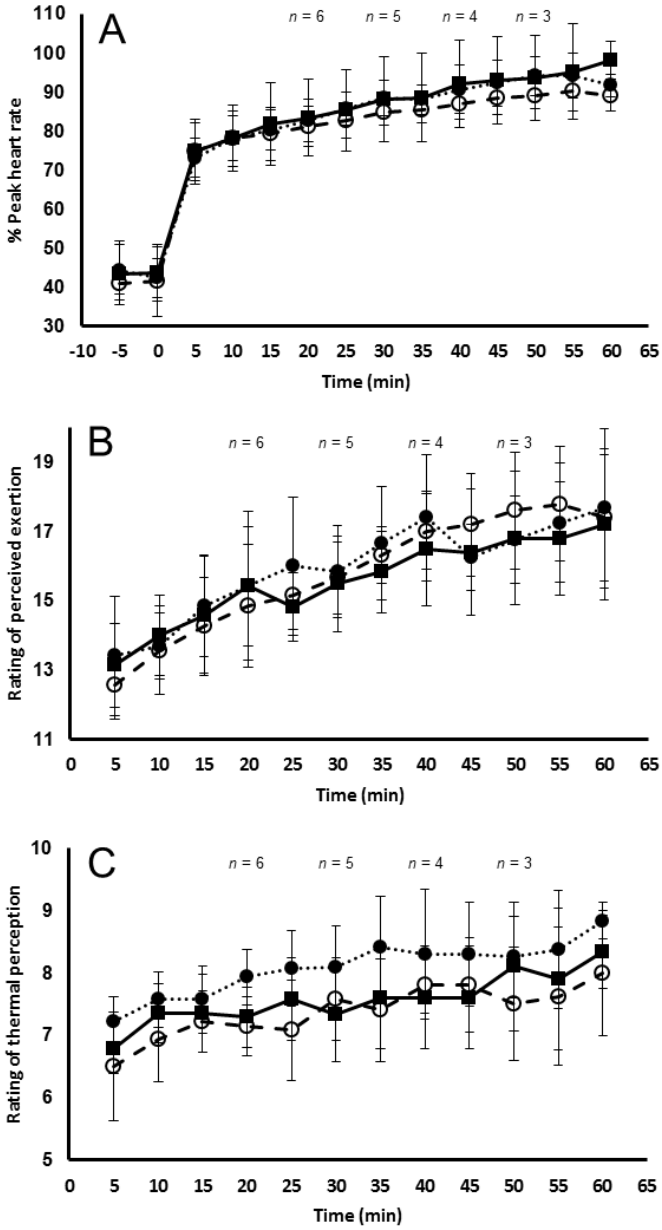

Figure 40: Cardiovascular and perceptual responses

A = heart rate response; B = rating of perceived exertion; C = rating of thermal perception. Data reported as mean ± SD. Open circles = 8°C. Squares = 14°C. Closed circles = 34°C. *n* = participant number.

4.6.4 Perceived exertion and thermal perception

Figure 40B shows RPE responses during exercise. There were no statistically significant differences ($P > 0.05$) in mean RPE between 8 °C and 14 °C (15.3 ± 2.0 and 15.2 ± 1.7 respectively) and 8 °C and 34 °C (15.6 ± 1.9). However, mean RPE for 14 °C was significantly less ($P < 0.05$) than 34 °C. Figure 40C shows responses for thermal perception during exercise. Mean thermal perception for 8 °C was statistically ($P < 0.05$) less than 14 °C (7.3 ± 0.8, 7.5 ± 0.8 respectively) and 34 °C (8.0 ± 0.7). Mean thermal perception for 14 °C was statistically less than 34 °C. Mean qualitative descriptors for 8, 14 and 34 °C corresponded to "warm", "warm-hot" and "hot".

4.6.5 Intestinal temperature

Figure 41A shows intestinal temperature responses during exercise. Intestinal temperature was similar between trials for the first 15 min of exercise but increases were attenuated by hand cooling. From 15 min onwards until the end of exercise the change was likely (77%) less in 8 °C compared to 14 °C (0.74 ± 0.29 °C and 0.83 ± 0.31 respectively); $d = 0.35$ [-0.01 to 0.69]. There was a very likely (99%) difference for change in intestinal temperature between 8 °C and 34 °C (1.00 ± 0.38 °C) from 15 min onwards until the end of exercise; $d = 0.84$ [0.42 to 1.25] and a likely (85%) difference between 14 °C and 34 °C over the same time period; $d = 0.55$ [-0.01 to 1.11]. Figure 42 shows these changes from 0 min until the end of exercise for each participant.

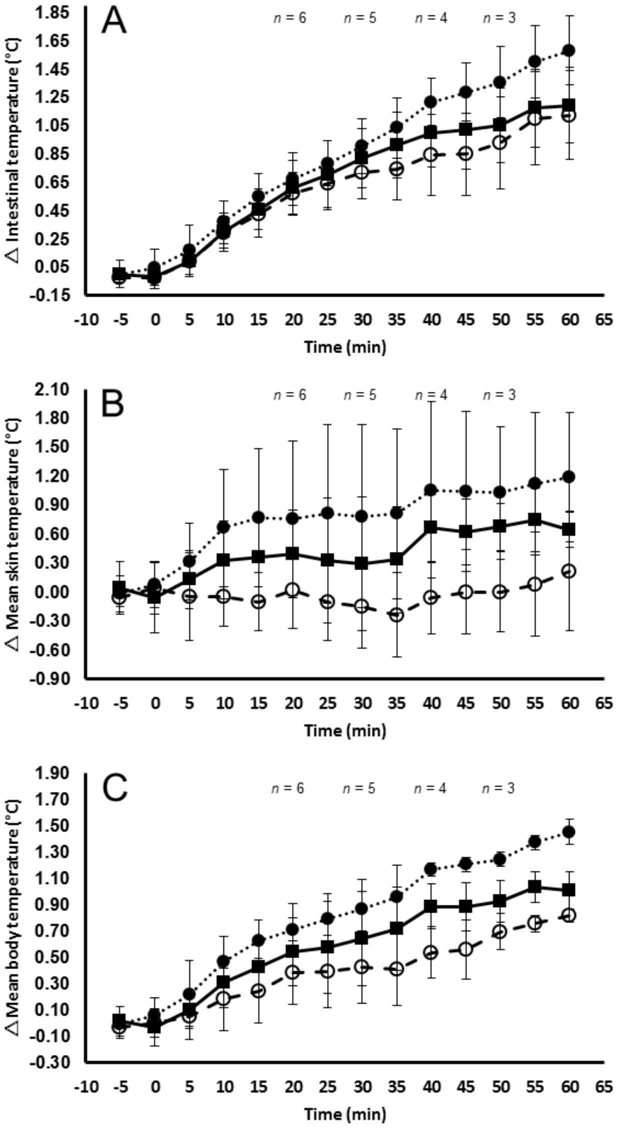

Figure 41: Body temperature responses

A = change in intestinal temperature; B = change in mean skin temperature; C = change in mean body temperature. Data reported as mean ± SD. Open circles = 8 °C. Squares = 14 °C. Closed circles = 34 °C.

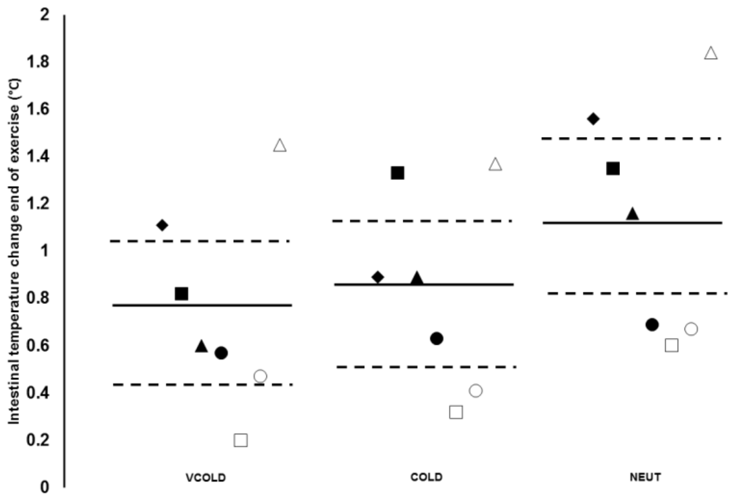

Figure 42: Individual data plot of change in intestinal temperature from baseline until the end of exercise

Solid black lines = mean. Dashed lines = 90% confidence interval of mean. VCOLD = 8 °C; COLD = 14 °C; NEUT = 34 °C.

4.6.6 Mean skin temperature

Change in mean skin temperature (Figure 41B) was less after 5 min and onwards to cessation of exercise in 8 °C compared to 34 °C (-0.09 ± 0.72 °C and 0.77 ± 0.30 °C respectively); *d* = 1.24 [0.45 to 2.03]. Change in mean skin temperature for 8 °C was also very likely (98%) less throughout exercise compared to 14 °C; *d* = 1.09 [0.43 to 1.76]. Change in mean skin temperature was likely (94%) less in 14 °C versus 34 °C throughout exercise; *d* = 0.63 [0.17 to 1.10].

4.6.7 Mean body temperature

Change in mean body temperature (figure 41C) at the end of exercise was likely (82%) less in 8 °C compared to 14 °C (0.47 ± 0.33°C and 0.71 ± 0.35°C respectively); *d* = 0.69 [-0.24 to 1.61] and very likely (99%) less than 34 °C (1.09 ± 0.38°C); *d* = 1.32 [0.60 to 2.04]. Change in mean body temperature at the end of exercise was likely (93%) less in 14 °C compared to 34 °C; *d* = 0.95 [0.09 to 1.81].

4.6.8 Fingertip temperature

During water immersion fingertip temperature (Figure 43A) was statistically ($P < 0.05$) less in 8 °C than 14 °C (15.20 ± 3.46 and 18.50 ± 3.30 respectively) and 34 °C (34.93 ± 0.93). 14°C was also statistically ($P < 0.05$) less than 34 °C.

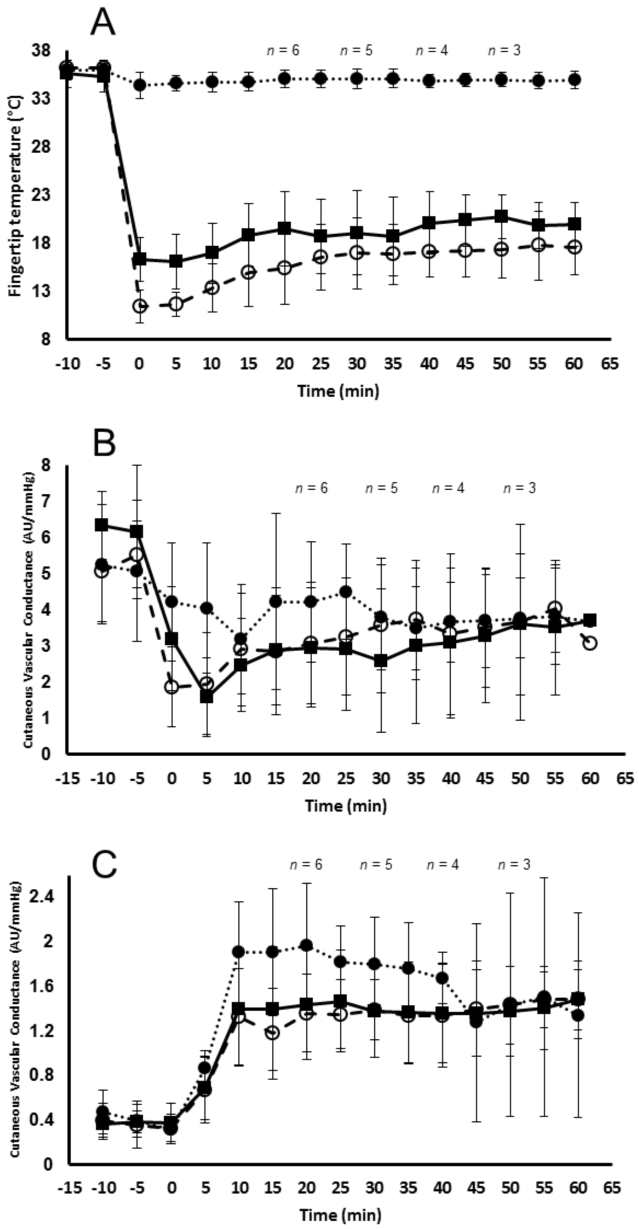

Figure 43: Fingertip temperature and blood flow responses

A = Fingertip temperature; B = Fingertip cutaneous vascular conductance; C = Forearm cutaneous vascular conductance. Data reported as mean ± SD. Open circles = 8 °C. Squares = 14 °C. Closed circles = 34 °C.

4.6.9 Skin blood flow

Figures 43B and 43C show skin blood flow responses during exercise. Mean fingertip CVC was significantly ($P < 0.05$) less in 14 °C than 8 °C (2.9 ± 1.6 and 3.2 ± 1.7 respectively) and 34 °C (3.9 ± 1.4). 8 °C was significantly (P <0.05) less than 34 °C for mean fingertip CVC during exercise. Mean forearm CVC was very likely (99%) less in 8 °C compared to 34 °C (1.30 ± 0.39 and 1.75 ± 0.47 respectively); d = 0.68 [0.51 to 0.86]. Mean forearm CVC was also very likely less (99%) in 14 °C (1.34 ± 0.44) compared 34 °C; d = 0.69 [0.48 to 0.91]. Mean forearm CVC was similar (86%) for 8 °C and 14 °C; d = 0.12 [0.00 to 0.23].

4.6.10 Sweat rate

Post-exercise body mass loss was 1.3 ± 1.2% in 8 °C, 0.5 ± 0.8% in 14 °C and 0.9 ± 0.9% in 34 °C. Sweat rate was similar (45%) between 8 °C and 34 °C (0.97 ± 0.21 $L \cdot hour^{-1}$ and 0.94 ± $L \cdot hour^{-1}$ respectively); d = 0.13 [-1.13 to 0.86]. Sweat rate was likely (94%) lower in 14 °C (0.69 ± 0.29 $L \cdot hour^{-1}$) compared to 8 °C; d = 0.69 [-0.12 to 1.84] and likely lower (88%) compared to 34 °C; d = 0.81 [0.09 to 1.71].

4.7 Discussion

The aim of this study was to assess the body temperature, cardiovascular and perceptual responses to hand cooling during exercise. In general, hand cooling attenuated an increase in body temperature, limited heat storage and lowered cardiorespiratory and skin blood flow demands. These effects were considered to be practically beneficial. There was a tendency for participants to exercise longer with hand cooling, however magnitude-based statistical analysis could not be performed as the data was not normally distributed and differences between groups were not statistically significant.

Previous research has demonstrated that hand immersion in cold water can reduce body temperature between bouts of exercise [207, 213, 214, 218, 267] and single-palm cooling using a heat extraction device applied continuously during exercise can extend exercise duration and improve cycling performance [13, 14].

Heat transfer from warm circulating blood is the likely mechanism responsible for these findings. For effective heat transfer there needs to be a balance between thermal gradient (hand cooling) and blood flow (limited vasoconstriction). In the present investigation fingertip temperature was greater than water temperature for 8 and 14 °C trials providing evidence of a thermal gradient. Fingertip temperature was also lower than mean skin temperature, providing evidence that the hands were cooled during the exercise trials. However, cooler temperatures might have limited fingertip blood flow and restricted heat transfer as cutaneous vascular conductance was lower in 8°C and 14 °C than during 34 °C trials.

At the onset of water immersion vasoconstriction occurred at the fingertip but not at the forearm (Figure 43B and 43C). This is likely because of an increase in local sympathetic noradrenergic vasoconstrictor activity in response to cold stress [274]. Fingertip skin blood flow remained similar in 34 °C before and after hand immersion but was lower at the onset of exercise. This probably occurred because of increased sympathetic vasoconstrictor activity at the onset of exercise [101, 102]. After 10 min of exercise fingertip skin blood flow began to increase in all conditions, probably because of vasoconstrictor withdrawal as autonomic heat loss mechanisms were activated [275]. Thereafter, dilation of arteriovenous anastomoses, dense microvascular networks and poor insulative properties of the hand [10–12] allowed heat from the blood to be conducted to the water down a thermal gradient. Thus cooler blood returned to the central circulation and presumably less body heat was stored. Therefore, the rate at which intestinal temperature increased during exercise was attenuated in 8 and 14 °C (Figure 41A). This was likely because of; 1) cooler blood returning directly from the hands; and 2) relatively cooler blood returning from the active muscles.

Mean skin temperature increase was also attenuated in 8 °C and 14 °C trials (Figure 41B). Whether this resulted from cooler blood returning to the central circulation through venous structures close to the skin, cold conductance from the hand to forearm, lower-temperature arterial blood circulated to the skin or less skin blood flow is unclear. However, forearm cutaneous vascular conductance was less in 8 °C and 14 °C compared to 34 °C suggesting there was less demand for skin blood flow to aid thermoregulation. This was evident up to 40 min, thereafter CVC in the control trial decreased and was similar to 8 °C and 14 °C. This likely occurred due to a combination of participant attrition and poor test-retest reliability. Less demand for skin blood flow also attenuated the demands on the cardiovascular system as evidenced by lower heart rates from 25 min onwards in the 8 °C condition compared to 14 °C and 34 °C.

Sweat rate was less in 14 °C than 8 °C and 34 °C but similar between 8 °C and 34 °C. The reason for the difference in sweat rate between 14 °C and 8 °C is unclear. However, the similarity between 8 °C and 34 °C sweat rate suggests that evaporative cooling was not impaired by hand cooling at this temperature. These results indicate that heat transfer via the hands was responsible for limiting body heat storage rather than evaporative cooling mechanisms.

However, despite associations between RPE and cardiovascular demand [272], there were no statistically significant differences in mean RPE (Figure 40B) between trials. This might have been a consequence of the difficulty of the exercise trials where perceived exertion reached near maximal ratings towards the end. However, whole body thermal perception scores were statistically less during the cooling trials with 8 °C statistically less than 14 °C.

Hsu et al. [14] used a cooling device (RTX CoreControl, AVAcore Inc., CA, USA) that circulated 22 °C water over one palm during fixed intensity (60% $\dot{V}O_{2peak}$) cycling in a hot environment (32 °C 25% RH). Similar to the present investigation core temperature change from baseline, measured at the tympanic membrane was less with palm cooling compared to no cooling (1.2 ± 0.2 °C; 1.8 ± 0.2 °C with and without hand cooling respectively). Using the same device during exercise in 40 °C 25% RH, Grahn et al. [13] reported an improved exercise tolerance (57.0 ± 6.4 min; 34.1 ± 3.0 min with and without hand cooling respectively) and attenuated rise in oesophageal temperature when compared to no cooling (2.1 ± 0.4°C; 2.8 ± 0.5°C with and without hand cooling respectively). The authors attributed these benefits to the vacuum induced negative pressure because hand cooling alone had little benefit over no cooling, however, the temperature of the water was 22 °C and much warmer than the 8 and 14 °C used in the present study. Even so, hand cooling prolonged exercise time compared to 34 °C by approximately 4 min, similar to Grahn et al. [13] even without negative pressure. However, the application of negative pressure at cooler temperatures might compromise heat transfer. Amorim et al. [219] used the same negative pressure cooling device during walking at 6.7 km·hour^{-1} 4% gradient, in 42 ± 1 °C, 30 ± 5% relative humidity whilst wearing military uniform and body armour. The authors reported 'negative' results for water temperatures of 15 °C (n = 3) and 18 °C (n = 3) yet assessed a further 4 participants at 22 °C and grouped all the data as a single condition. This approach is misleading since each of these temperatures would have led to differing magnitudes of fingertip vasoconstriction, heat transfer and physiological responses, however these responses were not assessed or reported nor were the magnitudes of any of the basic physiological, thermoregulatory or perceptual responses. Unsurprisingly the authors reported no statistically significant effects of hand cooling and concluded that palm cooling did not reduce heat strain during exercise in hot environments. This conclusion was also reached by Scheadler et al. [208] who reported that participants performed better in the control trial versus the palm cooling trial. However, it is unclear as to whether palm cooling actually occurred since neither Amorim et al. [219] or Scheadler et al. [208] reported fingertip or palm temperature or the magnitude of vasoconstriction so the mechanisms responsible for these findings are unclear. Unlike previous studies, we are confident that hand cooling occurred because fingertip temperature was less than mean skin temperature. We also aware that hand cooling caused vasoconstriction which was alluded to, but not investigated by previous research. However, despite this vasoconstriction, which was not maximal; and because we cooled the whole hand and not just the palm, it is likely that cooler blood returned to the central circulation resulting in our observed beneficial effects.

4.7.1 Practical implications

In the present study hand cooling tended to increase exercise duration and lessened the perception of heat strain. These effects were the result of an attenuated rise in body temperature. Heat strain is the principle cause of physiological strain and subsequent termination of exercise in fixed intensity trials in hot environments [108, 118, 128]. Therefore, it is important that athletic, military and occupational populations have practical methods available to reduce physiological strain in hot environments. However, unlike pre-cooling the majority of per-cooling methods have little influence on body temperature and performance improvements might be attributed to a lower perception of heat strain. This has practical implications because a mismatch between thermal perception and heat strain might impair pacing during self-paced trials and as exercise continues accelerate hyperthermia-mediated fatigue. In the present investigation both thermal perception and body temperature were less during hand cooling, alleviating concerns expressed by Tyler et al. [167] relating to a potentially detrimental mismatch.

4.7.2 Limitations

Our method provides a theoretical basis for future studies, however at present there are limitations to the practical application of the study. We used water buckets to cool the hands, a method that would be difficult to use outside the laboratory. Recumbent cycling was chosen because it enabled the hands to be cooled whilst minimising upper body movements that might have caused artefacts in laser-Doppler recordings limited the intensity of exercise and potential for heat strain. Mean body temperature at the end-of-exercise for 34 °C trial was around 38.5 °C and could be considered as moderate heat strain. Therefore, our results might not be applicable to exercise that induces greater heat strain. Finally, we were unable to report the amount of heat transferred by hand immersion because we maintained water temperature throughout the trial.

4.8 Conclusion

In this study we demonstrated that hand cooling during exercise had several practically beneficial effects. These included an attenuated rise in body temperature, reduced cardiorespiratory demands and improved thermal perception. These effects were observed because heat was transferred from the hands to the water allowing cooler blood to be circulated back to the body. Although the method we used in the present study has several logistical constraints it provides a mechanistic basis for the development of practical hand cooling methods during exercise in hot environments that might benefit athletic, military, occupational and athletic populations.

Chapter 5: Effects of cooling gloves on thermoregulatory, cardiovascular and perceptual responses during exercise in a hot environment

5.1 Abstract

Hand cooling improves body temperature; cardiovascular and perceptual responses to exercise in hot environments but the strategies used are impractical for use during continuous exercise. The aim of this study was to investigate the effects of prototype cooling gloves worn during exercise in a hot environment on body temperature and cardiovascular responses, thermal perceptions, rating of perceived exertion and endurance capacity. In a randomised cross-over design, seven trained cyclists (age = 30 ± 7 years; body mass 73.5 ± 8.5 kg; stature = 183 ± 7 cm; $\dot{V}O_{2peak}$ = 58.1 ± 7.1 $ml \cdot kg^{-1} \cdot min^{-1}$), exercised at a mechanical power equivalent to the first ventilatory threshold (219 ± 48 W) in 35 °C, 50% relative humidity wearing cooling gloves (13 °C) (experimental trial) and without (control trial). Indices of intestinal temperature, skin temperature, heart rate, oxygen uptake, perceived exertion, thermal sensation, thermal comfort and exercise duration were analysed using magnitude-based inferences and conventional significance testing. Cooling gloves decreased indices of intestinal (d = -0.33 to -0.81) and skin (d = -0.47 to -0.67) temperature and heart rate (d = -0.64). Beneficial effects were observed for oxygen uptake (d = -0.36) and sweat rate (d = -0.41). Mean rating of perceived exertion (13.6 ± 2.4 versus 14.5 ± 2.0), thermal sensation (5.9 ± 1.0 versus 6.5 ± 0.7) and thermal comfort (2.3 ± 0.8 versus 2.9 ± 0.6) were all statistically significantly ($P < 0.05$) less wearing cooling gloves. Exercise duration was extended (d = 0.41) wearing the hand cooling gloves. These findings have beneficial practical implications for exercise capability and performance in hot environments. Future research should improve the ergonomics of the cooling glove and

investigate the impact of the cooling gloves on exercise performance in hot environments.

5.2 Introduction

Human endurance capability is impaired in hot and humid environments [4]. Compared to temperate conditions, exercise duration is usually less when participants are asked to perform at fixed intensity [115], and intensity of exercise is typically less when participants are given a choice to modify behaviour [136]. The key determinants of exercise capability during fixed-intensity exercise are primarily autonomic (cardiovascular, circulatory and sudomotor responses) [69]. Whereas during self-paced challenges behavioural modifications driven by thermal perception and rating of perceived exertion (RPE) influence external intensity and performance outcomes [149, 276]. Strategies including heat acclimation [277], pre-cooling [6, 7] and cooling during exercise [8] have been trialled to improve exercise capability in the heat. The mechanistic actions of these strategies are context dependent, but confer benefits towards skin and core temperature, cardiovascular and sudomotor function, as well as thermal perception and RPE.

Cooling during exercise in hot environments has been studied less than pre-cooling and heat acclimation. Cooling strategies during exercise include cooling of the neck [166–168], head [187], torso [169], and palms [13, 14], as well as ice slurry ingestion [155, 233, 234] and cold fluid ingestion [278]. These interventions appear to benefit thermal perception and rating of perceived exertion which feedforward into improvements in self-paced exercise performance and exercise capacity in the heat [8]. However, few have demonstrated beneficial effects on cardiovascular, sudomotor or body temperature responses. Perhaps this is because the enthalpy of the cooling strategy is insufficient to have a meaningful effect, or the site of application has limited blood flow which constrains conductive and convective heat transfer thus the effectiveness of the cooling method.

The hands are a favourable site for cooling because of their anatomical structure [10, 229]. They have a high surface area to mass ratio that suits heat dissipation and are supported by networks of arteriovenous anastomoses and retia venosa (blood vessels) [11, 12] that enable a large volume of blood to flow near the palmar surface. The benefits of hand or palm cooling have been reported during continuous exercise, intermittent exercise and post exercise [13, 14, 207, 213, 214, 218, 266, 267]. However, some studies have reported unclear effects on exercise capacity and performance [208, 219, 279].

We have demonstrated that hand immersion in cold water during exercise extends exercise capacity by 7 to 8% and attenuates a rise in deep body temperature [280] while improving thermal perception. However, despite the efficacy of this strategy continuous hand immersion is impractical for competition or training. Utilising the effectiveness of cooling the hands with a practical approach is likely to be advantageous for health and performance. Therefore, the primary aim of this study was to investigate the effects of prototype cooling gloves on core (intestinal) temperature responses during exercise in a hot environment in well-trained male cyclists. Secondary aims were to assess cardiorespiratory demands, perceptual responses and exercise duration as a result of hand cooling.

5.3 Methods

5.3.1 Pilot work

Based on the results of study 2 a proto-type cooling glove was made. The glove was developed in various phases and eventually took the form of a flexible plastic and filled with liquid phase change material (PCM). The initial concept was designed to be manufactured to change phase at either 8 or 14 °C after being cooled (charged) based on study 3. PCM's change from solid to liquid only when it has absorbed its latent heat capacity, enabling a PCM to maintain its set-temperature for a much greater time than for example, water, which changes phase at 0 °C and thus has a lower latent heat capacity. Figure 44 shows the temperature changes of a phase change material set at 15 °C compared to a conventional gel based ice pack when exposed to an ambient temperature of 35 °C. Evident from figure 44 is that the PCM maintains a stable temperature for much longer than a gel pack, even in hot environments. It should be recognised that this data has been obtained from mainly radiative heat gain mechanisms, it is anticipated that the rate of heat storage from conduction (skin to PCM) will be much higher and therefore the effect of cooling shorter.

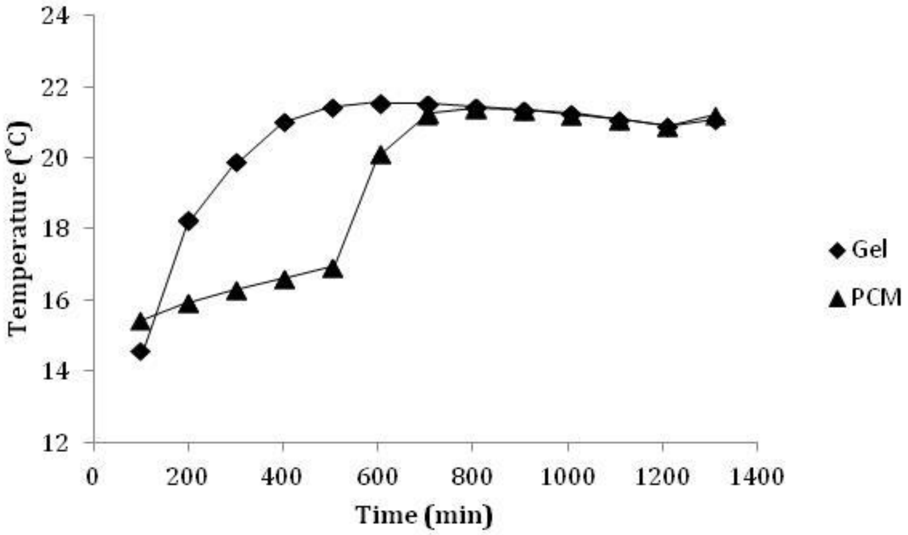

Figure 44: Temperature response of a gel ice pack vs PCM in an ambient temperature of 35 ˚C.

Figures 45 and 46 document the initial versions of the proto type cooling glove. The glove was made from two sealed pockets filled with, water, initially as the glove developed. The plastic was sealed with a heat press around all edges and when the liquid was introduced into each pouch. Water was used until the final prototype design, whereby phase change material was used. Figure 47 depicts the final structure of the gloves. Rectangular pockets were used to ensure there was some flex within the glove and to ensure the phase change liquid was evenly distributed around each pouch.

Figure 45: Initial prototyping of cooling gloves

***F**igure 46:* 2nd phase of prototyping including the glove used in the main trials (bottom images)

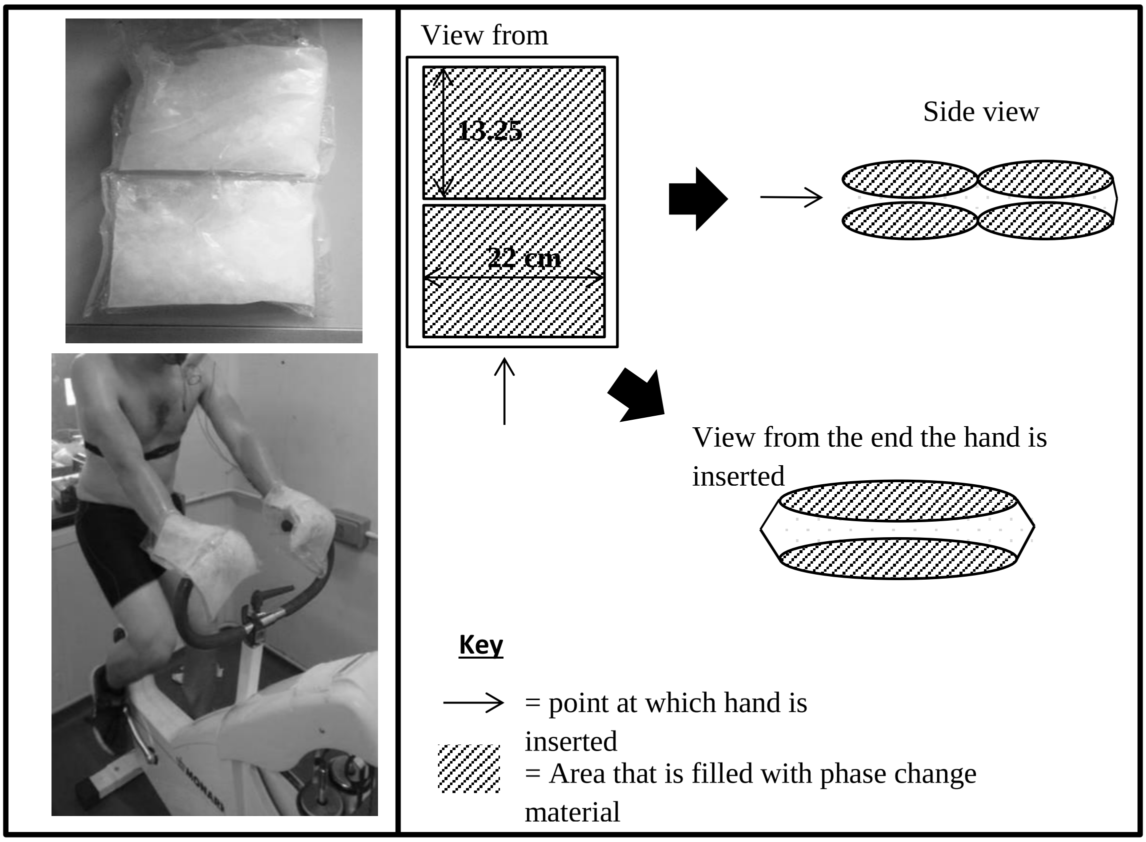

Figure 47: Schematic of final hand cooling design used in the main trials

5.3.2 Participants

Nine non-heat-acclimated physically active males (age = 30 ± 7 years; body mass 73.5 ± 8.5 kg; stature = 183 ± 7 cm; $\dot{V}O_{2peak}$ = 58.1 ± 7.1 ml·kg^{-1}·min^{-1}) volunteered for the study and provided written informed consent. All procedures were conducted in accordance with the ethical standards of the institutional research committee and the 1964 Helsinki declaration and later amendments. All experimental trials were conducted between the months of November 2016 and April 2017 when mean ambient temperatures ranged 5 to 16 °C. Participants refrained from heavy exercise, caffeine and alcohol 24 h before each trial and food 3 h before each trial. All participants recorded their diet 24 h prior to the first trial and replicated their diet for the remaining trials. Participants were naïve to the aims of the study but were told that the study involved placing their hands in cold gloves whilst exercising in the heat.

Participants visited the laboratory on three occasions, each visit separated by three days to 7 days. All trials were conducted between 1400 and 1600 and standardised for each participant to minimise the circadian rhythm impact on body temperature and gastrointestinal function [252]. Exercise trials were conducted on a verified, Monark Ergomedic 874 E (Monark Exercise AB, Vansbro, Sweden) (Bias ± 95% limits of agreement = 2.8 ± 11.4 W; r = 0.99; Coefficient of variation = 2.2%). In a randomised cross-over design each participant exercised with either the hand cooling gloves or without gloves. Participants were randomly allocated to receive counter-balanced treatments by personnel external to the study by drawing the trial out of a hat. The investigators involved in data collection were not blinded to the experimental condition after allocation, but perceptual responses were collected from the participant by personnel uninvolved with the study to minimise the risk of confirmation or wording bias.

5.3.3 Visit 1: Pre-experimental trial testing and accustomisation

Peak oxygen uptake ($\dot{V}O_{2peak}$) (Ultima, CardiO_2, Medgraphics, USA), peak minute external mechanical power (W_{peak}) and the first ventilatory threshold (T_{vent}) (Ventilatory equivalent and V-slope method determined from breath-by-breath analysis of expired air) were determined from a stepped 25 $W \cdot min^{-1}$ incremental exercise test to volitional exhaustion in a temperature controlled laboratory (18°C, 50% relative humidity). Heart rate was assessed continuously during exercise (RS400, Polar OY, Finland) and peak heart rate recorded. After 30 min of rest in a temperate environment, participants performed 30 min of cycling within the environmental chamber (35 °C, 50% relative humidity) at an external mechanical power output equivalent to T_{vent} to accustomise to the experimental procedures.

5.3.4 Experimental trials

Six hours before the experimental trial participants ingested a telemetry pill to assess intestinal temperature (CorTemp, HQinc, USA). This procedure has been demonstrated to provide reliable data under similar conditions [243]. The validity of temperature measurement of each pill was confirmed according to recommended guidelines [254] (mean $r^2 = 0.99$).

Before experimental trials the participant's nude body mass (kg) and urine osmolality ($mOsmol \cdot kg^{-1}$ H_2O) were assessed before dressing in standardised clothing (shorts, socks and running shoes). A urine osmolality of ≤700 $mOsmol \cdot kg^{-1}$ H_2O was used to verify pre-trial euhydration [114]. Participants rested for 30 min in the environmental chamber set at 35 °C, 50% relative humidity. No cooling fans were used, but air flow from the environmental chamber fans was ≈0.5 $m \cdot s^{-1}$.

Before exercise, participants were fitted with heart rate monitor (Bias ± 95% limits of agreement = 5 ± 8 $beats \cdot min^{-1}$; r = 0.96; Coefficient of variation = 4.2%). Skin thermistors (Grant Instruments, Cambridge, UK) were verified before the experimental trials using a calibrated thermometer (all coefficient of variation <0.33%; r = 0.99) and attached to the left side of the body at the medial calf, anterior mid-thigh, anterior mid-forearm, chest and index finger using acrylic dressing (Tegaderm, 3M Healthcare, USA), secured in place using hypoallergenic surgical tape (Transpore, 3M Healthcare, USA). Data was collected in 5 s intervals and averaged over 60 s (Squirrel 1000 series, Grant Instruments, UK). The position of each site was standardised for each participant. Hands were placed in the gloves immediately before the start of exercise and remained in the gloves until the exercise trial was complete. Each glove was filled with 800 ml of phase change material set to maintain a stable solid-state temperature of 10-12 °C. The gloves were replaced at 20 min with a new pair and these were worn until the end of exercise. This temperature was chosen because of the effectiveness of previous hand cooling research [280] that used 8°C and 14°C water**.** Heart rate, skin and intestinal temperature, rating of perceived exertion [272] and whole body, right hand and left-hand thermal sensation and comfort [67] were recorded, immediately before exercise (0 min) and then at 5-min intervals throughout the exercise trial. Participants were asked to cycle for 60 min at an external mechanical power output equivalent to T_{vent}. Expired air was assessed breath-by-breath every 15 min for 3 min (Bias ± 95% limits of agreement = 0.03 ± 0.20 $L \cdot min^{-1}$; r = 0.98; Coefficient of variation = 3.7% for steady state oxygen uptake assessed during last 30 s of submaximal exercise). The exercise test was terminated when one of the following criteria was met:

1) participants voluntarily stopped exercising, 2) intestinal temperature reached 39.5 °C or; 3) participants completed 60 min of exercise. Weighted mean skin temperature ($\bar{T}_{sk}$) was calculated using the equation of Ramanathan [241]. Mean body temperature ($\bar{T}_{body}$) was calculated using the equation of Colin et al. [255]. Sweat rate was calculated as the difference between body mass before and after exercise, accounting for fluid ingestion and urine output.

Figure 48: Image of participant wearing hand cooling gloves

5.3.4 Statistical analysis

Data obtained during previous hand cooling research [280] suggested a sample size of 8 participants would be adequate based on finding a 0.20 °C intestinal temperature difference between experimental and control conditions at the end of exercise, a standard deviation of 0.17 °C, $\beta = 0.20$ and $\alpha = 0.05$. Normal distribution was assessed using Kolmogorov-Smirnov test in IBM SPSS statistics version 24 (IBM Armonk, NY, USA). Data were assessed for meaningful between-trial differences using a magnitude-based approach [57]. The analysis was performed using a statistical spreadsheet [61] that calculates trial means, standard deviations, standardised effect sizes (Cohen's *d*) using the pooled standard deviation and confidence intervals. Standardised mean differences were reported as Cohen's *d* and assessed according to accepted thresholds; ≤ 0.2 (trivial), > 0.2 - 0.59 (small), 0.60 - 1.19 (moderate), 1.20 - 1.99 (large), > 2.0 - 3.99 (very large) and > 4.0 (extremely large) [57]. 90% confidence intervals were calculated for *d*. The probability (% chance) that the between-trial differences were less than, similar to or greater than the smallest worthwhile difference (calculated as 0.2 × between-trial pooled standard deviation) was assessed using a statistical spreadsheet [61]. Paired samples *t*-tests were used to assess statistically significant differences between experimental and control trials. The Wilcoxon Signed Rank Test was used to assess between-group differences when data violated assumptions of normality. Statistical significance was set at $P < 0.05$.

5.3.5 Research hypotheses

There will not be a statistically significant difference for environmental conditions, exercise duration, fingertip temperature, mean, change from baseline or final change in intestinal temperature, mean, change from baseline or final change in mean body temperature, mean heart rate, sweat rate, RPE, between trials whole body thermal comfort, hand thermal comfort, whole body thermal sensation and hand thermal sensation between trials.

5.4 Results

Environmental conditions (HC = 28.8 ± 0.5 °C; CON = 28.8 ± 0.5 °C wet bulb globe temperature; d = -0.01 [-0.03 to 0.01], P = 0.89), baseline intestinal and skin temperatures and thermal perceptions were standardised before experimental trials and were similar between conditions (table 14). Two participants were unable to complete the full experimental trials due to injury and illness. Two participants reached the 60 min exercise termination criteria in both conditions, there was one instance when a participant exceeded 39.5 °C intestinal temperature in the control trial and no adverse effects from exercising in the heat. Mean intensity of exercise was 219 ± 48 W and the duration of exercise was greater with hand cooling compared with control trial (HC = 47.4 ± 14.5 min; CON = 41.4 ± 15.0 min; d = 0.41 [-0.03 to 0.86], P = 0.12).

Table 14: Baseline body temperature and perceptions.

SD = standard deviation; CI = confidence interval.

	Cooling Glove Trial (mean ± SD)	Control Trial (mean ± SD)	*d* (± 90% CI)	*P*
Intestinal temperature (°C)	37.24 ± 0.1	37.25 ± 0.19	-0.05 (-1.00 to 0.91)	0.92
Mean skin temperature (°C)	35.49 ± 0.24	35.58 ± 0.30	-0.35 (-0.84 to 0.14)	0.22
Finger temperature (°C)	36.11 ± 0.17	36.05 ± 0.34	0.22 (-0.37 to 0.80)	0.51
Whole body thermal sensation	5.1 ± 0.4	5.1 ± 0.4		1.00
Hand thermal sensation	4.9 ± 0.4	4.9 ± 0.4		1.00
Whole body thermal comfort	1.4 ± 0.5	1.3 ± 0.5		0.32
Hand thermal comfort	1.6 ± 0.5	1.4 ± 0.5		0.32

5.4.1 Temperature data

Mean glove temperature was 12.8 ± 5.3 °C during the exercise trials which decreased mean finger temperature compared to the control trial (HC = 24.8 ± 6.7 °C; CON = 37.3 ± 0.9 °C; d = -2.54 [-3.35 to -1.73]; P < 0.01). Mean intestinal temperature (HC = 38.1 ± 0.5 °C; CON = 38.3 ± 0.6 °C) and mean change from baseline intestinal temperature (HC = 0.9 ± 0.5 °C; CON = 1.0 ± 0.6) were lower in hand cooling trials (d = -0.34 [-2.18 to 1.49], P = 0.75; and -0.33 [-0.53 to -0.13], P < 0.01, respectively). Final time-matched change from baseline intestinal temperature (HC = 1.4 ± 0.5 °C; CON = 1.8 ± 0.4 °C) was lower in hand cooling compared to control trials (d = -0.81 [-1.52 to -0.11]; P = 0.06) (figure 49). Mean skin temperature (HC = 36.7 ± 0.5 °C; CON = 37.0 ± 0.6 °C) and final time-matched change from baseline mean skin temperature (HC = 1.7 ± 0.5 °C; CON = 2.0 ± 0.5 °C) were lower in hand cooling compared to control trials (d = -0.47 [-1.09 to 0.15], P = 0.21; and d = -0.67 [-1.20 to -0.14], P = 0.04, respectively) along with mean change from baseline mean skin temperature (HC = 1.4 ± 0.6 °C; CON = 1.5 ± 0.6 °C, d = -0.20 [-0.33 to -0.07], P = 0.01). Mean body temperature (HC = 37.9 ± 0.5 °C; CON = 38.1 ± 0.6 °C), change in mean body temperature from baseline (HC = 1.3 ± 0.5 °C; CON = 1.5 ± 0.6 °C) and final time-matched change in mean body temperature from baseline (HC = 1.9 ± 0.5; CON = 2.2 ± 0.4 °C) were all lower in hand cooling compared to control trials (d = -0.33 [-0.75 to 0.10], P =0.20; d = -0.24 [-0.46 to -0.01], P = 0.08; d = -0.67 [-1.31 to -0.03], P = 0.09).

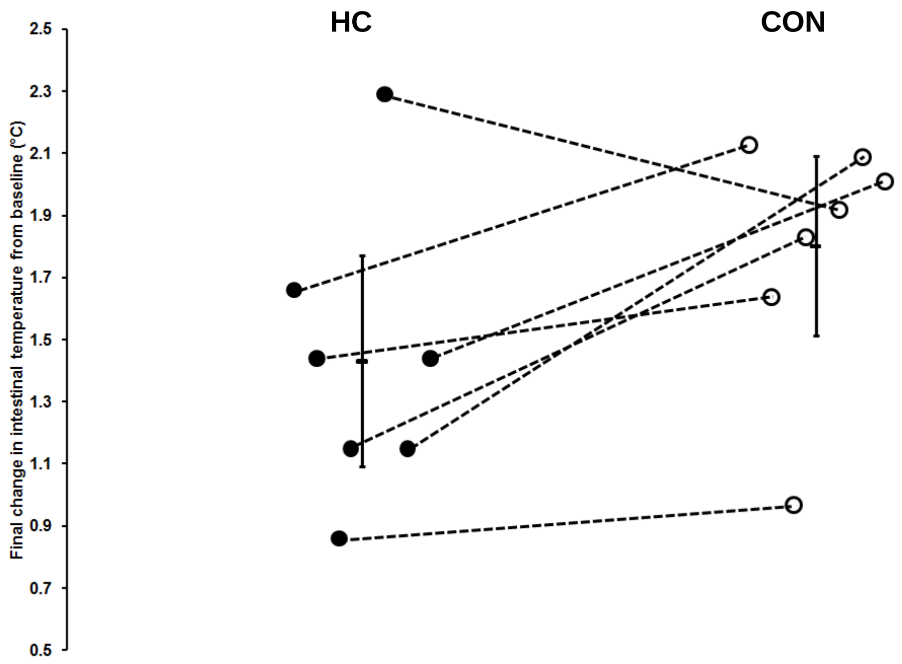

Figure 49*:* Individual data points demonstrating final change in intestinal temperature

Error bars and black horizontal line represent 90% confidence intervals and the mean, respectively. Closed circles represent hand cooling trials, open circles represent control trials.

5.4.2 Physiological data

Mean percentage of maximum heart rate (figure 50) (HC = 84 ± 6%; CON = 87 ± 5%), mean percentage of peak oxygen uptake (HC = 64.2 ± 7.3%; CON = 67.1 ± 9%) and sweat rate (1.62 ± 0.78 $L \cdot hour^{-1}$; CON = 1.9 ± 0.59 $L \cdot hour^{-1}$) were all lower in hand cooling trials compared to control (d = -0.64 [-1.01 to -0.26], P = <0.01; d = -0.36 [-0.74 to 0.03], P = 0.12; d = -0.41 [-0.84 to 0.02], P = 0.11).

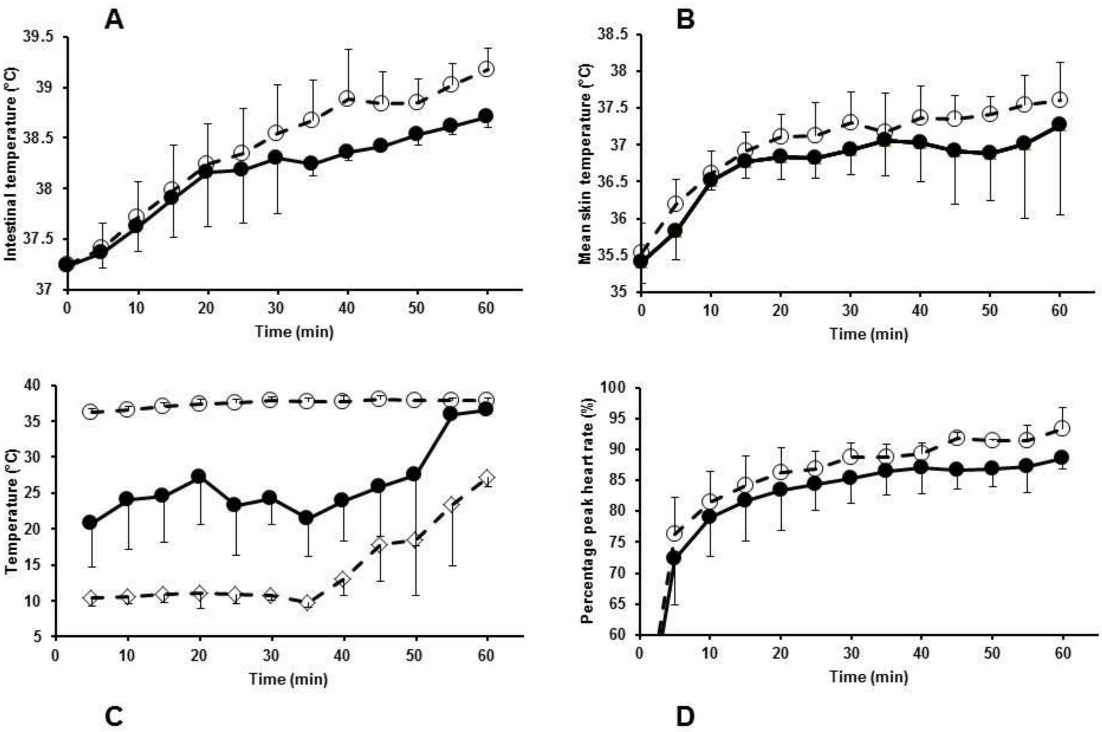

Figure 50: A = mean intestinal temperature during exercise; B = mean skin temperature during exercise; C = mean fingertip temperature and glove temperature; D = mean percentage peak heart rate.

Closed circles represent hand cooling trials, open circles represent control trials. Open diamonds represent glove temperature. Error bars = standard deviation.

5.4.3 Perceptual data

Perceptual data was not normally distributed and assessed non-parametrically using the Wilcoxon Signed Rank Test. Mean RPE (HC = 13.6 ± 2.4; CON = 14.5 ± 2.0), mean whole body thermal comfort (HC = 2.3 ± 0.8; CON = 2.9 ± 0.6), mean hand thermal comfort (HC = 1.6 ± 0.7; CON = 2.7 ± 0.9), mean whole body thermal sensation (HC = 5.9 ± 1.0; CON = 6.5 ± 0.7) and mean hand thermal sensation (HC = 2.8 ± 1.5; CON = 6.2 ± 0.8) were all statistically significantly lower ($P < 0.01$) in hand cooling compared to control trials. Figure 51 provides an illustration of individual RPE values at the end of exercise.

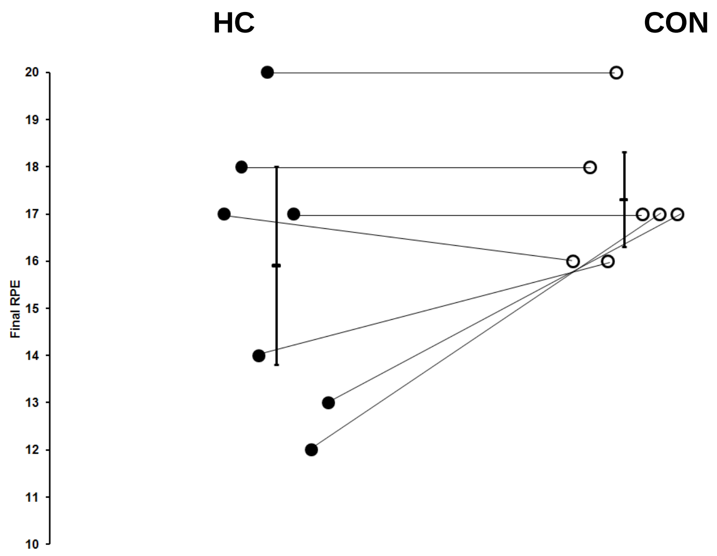

Figure 51: Individual data points demonstrating final RPE

Error bars and black horizontal line represent 90% confidence intervals and the mean, respectively. Closed circles represent hand cooling trials, open circles represent control trials.

5.5 Discussion

The aim of this study was to investigate the effects of cooling gloves on body temperature, cardiorespiratory and perceptual responses during exercise in a hot environment. The main findings are 1) the cooling gloves decreased finger temperature demonstrating that hand cooling via the gloves was successful; 2) this was accompanied by moderate attenuations in final time-matched change from baseline intestinal temperature, mean skin temperature, mean body temperature and mean percentage of heart rate maximum; 3) possible small beneficial effects were observed for mean intestinal temperature, mean skin temperature, mean body temperature, mean percentage of maximum for oxygen uptake throughout the trials, sweat rate and duration of exercise and 4) rating of perceived exertion, thermal sensation and thermal comfort were also statistically significantly lower during hand cooling trials.

Our findings are in agreement with previous meta-analyses that found cooling during exercise increased exercise duration in hot environments [6–8]. Ruddock et al. [8] suggested that improvements in exercise capacity using practical cooling strategies were likely mediated via improvements in thermal perception and RPE because these strategies did not alleviate heat strain or cardiorespiratory responses. In the present study, however, we observed that hand cooling did alleviate heat strain, evidenced by smaller intestinal, skin and mean body temperature and benefited perceptual responses, as well as heart rate and relative oxygen uptake. Other studies that have investigated hand cooling during exercise have used 'heat extraction' devices (RTX CoreControl, AVAcore Inc., CA, USA) [13, 14] and demonstrated alleviation in deep body temperature; whilst others have reported no statistically significant effects [208, 219]. However, it is difficult to ascertain whether hand cooling occurred or not because hand temperature or vasoaction was not reported. Moreover, these devices were only able to contact the palmar surface. Since the hands have a large surface area to mass ratio and low metabolic heat production [10], there is potential for the whole hand to be involved in heat transfer not just the palmar surface.

The magnitude of effect on intestinal temperature and percentage peak heart rate reported in the current investigation (ranging from d = -0.33 to -0.81) is similar to the moderate effects reported by Ruddock et al. [280] when hands were cooled in 8 °C and 14 °C water during recumbent cycling in an environmental temperature of 35 °C 50% relative humidity (d = -0.28 to -0.84). However, we observed a larger difference in RPE between cooling and control trials (0.9 units) in the present investigation compared to Ruddock et al. [280] (0.4 units). This might attributed to the different mode of exercise (recumbent vs. upright cycling) rather than cardiorespiratory or thermal demands as percentage peak heart rate was similar between studies and participants felt cooler with hand immersion in cold water and with cooling gloves. These combined benefits make it challenging to attribute a clear mechanism responsible for the extended exercise duration, although the largest beneficial effects were observed in heart rate and body temperature responses (table 15).

Table 15: Probability (% chance) that between-trial differences are beneficial, trivial or harmful in relation to the smallest worthwhile difference.

(calculated as 0.2 × between-trial pooled standard deviation)

	Likelihood/Probability (%)		
	Beneficial	Trivial	Harmful
Duration of exercise	80	19	2
Mean intestinal temperature	55	14	31
Final change from baseline intestinal temperature	93	6	1
Mean skin temperature	77	20	4
Final change from baseline mean skin temperature	48	52	0
Mean body temperature	69	29	2
Final change from baseline mean body temperature	89	9	2
Mean percentage of maximum heart rate	97	3	0
Mean percentage of maximum oxygen uptake	75	24	1
Sweat rate	80	18	1

The effectiveness of hand cooling is probably due to heat transfer from the skin surface to the cooling medium. Unlike previous studies, we quantified the temperature of the fingers and the cooling gloves and confirmed a temperature gradient existed between the cooling gloves and the hands (≈ 12 °C). The finger temperature observed in the current investigation is greater than reported for hand immersion in cold water by Ruddock et al. [280] who also tentatively reported vasoconstriction at the finger during exercise compared to a thermoneutral trial. We did not assess skin blood flow in this study, however, with the cautious interpretation of data from Ruddock et al. [280] we suggest that because finger temperature was greater than in Ruddock et al. [280] the magnitude of vasoconstriction was less. This is necessary for effective heat transfer because sufficient dilation of arteriovenous anastomoses is required to conduct heat from warm circulating blood to the cooler glove and enable relatively cooler blood to return to the central circulation. Our data suggests the beneficial effects observed for body temperature, heart rate, oxygen uptake and thermal perception in this investigation are due to effective heat transfer from the hands to the cooling gloves. Relatively cooler blood returning to the central circulation from the hands is mixed with warmer blood originating from metabolically active tissues, decreasing mean blood temperature compared to control, and observed as a decrease in the rate of change in intestinal and skin temperature during exercise. As a result systemic vasodilation that aids internal and external conductive and convective heat transfer, including the cutaneous vascular network, is reduced and the demand on the cardiovascular system to maintain mean arterial pressure by increasing cardiac output is lessened. We suggest these mechanisms are responsible for the observed decrease in the percentage of peak heart rate and oxygen uptake. It is unclear, however, if these physiological changes influenced whole body thermal sensation and comfort or whether the majority of the differences between trials can be attributed to the allesthesial sensitivity of the hands. Strategies such as neck cooling, benefit thermal perception but do not influence body temperature and similar methods are likely effective because of cold application to sites of high allesthesial sensitivity [81]. Cooling these regions makes participants feel cooler, as reported by assessments of thermal perception [8].

The hands are a site of moderate allesthesial sensitivity [81], even so, participants rated hand thermal sensation as ‘slightly cool’ and ‘hot’ for hand cooling and control respectively, and likely integrated into whole body thermal perception. However, when body temperature is less, thermal sensation is also less, therefore any attenuation in body temperature would also benefit thermal perception. Thus we cannot isolate whether changes in thermal perception were due to sensations of cold on the hand, decreases in body temperature or both. Based on the evidence we suggest the beneficial effects observed for thermal perception are due to a combination of alleviated heat strain and local application of cooling. Rating of perceived exertion is a whole body representation of musculoskeletal, cardiovascular and heat strain [149]. The relative contribution of these inputs is unclear and likely individual specific. However, we found attenuations in cardiovascular and heat strain and suggest these are responsible for the reduced RPE; it is unlikely the differences in RPE were due to different musculoskeletal demands as the intensity of exercise and environmental conditions were fixed.

We also found that hand cooling extended exercise duration to a similar magnitude reported by other cooling methods [6–8] however since the present study was designed to investigate time-matched thermophysiological and perceptual responses rather than exercise capacity, this data should be interpreted cautiously. Two participants reached 60 min, and their trials were terminated, as was the trial that exceed 39.5 °C. It is possible that the general trend observed for participants to exercise longer with the cooling gloves would have been extended to these individuals but we are unable to report this effect fully. RPE was ‘very hard’ for the individuals that voluntarily terminated exercise, intestinal temperature was in the region of 38.5 °C, skin temperature was around 37.2 °C (core-to-skin temperature gradient of 1.3 °C) and final thermal sensation in all control trials was rated as ‘hot’, which all participants found 'uncomfortable'. Since intestinal temperature is less than peak values reported in the literature, it is unlikely that deep body temperature or RPE alone, are responsible for the decision to stop exercising. Our data suggest that exercise termination was probably based on thermal sensation and comfort, influenced directly by core and skin temperature. In other words, participants felt hot and uncomfortable and decided they did not want to continue exercise because of these feelings.

5.6 Limitations and practical implications

Exercise capability and performance in the heat is determined by complex physiological and perceptual interactions [93], that are also environment and context specific. From a safety perspective, alleviating heat strain is important to regulate and prevent deleterious increases in body temperature. In the context of exercise capability and performance improving thermal sensation and comfort during exercise in hot environments, by local application of a cooling medium, is a simple and effective strategy. Thus a combination of the above would be favourable for performance. Hand cooling is well documented to improve exercise capacity as well as body temperature, cardiorespiratory and cardiovascular responses, although the current methods for applying cooling are impractical for use during exercise. While the approach utilised in the present study is still largely impractical for use during exercise, it is an advancement towards a practical cooling strategy that also alleviates heat strain.

Furthermore, while we found beneficial effects in this sample of trained cyclists, many confidence intervals overlap trivial effects; we recommend caution when applying our results to other situations before fully examining the utility of this strategy. Indeed, future research should ascertain whether the hand cooling gloves can be designed more ergonomically while retaining thermoregulatory effectiveness and improving endurance performance in the heat. The latent heat capacity of the cooling gloves as stated by the manufacturer of the phase change material was 155 $KJ \cdot kg^{-1}$, the gloves remained a stable surface temperature and were replaced at 20 min (figure 50 C); some but not all of the phase change material at this point changed from a solid to liquid state but this was non-uniform throughout the glove. It is therefore difficult to ascertain the latent and sensible heat capacity of the gloves. Future research should aim to quantity this to greater effect than in this preliminary study.

5.7 Conclusions

The aim of this study was to investigate the effects of cooling gloves on body temperature, cardiorespiratory and perceptual responses during exercise in a hot environment. We found that cooling via the gloves was successful and benefited participants primarily by attenuating intestinal, skin and mean body temperature, as well as heart rate. Hand cooling also benefited assessments of oxygen uptake, sweat rate, rating of perceived exertion, thermal sensation and thermal comfort and extended duration of exercise. Our research adds to the body of evidence detailing the effectiveness of hand cooling to alleviate thermoregulatory strain which has beneficial practical implications for exercise capability and performance and potentially for industrial and military applications involving physical activity in hot environments.

Chapter 6: General discussion

6.1 Main findings

The main aims of this programme of research were to; 1) identify practical cooling strategies during continuous exercise in hot environments; 2) investigate the utility of an intestinal telemetry pill system to assess core temperature in a hot environment and; 3) provide a mechanistic basis for the development of a practical hand cooling strategy designed to be used during exercise in a hot environment to alleviate heat strain.

Specifically, chapter 2 aimed to answer the following research questions: 1) In healthy participants, does practical cooling during continuous exercise in a hot environment, attenuate mean and final core temperature responses compared to a thermoneutral or no cooling condition in randomised cross-over trials? 2) In healthy participants, does practical cooling during continuous exercise in a hot environment, improve self-paced endurance performance and exercise capacity compared to a thermoneutral or no cooling condition in randomised cross-over trials? 3) Additional research questions sought to investigate the effects of cooling during exercise on mean skin temperature, heart rate, whole body sweat production, RPE and thermal perception, all of which have been implicated in the regulation of performance during exercise in the heat. A major finding from chapter 2 was that cooling during exercise benefited thermal perception and rating of perceived exertion. That is, participants felt cooler and subsequently felt the exercise was less intense. While these cooling strategies might not influence physiological responses they have the potential to improve exercise capability. Indeed, our analysis found that self-paced performance after a period of fixed-intensity exercise was improved, likely mediated by the perceptual benefits of cooling (figure 30). In chapter 3 we investigated the reliability of an ingestible telemetry pill system to assess gastrointestinal temperature. The day-to-day error was proportional to the magnitude of temperature, whereby error increased as temperature increased indicating the presence of heteroscedasticity. The different methods of statistical analyses we employed provided similar trends when the data was assessed in 10 min blocks of exercise and highlighted within-trial variability of intestinal temperature. This data was more variable than the data obtained by the analysis of the entire trial, which demonstrated better reliability than the 10 min time-period analysis. In chapter 4 participants hands were immersed in 3 different water temperatures (8, 14 and 34 °C) while recumbent cycling in a hot and humid environment (35 °C, 50% RH) at 50% of their maximum minute power. Intestinal temperature was similar between trials for 15 min but after that there was an attenuation in core temperature with hand cooling at 8 and 14 °C; similar responses were observed for mean skin temperature and mean body temperature. Fingertip temperature was also less in 8 and 14 °C trials and confirmed a temperature gradient existed between skin and hands. Fingertip blood flow was less in hand cooling trials, despite a cooling effect, and greater than forearm blood flow during exercise. Mean HR_{peak} was less with hand cooling but a meaningful change was only evident from 25 min onwards; there were trivial to small standardised effect sizes for mean $\%\dot{V}O2_{peak}$. Mean thermal perception was also less in hand cooling trials but rating of perceived exertion was similar between trials. Sweat rate was similar between conditions but likely less in 14 °C, compared to 8 and 34 °C conditions. Time to volitional exhaustion was improved between 7 and 9% with hand cooling compared to the thermoneutral trial, but there were no statistically significant differences between treatments. We were able to advance the knowledge attained in chapter 4 towards a more practical hand cooling strategy. Seven males cycled at an external mechanical intensity equivalent to their ventilatory threshold for up to 60-min in 35 °C, 50%

relative humidity. In one trial they wore a pair of hand cooling gloves and in another, no gloves. Almost all thermophysiological and perceptual responses were improved whilst wearing the hand cooling gloves, the effectiveness of this strategy was probably due to the same mechanisms elucidated in chapter 4. That is, relatively cooler blood returned to the central circulation and mixed with warmer blood originating from metabolically active tissues and alleviated heat strain as observed by a relative decrease in body temperature assessments. In chapter 2 we noted that thermal perception and rating of perceived exertion are key inputs in the observed performance improvements due to cooling during exercise. However, none of these practical methods alleviated heat strain whereas our hand cooling gloves improved thermal perception, rating of perceived exertion *and* alleviated heat strain during fixed intensity exercise.

Table 16: Hypothesis table

Chapter 3		
Null Hypothesis	**Rejected/failed to reject null hypothesis**	**Practical interpretation**
There will not be statistically significant differences between trials for environmental temperature and relative humidity	Failed to reject	Environmental temperature and humidity were similar between trials
There will not be statistically significant differences between trials for urine osmolality	Failed to reject	Urine osmolality at the start of trial 1 was similar to the start of trial 2
There will not be statistically significant differences between intestinal temperature at the start of exercise trials	Failed to reject	Intestinal temperature at the start of trial 1 was similar to the start of trial 2
There will not be statistically significant differences between mean skin temperature at the start of exercise trials	Rejected	Skin temperature was marginally lower at the start of trial 1
There will not be statistically significant differences in sweat rate between trials	Failed to reject	Sweat rate did not differ markedly between trials 1 and 2
There will not be statistically significant differences in changes in body mass between trials	Failed to reject	Body mass deficits between trials were similar
There will not be statistically significant differences in heart rate between trials	Failed to reject	Heart rate was similar between trials
There will be no statistically significant difference for mean intestinal temperature between trials	Rejected	There was a statistically significant mean difference between trials

There will not be a statistically significant correlation between trial 1 and 2 for intestinal temperature	Rejected	There was a statistically significant correlation between trial 1 and 2 indicating heteroscedasticity
Chapter 4		
There will not be a statistically significant difference for mean RPE between hand cooling trials	Failed to reject	There were no statistically significant differences in mean RPE between 8 °C and 14 °C
There will not be a statistically significant difference for mean RPE between hand cooling trials and the control condition	Failed to reject	There were no statistically significant differences in mean RPE between 8 °C and 34 °C
	Rejected	There was a statistically significant difference in mean RPE between 14 °C and 34 °C
There will not be a statistically significant difference for mean thermal perception between hand cooling trials and the control condition	Rejected	Mean thermal perception for 8 °C was statistically less than 14 °C and 34 °C Mean thermal perception for 14 °C was statistically less than 34 °C
There will not be a statistically significant difference for fingertip temperature between hand cooling trials and the control condition	Rejected	During water immersion fingertip temperature was statistically less in 8 °C than 14 °C and 34 °C Fingertip temperature was statistically less in 14 °C than 34 °C

There will not be a statistically significant difference for fingertip CVC between hand cooling trials and the control condition	Rejected	Mean fingertip CVC was significantly less in 14 °C than 8 °C and 34 °C. 8 °C was significantly less than 34 °C for mean fingertip CVC
Chapter 5		
There will not be a statistically significant difference for environmental conditions between trials	Failed to reject	Environmental conditions were similar between trials
There will not be a statistically significant difference for exercise duration between trials	Rejected	Duration of exercise was greater with hand cooling compared with control trial
There will not be a statistically significant difference for fingertip temperature between trials		Mean finger temperature was less with hand cooling compared to the control trial
There will not be a statistically significant difference for mean intestinal temperature between trials	Failed to reject	There were no statistically significant differences in mean intestinal temperature between trials
There will not be a statistically significant difference for change from baseline intestinal temperature between trials	Reject	Change from baseline intestinal temperature was less with hand cooling
There will not be a statistically significant difference for final change in intestinal temperature between trials	Failed to reject	Final change from baseline intestinal temperature was not statistically different between trials
There will not be a statistically significant difference in mean skin temperature between trials	Failed to reject	Mean skin temperature was not statistically different between trials
There will not be a statistically significant difference for final change	Reject	Final change from baseline skin temperature was less

in intestinal temperature between trials		with hand cooling
There will not be a statistically significant difference for change from baseline skin temperature between trials	Reject	Change from baseline skin temperature was less with hand cooling
There will not be a statistically significant difference in mean body temperature between trials	Failed to reject	Mean body temperature was not statistically different between trials
There will not be a statistically significant difference for final change in mean body temperature between trials	Failed to reject	Mean body temperature was not statistically different between trials
There will not be a statistically significant difference for change from baseline mean body temperature between trials	Failed to reject	Mean body temperature was not statistically different between trials
There will not be a statistically significant difference for mean heart rate between trials	Reject	Mean percentage of maximum heart rate was less with hand cooling
There will not be a statistically significant difference for mean percentage peak heart rate between trials	Failed to reject	Mean percentage peak heart rate was not statistically different between trials
There will not be a statistically significant difference for sweat rate between trials	Failed to reject	Sweat rate was not statistically different between trials
There will not be a statistically significant difference for RPE, whole body thermal comfort, hand thermal comfort, whole body thermal sensation and hand thermal sensation between trials	Reject	RPE, whole body thermal comfort, hand thermal comfort, whole body thermal sensation and hand thermal sensation between trials were less with hand cooling

6.2 Thermometry

Quantifying temperature is important in sport and exercise science because it enables safe practice for individuals exercising in hot environments as well the assessment of interventions designed to improve capability in the heat. The formal quantification of temperature emerged from the industrial revolution along with the laws of thermodynamics that govern energy transfer [5]. In the sport sciences, two key considerations should be made in relation to thermometry. Firstly, the assessment site should be evaluated based upon the underpinning mechanisms that influence temperature, for example, rectal temperature is influenced by conduction of heat from surrounding tissues; whilst oesophageal temperature is influenced by convective and conductive heat exchange from nearby vascular structures [5, 32]. Secondly, once a site has been appraised mechanistically, logistically and practically it is important to determine the validity, reliability and sensitivity because these are crucial to the interpretation of temperature assessment. Of these concepts, reliability is the very important, since a clear interpretation of treatment effects can be made when the assessment tool has low error, noise or variation, in contrast, assessments with poor reliability make the true effect of an intervention difficult to ascertain [44, 58]. Rectal temperature is frequently used to assess core temperature during exercise in hot environments, although gastrointestinal telemetry pill systems are being increasingly utilised. Several studies have proposed that telemetry pill systems are valid assessments of core temperature [32, 33, 248]. However, the reliability of intestinal temperature assessed using an ingestible pill system during exercise in a hot environment was unknown. Therefore, the purpose of chapter 3 in this programme of research, to investigate the inter-day reliability of gastrointestinal temperature assessment during exercise in a hot environment. This was important because gastrointestinal temperature was a primary outcome variable within this programme of research and is frequently used an assessment of core temperature in scientific literature.

6.3 Reliability of intestinal temperature using an ingestible telemetry pill system during exercise in a hot environment

Twelve male volunteers exercised at 50% of the mechanical power associated with their peak minute power from an incremental step test to exhaustion in 35 °C, 50% relative humidity for a mean of 55.4 ± 9.4 min on two separate occasions. We observed that the day-to-day error was proportional to the magnitude of temperature, whereby error increased as temperature increased and indicating the presence of heteroscedasticity. We also presented a wide range of reliability statistics to help scientists interpret our data according to their preferred method. In general, these different analyses provided similar trends when the data was assessed in 10 min blocks of exercise and highlighted the within-trial variability of intestinal temperature. This data was more variable than the data obtained by the analysis of the entire trial, which demonstrated better reliability than the 10 min time-period analysis. This is probably due to a larger data set within the whole trial analysis. Our general findings were in agreement of those of other research detailed in chapter 3 who also concluded the telemetry pill system was a reliable assessment of intestinal temperature; although we observed a mean bias less than Goosey-Tolfrey et al. [207] but greater than Gant et al. [248]. These differences were likely due a small sample size, and large variation of one individual in Goosey-Tolfrey et al. [207] and potentially because of differences in the mode of exercise (running vs cycling) and a cooler environmental (Gant et al. [248] temp 15 °C, 62% relative humidity vs 35 °C, 50% relative humidity). The latter might have introduced differences in splanchnic blood flow, which gastrointestinal temperature would be sensitive to, given that it is influenced by conductive heat transfer in this area. Indeed, Jette et al. [257] noted similar trends in rectal temperature during exercise, whereby the error increased in magnitude as temperature increased. The gastrointestinal system, however, likely has more sources of influence from a temperature perspective than rectal temperature. Some regions of the gastrointestinal tract (Duodenum, Ileum, Ascending Colon) are located close to the stomach and can be influenced by stomach temperature especially when cold beverages are ingested (figure 52).

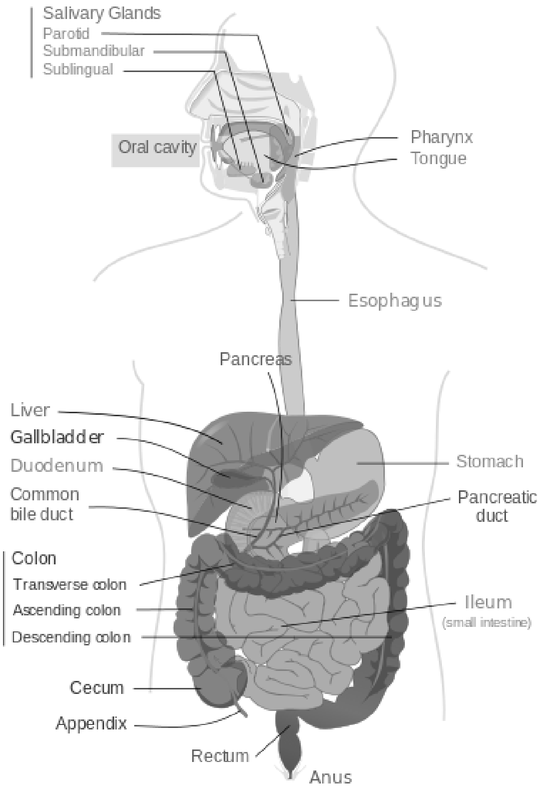

Figure 52: Illustration of the gastrointestinal tract

Extracted from [281]

Gastric emptying can also influence temperature assessments due to gut transit and peristalsis. In this investigation, we standardised pill ingestion time and verified that foods and fluids were consumed at similar times to minimise these influences. Moreover, to limit changes in stomach temperature we provided participants with room temperature water (35 °C). However, despite these controls, there is a possibility that peristaltic velocity might have been influenced by exercise as the pill transitioned along the gastrointestinal tract. Indeed, there is a temperature gradient within the tract as rectal temperature is consistently reported to be less than gastrointestinal temperature [5, 248]. These differences are likely related to the combination of proximity to metabolically-active tissues and blood flow around different regions. We concluded that an ingestible telemetry pill system (CorTemp, HQinc, USA) is capable of providing scientists with reliable temperature assessments. Indeed, using the method of Hopkins et al. [61] we determined that a change in intestinal temperature of ≈ 0.34°C would be a likely beneficial change.

6.4 Thermoregulation

Section 1 detailed the importance of reliable quantification of intestinal temperature, and other assessments of core temperature, primarily because many studies focus on core temperature as a primary outcome measure and use it to contextualise thermoregulation within limits of human exercise capability. Indeed, there are many models of thermoregulation, most which are derived from engineering concepts involving simple feedback loops whereby a central controller, regulates a 'set-point' temperature which initiates physiological responses in an attempt to maintain homoeostasis [67]. The understanding of what controls effector responses, i.e. central, peripheral, local or a specific context-dependent combination of all three, is limited in relation to the knowledge of each effector response. For example, there is no convincing understanding as to why body temperature is regulated around 37 °C; perhaps this value is simply a reflection of mean body temperature, influenced by independent temperature regulation of local tissues since there are wide site-to-site variations in temperature which are dependent on local influencers such as perfusion and proximity to metabolically active tissues [5]. Nevertheless, these models propose a simple approach to understanding temperature regulation; when thermal afferents from temperature sensitive sources converge an effector response occurs. Whether a central controller integrates and co-ordinates these variables is unclear, but lesion studies implicate the preoptic anterior hypothalamus as an important site in thermoregulation [71, 72].

These models of thermoregulation are perhaps more suited to the explanation of autonomic thermophysiological responses of laboratory-based fixed-intensity origin, rather than thermoregulatory actions that occur in physical activity and self-paced athletic competition, as presented in section 1. In the latter context, the concept of behavioural thermoregulation is important, whereby an individual chooses to modify behaviour to regulate temperature rather than rely on energetically and resource (e.g. fluid) dependent autonomic responses [76, 148, 149, 227]. For example, an individual will feel hot before the initiation of profuse sweating, and, environment permitting, will seek a cooler location or remove clothing, principally to improve thermal comfort and sensation. These decisions are made consciously to defend against unnecessary energy depletion and fluid losses. Unlike autonomic responses, behavioural thermoregulation is influenced by motivation, previous experience, anticipation, mood, thermal sensation and thermal comfort. In the context of exercise in a hot environment, warmth sensation is dependent on skin and core body temperature while feelings of discomfort primarily on skin wettedness [77, 78].

During self-paced exercise, perhaps the weighting towards core temperature that determines mean body temperature overlooks the key role of thermal perception in modifying behaviour. Autonomic and behavioural responses are distinct regulators of body temperature, as are the exercise models that modify these different responses. Most studies examining thermophysiological responses to exercise have used fixed-intensity models and an understanding of the differences between this method and self-paced methods is required to appreciate the physiological responses to exercise capability and heat stress and as well as strategies to alleviate heat strain and improve performance.

6.5 Physiological responses

An appreciation of physiological responses and the mechanisms required to control body temperature are important because they allow thermal physiologists and sport scientists to describe the needs and physiological demands of exercise in the heat and explain the effects of training or interventions designed to maximise performance or improve safety. The two primary mechanisms for transferring heat away from the exercising muscle are: 1) intracellular conductive heat transfer and; 2) vascular convective heat transfer [88]. The latter is dependent on tissue blood flow and arteriovenous temperature difference, which makes the initial vascular response to exercise a key first step in thermoregulation. Sympathetic withdrawal mediates the early response to heat production that aids vasodilation, blood flow and convective heat transfer. After this period, compounds formed as part of the physiological and mechanical response to exercise increase and contribute to endothelial vasodilation. Crucially, however, vasodilation does not increase linearly with increasing demands for heat transfer. Instead, vascular conductance is limited to protect mean arterial pressure. Indeed, several circulatory adjustments are made to account for the increased vasodilation at the muscular level, the most prominent being splanchnic vasoconstriction and increases in stroke volume, heart rate and cardiac output. These adjustments are critical to maintaining perfusion pressure at vital organs while assisting heat transfer from the muscle [88, 90, 94]. Changes in local blood temperature are detected by thermosensors and integrate to initiate cutaneous vasodilation that occurs to assist heat transfer to the environment.

The responses of the cutaneous circulation to the demands of exercise are integral to human thermoregulation but are often overlooked in favour of core temperature responses. The control of skin blood flow is complex, involving the sympathetic nervous system and active vasodilation and the physiological responses to exercise are slightly different when heat stress and strain are imposed as heat transfer is more difficult and places greater strain on key regulatory systems [75]. For example, heat is a potentiator of local muscle vasodilation, which increases cardiac demands. Increased heat production also increases skin temperature and cutaneous vasodilation, as does external heat stress from the environment. Conversely, a reduced skin temperature, or cooler skin, increases the internal threshold for vasodilation. This has consequences for heat transfer because although the core-to-skin temperature gradient increases, and facilitates internal conductive and convective heat transfer to the shell, transfer of this heat to the environment is limited as cutaneous vasodilation, and sweat production are delayed. This understanding is important for interventions that are designed to cool large areas of the skin surface before exercise, as this could increase heat storage and body temperature and place blood pressure regulation under strain, if vasodilation occurs too quickly. Indeed, these concerns were presented within section 3 of the thesis. It also has performance implications because if an athlete feels less hot because the intervention has successfully decreased skin temperature, they might increase intensity earlier in the challenge. This would increase metabolic heat production but because of a delayed thermoeffector responses would also increase heat storage. Consequently, an athlete's typical perception-performance link is uncoupled and might result in performance impairment during the latter stages of competition as body temperature, physiological demand, perceived exertion and thermal perception increases.

Equally, warm but not hot, skin combined with exercise in the heat would likely favour the initiation of heat loss mechanisms such as increased skin vasodilation and onset of sweat production. Elevation in skin temperature also buffers against external heat gain and increases cutaneous water vapour pressure which improves evaporative heat transfer [5]. Indeed, consuming hot fluids before and during exercise improves net heat loss primarily because it initiated earlier and more profuse sweat onset [282], more data is required to corroborate these findings. Furthermore, these effects would only be useful in compensable environments that enable evaporative heat transfer. Another key physiological change during exercise and heat stress is an increased reliance on carbohydrate metabolism, possibly caused by allosteric activation of phosphofructokinase and phosphorylase that increase flux through glycolysis, mediated by an increased cellular energy state. In addition, increased adrenaline secretion, as well as a reliance on type II muscle fibres during prolonged intense exercise would also contribute to carbohydrate oxidation [117, 283]. Despite circulatory adjustments that limit blood flow to visceral organs, skin and muscle blood flow demands place considerable strain on the cardiovascular system. Indeed, current evidence suggests that during fixed-intensity exercise vasodilation increases at skin and active muscle until blood pressure regulation is impaired, at this point O_2 delivery to muscle decreases and exercise capability decreases inducing fatigue [91, 118] and limits exercise capability in the heat.

6.6 Limits of exercise capability in the heat

The consistent findings of impaired exercise capacity and performance have been documented for millennia, but the formalisation or quantification for the key determining factors are yet to be fully elucidated. Several theories have been proposed to explain what causes such impairments, most notably, the critical core temperature hypothesis which is probably too simple fully explain limits to exercise capability [131]. Indeed, temperatures exceeding the hypothetical critical limit of 40 °C and less than 40 °C are routinely reported at exhaustion in the scientific literature. Indeed, in the studies within this programme of research, voluntary termination of exercise occurred well before 40 °C, indicating that fatigue is complex and context dependent and cannot be explained generically. Ideally, the limits of exercise capability should be considered in context to the type and intensity of the exercise challenge, environmental conditions, they key physiological responses that determine thermoregulation; that are muscle blood flow, cardiovascular and cutaneous responses as well as sudomotor function. These are often difficult to assess during exercise, nevertheless the assessments used throughout this thesis such as heart rate, skin temperature and changes in body mass are logistical, relatively low-cost, widely accessible and reliable and are routinely quantified to assess the effectiveness of strategies to alleviate heat strain. These strategies can be broadly categorised as heat acclimation protocols or cooling strategies.

6.7 Pre-cooling

The main aim of pre-cooling is to decrease deep body temperature by around 0.5 °C before exercise in the heat [7]. Often these reductions are not always achieved especially with external cooling. Nevertheless, skin temperature is almost always decreased as a result and despite physiological constraints this imposes, is reported to confer benefits towards internal heat transfer. Section 3 of the thesis examined the current literature on pre-cooling, which in general reports only trivial benefits of pre-cooling on the change in skin temperature to performance relationship. Indeed, Bongers et al. [7] found similar trivial effects for the relationship between changes in core temperature and heart rate on performance. Whether these findings are due to physiological changes or the systematic search strategy used to include studies is unclear. What is clear is that pre-cooling is context specific and dependent on the type of cooling (internal, external, mixed-method) and exercise type (sprint, intermittent, prolonged). However, when these studies are combined into a meta-analyses the data are unfortunately confounded by methodological heterogeneity. Indeed, the magnitude of cooling differs between studies and are often not applied relative to an individual's somatotype or body surface area. While these strategies might have a practical element and strong ecological validity, they make interpretation of physiological mechanisms difficult. Thus studies of pre-cooling strategies need to consider the magnitude of cooling stimulus, duration of application, the warm-up, the type of exercise challenge, ability of the individual to thermoregulate and the environment. These factors also need to be considered when evaluating the literature. Moreover, acknowledgement of fundamental concepts in heat exchange should be appreciated. Newton's cooling law states that irrespective of starting temperature, thermal equilibrium will be achieved at a similar time point and the only main variable that will change is the rate of change in heat storage [5]. These concepts were illustrated at the muscular level in section 3 figure 17 [160] and should be appreciated during fixed-intensity exercise. Further complications arise when considering self-paced exercise. Pre-cooling threatens the link between thermal perceptions, perceived exertion and performance and risks a detrimental change in pacing strategy that might compromise performance. For example, if an athlete undertakes a pre-cooling strategy which successfully lowers core and skin temperature, this might lessen their thermal perception and perceived exertion, encouraging the athlete to perform at an intensity greater than their pre-planned strategy earlier in the event thus risking performance during the critical final stages of competition. More worryingly is that body temperature might increase to critical levels, risking the health and safety of an athlete during the final stages of an event. Such rapid changes in heat strain and physiological demands, from cooler to hotter thermal states can be likened to a change in environmental temperature from cold or temperature conditions to warm, hot and/or humid conditions. There are several high-profile, yet anecdotal instances where endurance athletes have under-performed and/or withdrawn from competition due to heat strain because the transition from colder training climates was insufficient to prepare them for competition intensity in warmer conditions. Indeed, there is evidence to suggest that cases of exertional heat illness are increased when races are held in unseasonably hot weather, such as on a hot day in spring [284] highlighting the risks of changes in temperature. Interestingly, heat acclimation might offer some advantage to protect against the risk of pre-cooling as the body will be able to deal with the associated physiological demands much better. However, some of the most successful pre-cooling strategies, such as water immersion are the most impractical and what might be represented in the literature as effective might not necessarily be reflected in a sporting environment.

6.8 Cooling during exercise

The above concerns are also true for cooling during exercise, but these strategies might be more suited to overcome some of the practical limitations of pre-cooling. Indeed, pre-cooling and cooling during exercise have often been combined using external and internal cooling strategies. In section 3 it was concluded that this approach confers benefits towards the key physiological mechanisms involved in thermoregulation and improves exercise capability but again is context dependent [6, 7]. For example, when fluid ingestion is used for both pre-cooling and cooling during exercise there is an additive effect; but when ice-slurry is used during exercise, there is likely no additional benefit from pre-cooling.

Cooling strategies during exercise can be classified according to the time point they are applied. This might be intermittent during recovery periods or continuous where there are no breaks in exercise. Similarly, cooling might be applied intermittently, such as when drinking cold fluids, or applied continuously via an external strategy such as an ice vest. Such classification of cooling strategies, however, has not been considered in the scientific literature. Indeed, neither the meta-analytical reviews of cooling strategies during exercise of Bongers et al. [7] or Tyler et al. [6] addressed these subtle differences or recognised the key differences between exercise capacity tests and performance trials. Critically, and for the translation of this evidence to be utilised in practice, there needs to be an appraisal of which strategies would be useful during training or competition. For example, neck cooling might be considered a practical cooling strategy because it is lightweight and unobtrusive whereas ice vests might be considered impractical for use during competition primarily because of their mass. Despite these classifications at present, there is no consensus within the scientific community as to what constitutes a practical cooling strategy. Ideally these decisions would be athlete and coach led, and their opinion should be used as a guide for the investigation of practical cooling strategies.

6.9 Practical cooling strategies during continuous exercise in hot environments: A systematic review and meta-analysis

We sought to investigate the effects of practical cooling strategies during continuous exercise in hot environments on their ability to improve exercise capability and alleviate thermal demands. Accordingly the primary research questions were:

In healthy participants, does practical cooling during continuous exercise in a hot environment, attenuate mean and final core temperature responses compared to a thermoneutral or no cooling condition in randomised cross-over trials?

In healthy participants, does practical cooling during continuous exercise in a hot environment, improve self-paced endurance performance and exercise capacity compared to a thermoneutral or no cooling condition in randomised cross-over trials?

Secondary research questions sought to investigate the effects of cooling during exercise on mean skin temperature, heart rate, whole body sweat production, RPE and thermal perception, all of which have been implicated in the regulation of performance during exercise in the heat.

We identified 14 studies that met the inclusion criteria. The participant characteristics, intensity, duration of exercise and environmental conditions had small methodological heterogeneity, therefore, physiological responses for fixed-intensity exercise were meta-analysed. Self-paced exercise trials were also meta-analysed, but only four studies assessed time to exhaustion at a fixed intensity and had large heterogeneity and were not meta-analysed. Data analysis suggested there were unclear effects for cooling during exercise on mean and end-exercise core temperature, mean skin temperature, mean heart rate and sweat rate. However, cooling during exercise improved thermal perception, rating of perceived exertion and self-paced performance after a period of fixed-intensity exercise but not stand-alone self-paced performance. Our findings contrast those of previous meta-analyses because they found clear improvements in exercise capability but not perceptual responses. These differences are probably due to study selection criteria and the careful approach we took to define fixed-intensity exercise, self-paced exercise, physiological responses, strict adherence to a thermoneutral comparator trial and a cooling strategy that could be used during continuous exercise in a hot environment. Some of the strategies included in previous reviews would not be appropriate for use during competition; these include head/face spray or water cooling, liquid, water or air cooling garments, partial limb immersion, ice cooling vests and large fluid consumption. Unless the focus of previous research is strictly on the physiological responses of these strategies it is difficult to see how most could be applied within sports performance. Additionally, the differences might be attributed to the inclusion of cold fluid and ice slurry in our study but not in the review of Tyler et al. [6] However, cold fluid was included in Bongers et al. [7] and whilst cold fluid should be considered a practical cooling strategy care should be taken in interpreting standardised effect sizes from individual studies because not all use a thermoneutral condition as a comparator. While it might be useful to compare ‘applied’ practices, the research base does not yet warrant such an approach. This is because there first needs to be an appraisal of the mechanistic underpinning of a cooling strategy; this can only be adhered to if studies or reviews use a thermoneutral or no cooling trial as a comparator.

In our systematic review and meta-analysis, we used core temperature as a primary outcome measure. This is because of its clinical importance and historical use as an important variable in determining the effectiveness of an intervention. Frequently, however, core temperature is often interpreted on its own without an appreciation of the complex-integrative physiological responses required to exercise in the heat (figure 12). The critical core temperature hypothesis was used in the conclusion of Bongers et al. [7] to suggest that cooling strategies would be most effective if they decreased core temperature. This approach is too simple and ignores the complexity of human thermoregulation. Moreover, we were unable to detect a clear beneficial effect of any practical cooling methods capable of benefiting core temperature responses, possibly because the enthalpy of cooling was insufficient at the site of application or the site itself had limited tissue perfusion which is required for effective heat transfer. A site with a high rate of perfusion would seem to be an ideal location for continuous cooling during exercise.

A major finding within the systematic review is that cooling during exercise benefited thermal perception and rating of perceived exertion. That is, participants felt cooler and subsequently felt the exercise was less intense. While this might not influence physiological responses during fixed intensity exercise, it has the potential to improve exercise capability. A small number of studies investigated exercise capacity but they were methodologically heterogeneous, and the effects were unclear. We did, however, find that self-paced performance after a period of fixed-intensity exercise was improved likely mediated by the perceptual benefits of cooling (figure 30). This type of research design, whereby fixed-intensity exercise precedes a self-paced trial extends to sports whereby a period of submaximal exercise precedes high-intensity efforts. This is often seen in professional road cycling where flat topographical profiles lead into mountain climbs. While this approach has some ecological validity it does introduce a range of confounding influences before the start of the self-paced effort, particularly if the start of the trial is determined by a fixed time period. This is because intra-individual differences in the effectiveness of cooling or the relative intensity in the preceding fixed-intensity period will influence the starting physiological state of the participants. Caution should be applied when extrapolating this data to other scenarios. However, we found an unclear effect on standalone self-paced performance, but there were only three trials included in this data set. Authors might also wish to investigate pacing profiles because of cooling to investigate whether there is an optimal time for performance benefits. This would add further practical advantages to coaches and athletes who would be able to use this information in strategic planning. For example, understanding where the maximum benefit of cooling occurs whether physiological or perceptual would enable athletes to increase intensity during this time and gain a competitive advantage. Similarly, understanding where intensity naturally decreases could be used to an athlete's advantage. Pacing profiles typically take the form of a U-shape, whereby intensity decreases during the mid-phase of a trial. Here, an athlete could take advantage of this knowledge and apply cooling during this phase, even if there is no physiological benefit, it is likely that it would benefit thermal perception and rating of perceived exertion enabling a higher intensity of exercise and improve performance.

All the studies within the systematic review were randomised control trials, but it was not clear how randomisation or allocation concealment occurred. Moreover, few studies reported the temperature of the cooling method of the temperature at the cooling site; the formal quantification of cooling is therefore difficult. While this might be relatively simple externally, involving skin thermistors and thermistors on the cooling medium, it is more challenging when cooling is provided internally. Perhaps a potential solution is the dual use of gastrointestinal pills to assess stomach temperature, while a rectal or oesophageal probe is used to assess core temperature. In addition, more information regarding feelings of uncomfortableness, irritability, adverse effects and general appraisals from participants would be useful to refine practical approaches to cooling during exercise. To date, no studies have documented the combined use of practical cooling strategies during exercise. Neck cooling, ice slurry and cold-water ingestion might have an additive effect, but any new approach to cooling during exercise should be guided by coaches and athletes so that scientists can develop high impact, ecologically valid and physiologically effective cooling methods.

Taking into account this body of research table 17 provides an overview of potential cooling strategies along with a subjective recommendation for use in practice (i.e. a competitive environment). The final recommendation takes into account 6 categories: 1) logistics required to set-up and maintain the cooling stimulus; 2) how the strategy might irritate an athlete and cause unnecessary psychological burden; 3) the approximate mass of the system, a heavier mass is associated with less practicality; 4) cost, a lower cost tends to be more practical; 5) how the strategy might influence performance based on current research, an unclear effect is associated with both harmful and beneficial effects, while possibly beneficial reflects trivial to clearly beneficial effects as assessed via standardised mean effect size; 6) considers the potential physiological and/or perceptual mechanisms of action; finally a practical recommendation is made on the basis of this evidence. A limitation of this approach is that it is not based on a consensus generated by coaches, athletes or practitioners and future research should validate this approach through qualitative analysis.

Nevertheless, at present the most practical cooling strategy for most athletes to use during competition would be to drink cold water (4 °C). Not only does this serve as a simple and effective cooling strategy for perceptual and body temperature responses it also helps to maintain positive fluid balance which is important for cardiovascular stability that is the most likely physiological limiter to health and performance during exercise in thermally stressful environments.

In determining best practice for competing in the heat and choosing an appropriate cooling strategy the following steps are recommended:

1) Assess the thermal environment

2) Asses athlete attributes

- Morphology
- Body surface area to mass ratio
- Acclimation state
- Clothing
- Recent illness (such as viral infections)
- Preparatory environmental conditions

3) Predict or assess race profile

4) Predict or assess thermophysiological responses

5) Assess support locations and suitability for providing cooling

6) Determine most practical cooling strategy

Table 17: Overview of potential cooling strategies during exercise

Cooling strategy	When could it be applied?	Logistics	Irritation	Mass	Cost	Performance effects	Potential mechanisms of effect	Recommendation for practical use
Cooling vests	During exercise During breaks	Requires freezing or cooling and storage (e.g. ice/cooler box)	Worn under or over minimal clothing; cold application close to skin can be uncomfortable and garments might cause skin abrasion	Vests can weigh from 500 g to 4 kg. Likely too heavy for most athletes to wear during competition	£30 to £650	Unclear	Thermal comfort, sensation and perceived exertion	Not harmful but likely ineffective for endurance performance
Ice slurry	During exercise During breaks	Requires freezing or cooling and storage (e.g. ice/cooler box/bottle)	Large bolus of cooling required to elicit changes in body temperature that might be uncomfortable; smaller bolus probably effective to induce perceptual changes but research unclear	Typically under 300 g per bolus. Needs to be consumed over several minutes to achieve full ingestion.	< £10 for fluid + storage	Unclear	Thermal comfort, sensation and perceived exertion	Not harmful but likely ineffective for endurance performance
Neck cooling collar	During exercise During breaks	Requires freezing or cooling and storage (e.g. ice/cooler box/bottle)	None reported. Cooling sensation on neck might be strong for some individuals and therefore uncomfortable	Around 155 g	Unknown	Unclear	Thermal comfort, sensation and perceived exertion	Not harmful but likely ineffective for endurance performance

Cooling headband	During exercise During breaks	Requires freezing or cooling and storage (e.g. ice/cooler box/bottle)	None reported. Cooling sensation on forehead might be strong for some individuals and therefore uncomfortable	< 100 g	< £5	Unclear	Thermal comfort, sensation and perceived exertion	Not harmful but likely ineffective for endurance performance
Cold water ingestion	During exercise During breaks	Requires cooling and storage (e.g. ice/cooler box/bottle)	Large bolus of cooling required to elicit changes in body temperature that might be uncomfortable; smaller bolus probably effective to induce perceptual changes but research unclear	200 to 400 g per bolus	< £5	Possibly beneficial if fluid temperature ~ 4°C	Thermal comfort, sensation and perceived exertion	Likely effective for endurance performance
Rapid thermal exchanger	During breaks During exercise	Requires cooling and storage (e.g. ice/cooler box/bottle) Requires power source	Possible uncomfortable cold sensations on palm	> 5 kg	£1500	Possibly beneficial	Attenuation in body temperature responses improved thermal comfort, sensation and perceived exertion	Could be used during breaks but not during exercise Likely effective for endurance performance
Limb water immersion (arms/legs)	During breaks	Requires cooling and storage (e.g. ice/cooler box/bottle)	Possible uncomfortable cold sensations on appendage	5 to 10 kg	< £5	Possibly beneficial	Attenuation in body temperature responses improved	Could be used during breaks but not during exercise Likely effective for

							thermal comfort, sensation and perceived exertion	endurance performance
Hand cooling - Phase change/glove mitten	During breaks During exercise	Requires cooling and storage (e.g. ice/cooler box/bottle)	Possible uncomfortable cold sensations on hands	800 g	< £250	Possibly beneficial	Attenuation in body temperature responses improved thermal comfort, sensation and perceived exertion	Could be used during breaks but not during exercise Likely effective for endurance performance
Face and head cooling with cold water and fans	During breaks During exercise	Requires cooling and storage (e.g. ice/cooler box/bottle) Requires fans and power source	Possible feeling of uncomfortableness caused by cold water on head/skin	2 to 5 kg	< £30	Possibly beneficial	Attenuation in skin temperature responses improved thermal comfort, sensation and perceived exertion	Could be used during breaks but not during exercise Likely effective for endurance performance
Whole or partial body mechanical cold water or air circulation	During breaks During exercise	Requires specialised garment with internal tubing or air pumps Requires cooling and	Possible feeling of uncomfortableness caused by cold application to skin	Dependent on method	Dependent on method	Possibly beneficial	Attenuation in body temperature responses improved thermal comfort, sensation and perceived	Impractical for use during endurance performance

	storage (e.g. ice/cooler box/bottle) Requires power source		exertion

6.10 The hands

The hands have morphological characteristics that are suited to heat transfer. They are relatively inactive, have limited heat production and are poorly insulated. The hands have a surface to mass ratio 4 to 5 times larger than the rest of the body as a whole and contain arteriovenous anastomoses, which enables high rates of blood flow [10]. This blood flow is influenced more by core temperature than local temperature, which is ideal when hyperthermia is combined with local conductive cooling strategies [205]. A large proportion of hand cooling studies have used military or occupational personnel in their typical heat stressed environment, which often occurs in the heat while wearing protective clothing (table 9). Moreover, they have applied cooling according to the context by which they work, which does not hold much external validity to sport performance. Hand, palm or forearm cooling has been studied during periods of rest, either from a single bout or multiple bouts of exercise. These bouts of exercise are typically low-intensity (relative to sport performance) and designed with the sole purpose of inducing moderate magnitudes of hyperthermia which is almost always arbitrarily determined by a core temperature of 38.5 °C. There appears to be little rationale for this absolute figure and an under appreciation for changes from baseline temperature. Moreover, the importance of skin temperature, cardiovascular and perceptual responses are overlooked in preference for a single core temperature value when prescribing exercise termination points and determining the success of the intervention. In addition, the intensity of exercise is often poorly prescribed as an absolute external intensity, which is not relative to the individual, their fitness, body mass or surface area. This is surprising because the low-intensity of exercise and moderate magnitude of hyperthermia would unlikely be the limiting factor to exercise capability; it is more likely cardiovascular in origin but this is rarely investigated in the literature [206]. What is clear, however, is that studies that induced the greatest magnitude of hyperthermia also noted the greatest rates of cooling. This is in line with two concepts; 1) that blood flow to the hands is mediated to a greater extent by core body temperature than local temperature, enabling high rates of blood flow despite cold application and; 2) Newton's cooling law that predicts the rate of change in temperature is proportional to the initial temperature difference. Heat will, therefore, be exchanged quickly from the skin surface to the cold water when the temperature difference is largest.

6.11 Effect of hand cooling on body temperature, cardiovascular and perceptual responses during recumbent cycling in a hot environment

Despite the potential for hand cooling to be a practical strategy for cooling during continuous exercise, the mechanisms that underpin this have yet to be determined. Therefore, in chapter 4 we investigated the cardiovascular, body temperature and perceptual responses to hand immersion in different water temperature to address this gap in knowledge. Specifically, the purpose of this study was to provide a mechanistic basis for the development of a practical hand cooling strategy. Participants undertook three trials of recumbent cycling at 50% W_{peak} in 35°C 50% relative humidity. The trials were terminated when either participants reached 39.5°C intestinal temperature, 60 min of exercise or they voluntarily stopped exercising. They immersed their hands up to the Ulna head in 3 water temperatures; a control thermoneutral temperature of 34 °C, and experimental conditions of 14 and 8 °C. These temperatures were chosen based on the effectiveness of hand cooling from previous research. The temperature of the water was maintained throughout exercise by close monitoring. Crucially, unlike previous research, we quantified fingertip temperature and cutaneous vascular conductance of the fingertip and forearm. This enabled us to quantify a temperature gradient between the water, and the hand and subsequent vasomotion. Initial hand immersion at rest had no influence on any physiological variables but did lower indices of thermal perception. Intestinal temperature was similar between trials for 15 min but after that there was an attenuation in core temperature with hand cooling; similar responses were observed for mean skin temperature and mean body temperature. Fingertip temperature was also less in 8 and 14 °C trials and confirmed a temperature gradient existed between mean skin and the thermoneutral trial. Fingertip CVC was less in hand cooling trials but still greater than forearm CVC. Mean HR_{peak} was less with hand cooling but a meaningful change was only evident from 25 min onwards; there were trivial to small standardised effect sizes for mean %$\dot{V}O2_{peak}$. Mean thermal perception was also less in hand cooling trials but rating of perceived exertion was similar between trials. Sweat rate was similar between conditions but likely less in 14 °C, compared to 8 and 34 °C conditions. Finally, time to volitional exhaustion was improved between 7 and 9% with hand cooling compared to the thermoneutral trial, but there were no statistically significant differences between treatments.

In chapter 4 we examined the potential mechanisms responsible for our findings and suggested that heat transfer from warm circulating blood as the major contributor. For effective heat transfer, there needs to be a balance between the thermal gradient and sufficient blood flow. That is, the water temperature cannot be too cold that it induces considerable vasoconstriction because the primary means by which hand cooling is effective is through the potential for high rates of blood flow. Too much vasoconstriction would reduce blood flow to the hands, limit heat transfer and reduce the potential for cooler venous blood flow to return to the central circulation. A limitation of previous studies is that they did not confirm that the application of the cooling strategy caused localised cooling. Fingertip temperature was greater than water temperature for the 8 and 14 °C trials and provided evidence of a thermal gradient. Moreover, fingertip temperature was also less than mean skin temperature, confirming a temperature gradient existed between the body and the hands. However, we noted that cutaneous vascular conductance; an index of skin blood flow was less in 8 and 14 °C compared with 34 °C indicating that local cooling influenced vasoaction. At the onset of water immersion there was an immediate vasoconstriction at the fingertip, but not at the forearm (which was not immersed). This finding is consistent with the research presented in section 4 of this thesis that observed that hand blood flow could be restricted by local application of cooling when body temperature was relatively thermoneutral [205]. After 10-min of exercise cutaneous vascular conductance increased in all conditions, likely because hand blood flow is influenced to a greater extent by increases in core temperature compared to local cooling. In much the same way heat is transferred from muscle to the blood and surrounding tissues via conduction and convection, similar mechanisms might be attributed to the effectiveness of hand cooling. For example, the site closest to the hands was the forearm at which we assessed skin temperature and skin blood flow. Skin temperature at the forearm was less than the chest, thigh and calf and this might have been influenced by tissue-to-tissue conductive energy transfer, since a temperature gradient existed between the hand and forearm, and according to the 2nd law of thermodynamics, heat would be transferred down a temperature gradient. Thus the forearm might have been cooled via conductance. Another explanation is related to cooler blood flow through the venous circulation, which would have a relatively cooler temperature than adjacent forearm tissues, again heat would be transferred via conduction and convection between these sites. A third explanation is that the cooled blood returned to the central circulation, observed as a lower intestinal temperature compared to the thermoneutral trial, and was distributed to the forearm where we observed a lower temperature than the thermoneutral trial. The contribution from each potential mechanism is unknown. However, a subsequent relative decrease in forearm cutaneous vascular conductance has a cardiovascular advantage. A lower demand skin blood flow would help to maintain perfusion pressure to vital organs, and although we did not assess cardiac dynamics, we did note that $\%HR_{peak}$ was less in hand cooling trials. Yet, despite strong associations between heart rate and rating of perceived exertion reported by others we did not observe any differences between trials for rating of perceived exertion. This might have been caused by the unfamiliar mode of recumbent cycling, however, as presented in chapter 4, there appears to be limited evidence to suggest that recumbent cycling is substantially different to upright cycling in terms of physiological or perceptual responses. Thermal perception, however, which appears to be a key, yet overlooked input in exercise capability was improved by hand cooling. Although not statistically significant we did observe an improvement in exercise capacity as a result of hand cooling. Moreover, we documented the core temperature response of each participant. Such an approach is important because group mean responses can mask meaningful changes at an individual level [285, 286]. In this study we were the first to document that hand cooling during continuous exercise in the heat, using water immersion, can improve body temperature, cardiovascular and perceptual responses. This study advanced knowledge and our understanding of how hand cooling could be used as a strategy to help alleviate heat strain. However, the water-bath model we used in this study is impractical for use during competition; recumbent cycling is an unfamiliar mode of exercise to most individuals and limits external validity of the study; furthermore, because we maintained the water temperature we were unable to quantify the magnitude of heat transfer from each hand. This might have been useful to study how hand surface area, heat transfer and body temperature are related at an individual participant level.

6.12 Effects of cooling gloves on thermoregulatory, cardiovascular and perceptual responses during exercise in a hot environment

We were able to address some of these limitations in chapter 5, and advance the knowledge attained in chapter 4 towards a more practical hand cooling strategy. In the final study we investigated the effects of prototype hand cooling gloves. Seven males cycled at an external mechanical intensity equivalent to their ventilatory threshold for up to 60-min in 35 °C, 50% relative humidity. In one trial they wore a pair of hand cooling gloves and in another, no gloves. The gloves (figure 46) were made from 4 plastic pockets each containing 200 ml of phase change material set to maintain a stable temperature of 10 to 12 °C. Mean glove temperature throughout the trials was 12.8 ± 5.3 °C that decreased mean finger temperature compared to the control trial. This demonstrated that hand cooling was successfully achieved. Indeed, almost all thermophysiological and perceptual responses were improved whilst wearing the hand cooling gloves, the effectiveness of this strategy was probably due to the same mechanisms elucidated in chapter 4. That is, relatively cooler blood returned to the central circulation and mixed with warmer blood originating from metabolically active tissues and alleviated heat strain as observed by a relative decrease in body temperature assessments. In this study we also investigated the local perceptual effects of hand cooling, as allesthesial sensitivity is an important component of thermal perception. Hand cooling improved hand thermal sensation and thermal comfort as well as whole body thermal comfort and thermal sensation. These feelings of improved comfort and sensation combined with thermal and cardiovascular benefits were likely mediators for the improved rating of perceived exertion. Although we did not assess performance, and the exercise trial was limited to 60 min, this has important implications for exercise capability. Hand cooling gloves have the potential to be developed into a practical cooling strategy during exercise in the heat that might have performance benefits. In study 1 we noted that thermal perception and rating of perceived exertion are key inputs in the observed performance improvements due to cooling during exercise. However, none of these practical methods alleviated heat strain. The hand cooling gloves improved thermal perception, rating of perceived exertion and alleviated heat strain during fixed intensity exercise. Future research should build on these findings by assessing performance whilst wearing the gloves, or more logically, refining ergonomics and re-testing a more practical hand cooling glove than those developed within this programme of research. Indeed there are several forms this might take, including a glove combined with a lightweight forearm sweat-wicking fabric containing microencapsulated menthol crystals. The glove might contain phase change material much like that used in chapter 5 to help conductive heat transfer, while a lightweight wicking fabric over the forearm would assist evaporative heat loss and encapsulated menthol would provide a feeling a cooling and improved thermal comfort. These might be combined as one garment or be separable. Moreover, hand cooling might be combined with other strategies identified as practically useful during this programme of research, including neck cooling and ice slurry and cold water ingestion.

6.13 How does cooling during exercise influence intensity of exercise?

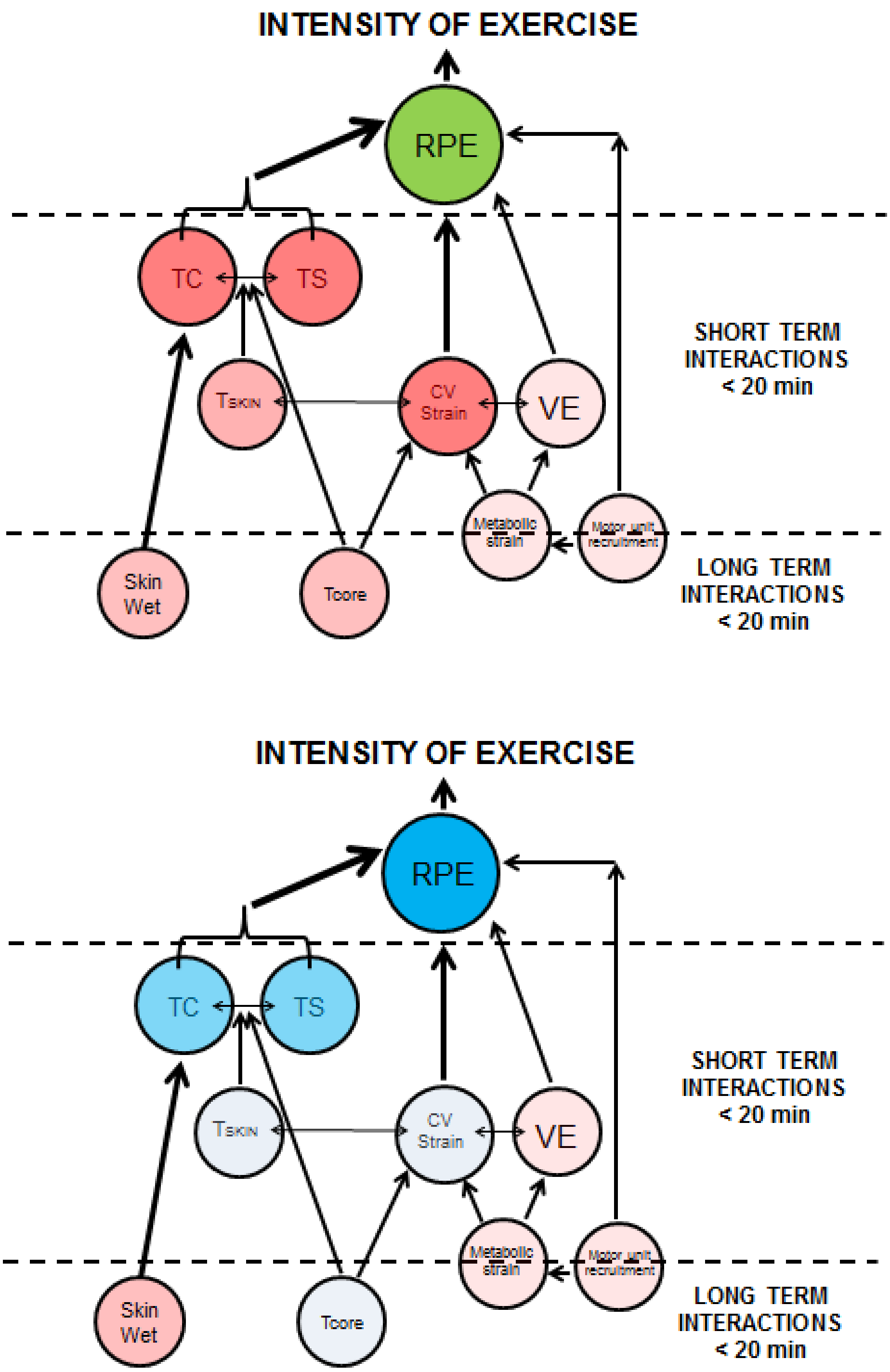

Figure 53: Proposed model of the effects of cooling during exercise on physiological and perceptual interactions that determine exercise capability.

RPE = rating of perceived exertion; TC = Thermal comfort; TS = Thermal sensation; Tskin = skin temperature; CV strain = cardiovascular strain; VE = ventilation; SkinWet = Skin wetedness; Tcore = integrated core body temperature; Metabolic strain = metabolic acidosis; rate of glycolysis; ATP:ADP.

Figure 53 depicts a model of the key physiological and perceptual interactions that are thought to determine intensity of exercise in thermally stressful environments. The primary controller of intensity is thought to be RPE [149], that is the overall integration of various inputs into a perception of immediate or short-term (< 30 s) exertion that determines the ability to continue exercising at the current intensity. During exercise in hot environments the two key inputs directly related to RPE are the rate of increase and/or magnitudes of thermal sensation, thermal comfort and cardiovascular strain [149]. The top panel in figure 53 depicts exercise in a hot environment with no cooling, whereby deeper red and larger circles represent greater inputs into the 'system'. The figure is also split into two sections to differentiate the key drivers for RPE as exercise duration increases. For example, initial predictions regarding intensity of exercise are primarily made based upon skin temperature, thermal comfort and thermal sensation followed by cardiovascular strain and ventilatory rate (breathlessness). Whilst these inputs remain important as exercise continues there is an additional contribution from various sources of body temperature that integrate to determine core body temperature, whilst sweat rate and the ability to evaporate sweat from the skin surface determine skin wettedness with additional inputs from metabolic strain and motor unit recruitment.

Panel 2 of figure 53 relates primarily to findings from studies 1, 3 and 4 of the current programme of research. In chapter 2, we identified that cooling during exercise improved exercise capability mediated via improved thermal perception and rating of perceived exertion, we also found that hand cooling improved thermal perception and RPE in studies 3 and 4 compared to the control trial. In figure 53 these effects are illustrated in blue, indicating that cooling during exercise influences these components. Thermal sensation and thermal comfort are also depicted by larger circles that represent the relative weighting of these inputs to RPE. The 'strength' of the signal is also identified by using a bold arrow, that is, thermal sensation and thermal comfort have a large weighting in the 'calculation' of RPE (as well as being influenced to a large extent by cooling) and the 'strength' of this signal is also large. In contrast, skin wettedness has a small circle/weighting, this is because cooling during exercise does not clearly influence sweat rate as determined in chapter 2 and 4 (but did in chapter 5); however, it is a large contributor to feelings of thermal comfort and therefore has a 'strong' signal input. Cardiovascular strain also has strong signal input towards RPE, but is a lighter coloured blue and has a smaller circle than the two thermal perception assessments because cooling might, as found in chapter 4 and 5, or may not, as found in chapter 2, influence heart rate response during exercise. Depending on the type of strategy used, cooling might (as determined in chapter 4 and 5) or might not influence mean skin temperature which is an important contributor to thermal perception, particularly in the early stages of exercise or later in exercise if a new cooling stimulus is applied whilst body temperature is elevated. Indeed, core body temperature, when elevated has an influence on thermal perceptions and can also influence cardiovascular strain through central (hypothalamic) and local mediated vasodilatory responses as evidenced in section 2. Skin temperature, core temperature and cardiovascular strain are therefore key inputs into the 'system' but at present the evidence base regarding the effects of cooling during exercise on these thermophysiological variables does not support the same level of influence that cooling has on thermal perceptions. Additional factors that are involved in the regulation of exercise intensity are ventilatory rate, metabolic strain and motor unit recruitment. Ventilatory rate, or breathlessness, was one of the first physiological inputs observed by Borg [287] to be a key driver of RPE. Metabolic strain which encompasses general energetic demands and associated metabolic costs including an increased reliance on carbohydrate metabolism mediated by an increased cellular energy state, as well as increased adrenaline secretion, as well as a reliance on type II muscle fibres during prolonged intense exercise would also contribute to metabolic strain [117, 283] all of which have well established effects on cardiovascular strain (see section 2), in particular the delivery of oxygen to locomotor muscles [138]. Finally, motor unit recruitment, either the magnitude of rate coding or the recruitment of high-threshold motor units influences RPE in both the short and long term [140], although there is at present no research that has examined the effects of cooling during exercise on motor unit recruitment.

Chapter 7: Thesis Conclusions

The main aims of this programme of research were to; 1) identify practical cooling strategies during continuous exercise in hot environments; 2) investigate the utility of an intestinal telemetry pill system to assess core temperature in a hot environment and; 3) provide a mechanistic basis for the development of a practical hand cooling strategy designed to be used during exercise in a hot environment to alleviate heat strain. In chapter 3, we sought to examine the body of literature pertaining to practical cooling strategies during continuous exercise in hot environments. The systematic approach to this review of literature had not been undertaken before, and after meta-analysing data obtained from a range of studies in a distinct manner, we were able to identify key factors that contributed to the success of interventions designed to alleviate heat strain. Our analysis demonstrated that thermal perception and rating of perceived exertion were key mediators in performance improvements while there were unclear effects on thermophysiological variables. This has important practical implications for coaches and athletes since we demonstrated that alleviating heat strain does not always have to occur to improve performance. Nevertheless, if a strategy existed that improved thermal perception, rating of perceived exertion and thermophysiological responses then it might prove to be practically meaningful from a performance and safety perspective. In Chapter 4, we were able to advance knowledge by determining the reliability of intestinal temperature during exercise in a hot environment. This had not been fully investigated before, and we were able to recommend how scientists and coaches should focus their practice based on the likelihood of changes in intestinal temperature as a result of an intervention. Moreover, as a result of this data, and continued assessments of reliability throughout the programme of research, we were able to improve the confidence in our interpretations of physiological responses. Hand cooling has been demonstrated to improve exercise capability and alleviate heat strain, but this research has been conducted with a focus on military and occupational operations often using an approach that would be impractical for use during sporting competition. In chapter 4, we used this understanding of previous research to cool the hands during continuous exercise in the heat, an approach that had not been performed previously. The key to this study was the mechanistic focus that enabled the study to be used as a knowledge base for future studies. We found that hand cooling induced favourable thermophysiological and perceptual responses and this knowledge informed the advancement towards a more practical approach to hand cooling which was investigated in chapter 5. In this study, we developed a pair of novel cooling gloves, which were designed to be used during exercise in a hot environment. Using fixed-intensity exercise we examined the thermophysiological responses to heat strain with and without the gloves. Hand cooling improved body temperature, cardiovascular and perceptual responses and mediated a possible improvement in exercise capability. Future research should continue to improve the ergonomics of the hand cooling glove to make it more practical, examine the effects of this glove on performance and investigate the thermophysiological responses and ergogenic potential of a combination of practical cooling strategies during exercise in a hot environment.

References

1. Winter EM, Fowler N (2009) Exercise defined and quantified according to the Systeme International d'Unites. J Sports Sci 27:447–460

2. Peiser B, Reilly T (2004) Environmental factors in the summer Olympics in historical perspective. J Sports Sci 22:981–1001

3. Hargreaves M (2008) Physiological limits to exercise performance in the heat. J Sci Med Sport 11:66–71

4. Guy JH, Deakin GB, Edwards AM, Miller CM, Pyne DB (2015) Adaptation to hot environmental conditions: an exploration of the performance basis, procedures and future directions to optimise opportunities for elite athletes. Sport Med 45:303–311

5. Taylor NAS, Tipton MJ, Kenny GP (2014) Considerations for the measurement of core, skin and mean body temperatures. J Therm Biol 46:72–101

6. Tyler CJ, Sunderland C, Cheung SS (2015) The effect of cooling prior to and during exercise on exercise performance and capacity in the heat: a meta-analysis. Br J Sports Med 49:7–13

7. Bongers CCWG, Thijssen DHJ, Veltmeijer MTW, Hopman MTE, Eijsvogels TMH (2015) Precooling and percooling (cooling during exercise) both improve performance in the heat: a meta-analytical review. Br J Sports Med 49:377–384

8. Ruddock A, Robbins B, Tew G, Bourke L, Purvis A (2017) Practical cooling strategies during continuous exercise in hot environments: a systematic review and meta-analysis. Sport Med 47:517–532

9. Stevens CJ, Taylor L, Dascombe BJ (2017) Cooling during exercise: an overlooked strategy for enhancing endurance performance in the heat. Sport Med 47:829–841

10. Taylor NAS, Machado-Moreira CA, van den Heuvel AMJ, Caldwell JN (2014) Hands and feet: physiological insulators, radiators and evaporators. Eur J Appl Physiol 114:2037–2060

11. Manelli A, Sangiorgi S, Ronga M, Reguzzoni M, Bini A, Raspanti M (2005) Plexiform vascular structures in the human digital dermal layer: a SEM - corrosion casting morphological study. Eur J Morphol 42:173–177

12. Sangiorgi S, Manelli A, Congiu T, Bini A, Pilato G, Reguzzoni M, Raspanti M (2004) Microvascularization of the human digit as studied by corrosion casting. J Anat 204:123–131

13. Grahn DA, Cao VH, Heller HC (2005) Heat extraction through the palm of one hand improves aerobic exercise endurance in a hot environment. J Appl Physiol 99:972–978

14. Hsu AR, Hagobian TA, Jacobs KA, Attallah H, Friedlander AL (2005) Effects of heat removal through the hand on metabolism and performance during cycling exercise in the heat. Can J Appl Physiol 30:87–104

15. Liebenberg L (2013) Persistence hunting by modern hunter-gatherers. Curr Anthropol 47:1017–1026

16. Maslin MA, Brierley CM, Milner AM, Shultz S, Trauth MH, Wilson KE (2014) East african climate pulses and early human evolution. Quat Sci Rev 101:1–17

17. Monika A, Byadgi PS, Dwibedy BK (2017) Importance of ayu pareeksha for the management of diseases. J Clin Diagnostic Res 11:OE01-OE04

18. McArdle W, Katch F, Katch V (2010) Exercise physiology: nutrition,energy and human performance., 7th ed. Lippincott Williams & Wilkins, Baltimore, MD

19. Moran DS, Mendal L (2002) Core temperature measurement: methods and current insights. Sports Med 32:879–885

20. Taylor NAS, Machado-Moreira CA, Sato K, et al (2013) Regional variations in transepidermal water loss, eccrine sweat gland density, sweat secretion rates and electrolyte composition in resting and exercising humans. Extrem Physiol Med 2:4

21. Pearce JMS (2002) A brief history of the clinical thermometer. QJM 95:251–252

22. Royal Society (1975) Quantities, units and symbols: a report. Royal Society, London

23. Mangum BW, Furukawa GT, Kreider KG, et al (2001) The Kelvin and temperature measurements. J Res Natl Inst Stand Technol 106:105–149

24. Atkins P (2010) The laws of thermodynamics: a very short introduction. Oxford University Press, Oxford

25. Health and Safety Executive (2011) Breaking containment - mercury.

26. James CA, Richardson AJ, Watt PW, Maxwell NS (2014) Reliability and validity of skin temperature measurement by telemetry thermistors and a thermal camera during exercise in the heat. J Therm Biol 45:141–149

27. Ng EYK, Kawb GJL, Chang WM (2004) Analysis of IR thermal imager for mass blind fever screening. Microvasc Res 68:104–109

28. Ring EFJ, Ammer K (2012) Infrared thermal imaging in medicine. Physiol Meas 33:R33–R46

29. Buono MJ, Jechort A, Marques R, Smith C, Welch J (2007) Comparison of infrared versus contact thermometry for measuring skin temperature during exercise in the heat. Physiol Meas 28:855–859

30. Kenny GP, Jay O (2013) Thermometry, calorimetry, and mean body temperature during heat stress. Compr Physiol 3:1689–1719

31. Todd G, Gordon CJ, Groeller H, Taylor NAS (2014) Does intramuscular thermal feedback modulate eccrine sweating in exercising humans? Acta Physiol 212:86–96

32. Casa DJ, Becker SM, Ganio MS, et al (2007) Validity of devices that assess body temperature during outdoor exercise in the heat. J Athl Train 42:333–342

33. Ganio MS, Brown CM, Casa DJ, Becker SM, Yeargin SW, McDermott BP, Boots LM, Boyd PW, Armstrong LE, Maresh CM (2009) Validity and reliability of devices that assess body temperature during indoor exercise in the heat. J Athl Train 44:124–35

34. Shiraki K, Konda N, Sagawa S (1986) Esophageal and tympanic temperature responses to core blood temperature changes during hyperthermia. J Appl Physiol 61:98–102

35. Nybo L, Secher NH, Nielsen B (2002) Inadequate heat release from the human brain

during prolonged exercise with hyperthermia. J Physiol 545:697–704

36. Shibasaki M, Kondo N, Tominaga H, Aoki K, Hasegawa E, Idota Y, Moriwaki T (1998) Continuous measurement of tympanic temperature with a new infrared method using an optical fiber. J Appl Physiol 85:921–926

37. Byrne C, Lim CL (2007) The ingestible telemetric body core temperature sensor: a review of validity and exercise applications. Br J Sports Med 41:126–133

38. Goodman D a, Kenefick RW, Cadarette BS, Cheuvront SN (2009) Influence of sensor ingestion timing on consistency of temperature measures. Med Sci Sports Exerc 41:597–602

39. Wilkinson DM, Carter JM, Richmond VL, Blacker SD, Rayson MP (2008) The effect of cool water ingestion on gastrointestinal pill temperature. Med Sci Sports Exerc 40:523–528

40. Kvietys PR (2010) The Gastrointestinal circulation. Morgan & Claypool Life Sciences

41. Perko MJ, Nielsen HB, Skak C, Clemmesen JO, Schroeder T V, Secher NH (1998) Mesenteric, coeliac and splanchnic blood flow in humans during exercise. J Physiol 513 (Pt 3):907–13

42. Wang Z, Ying Z, Bosy-Westphal A, Zhang J, Schautz B, Later W, Heymsfield SB, Müller MJ (2010) Specific metabolic rates of major organs and tissues across adulthood: evaluation by mechanistic model of resting energy expenditure. Am J Clin Nutr 92:1369–77

43. Harper D (2017) Validity. In: Online Etymology Dict. http://www.etymonline.com/. Accessed 25 May 2017

44. Atkinson G, Nevill AM (1998) Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. Sport Med 26:217–238

45. Harper D (2017) Precision. In: Online Etymology Dict. http://www.etymonline.com. Accessed 25 May 2017

46. Harper D (2017) Religate. In: Online Etymology Dict. http://www.etymonline.com. Accessed 25 May 2017

47. Harper D (2017) Reproduce. In: Online Etymology Dict. http://www.etymonline.com. Accessed 25 May 2017

48. Harper D (2017) Agree. In: Online Etymology Dict. http://www.etymonline.com. Accessed 25 May 2017

49. Harper D (2017) Sensitive. In: Online Etymology Dict. http://www.etymonline.com. Accessed 25 May 2017

50. Currell K, Jeukendrup AE (2008) Validity, reliability and sensitivity of measures of sporting performance. Sports Med 38:297–316

51. Harper D (2017) Accurate. In: Online Etymology Dict. http://www.etymonline.com. Accessed 25 May 2017

52. Thomas JR, Nelson JK, Silverman S (2015) Research Methods in Physical Activity, 4th ed. Human Kinetics, Champaign, IL

53. Bland JM, Altman DG (1986) Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1:307–310

54. Atkinson G, Davison RCR, Nevill AM (2005) Performance characteristics of gas analysis systems: what we know and what we need to know. Int J Sports Med 26 Suppl 1:S2-10

55. Cohen J (1988) Statistical power analysis for the behavioral sciences, 2nd ed. Lawrence Erlbaum Associates, Mahwah, NJ

56. Lakens D (2013) Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. Front Psychol 4:1–12

57. Hopkins WG, Marshall SW, Batterham AM, Hanin J (2009) Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc 41:3–13

58. Hopkins WG (2000) Measures of reliability in sports medicine and science. Sports Med 30:1–15

59. Cumming G (2014) The new statistics: why and how. Psychol Sci 25:7–29

60. Zaki R, Bulgiba A, Ismail R, Ismail NA (2012) Statistical methods used to test for agreement of medical instruments measuring continuous variables in method comparison studies: A systematic review. PLoS One 7:e37908

61. Hopkins WG (2003) A spreadsheet for analysis of straightforward controlled trials. Sportscience. doi: 10.1119/1.14219

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

63. Mee JA, Doust J, Maxwell NS (2015) Repeatability of a running heat tolerance test. J Therm Biol 49:91–97

64. Willmott AGB, Hayes M, Dekerle J, Maxwell NS (2015) The reliability of a heat acclimation state test prescribed from metabolic heat production intensities. J Therm Biol 53:38–45

65. Gisolfi C V, Wenger CB (1984) Temperature regulation during exercise: old concepts, new ideas. Exerc Sport Sci Rev 12:339–372

66. Marino FE (2008) The Evolutionary Basis of Thermoregulation and Exercise Performance. In: Thermoregul. Hum. Perform. Karger, Basel, pp 1–13

67. Parsons K (2014) Human thermal environments: The effects of hot, moderate, and cold environments on human health, comfort, and performance., 3rd ed. CRC Press, Boca Raton, FL

68. Werner J, Mekjavic IB, Taylor NAS (2008) Concepts in physiological regulation: a thermoregulatory perspective. In: Physiol. Bases Hum. Perform. Dur. Work Exerc., 1st ed. Elselvier, Edinburgh, pp 325–340

69. Sawka MN, Leon LR, Montain SJ, Sonna LA (2011) Integrated physiological mechanisms of exercise performance, adaptation, and maladaptation to heat stress. Compr Physiol 1:1883–1928

70. Boulant JA (2006) Neuronal basis of Hammel's model for set-point thermoregulation. J

Appl Physiol 100:1347–1354

71. Boulant JA (1998) Hypothalamic neurons. mechanisms of sensitivity to temperature. Ann N Y Acad Sci 856:108–115

72. Boulant JA (2000) Role of the preoptic-anterior hypothalamus in thermoregulation and fever. Clin Infect Dis 31:S157–S161

73. Romanovsky A (2007) Thermoregulation: some concepts have changed. Functional architecture of the thermoregulatory system. Am J Physiol Regul Integr Comp Physiol 292:R37–R46

74. Romanovsky A (2014) Skin temperature: its role in thermoregulation. Acta Physiol 210:498–507

75. Johnson JM (2010) Exercise in a hot environment: the skin circulation. Scand J Med Sci Sports 20:29–39

76. Schlader ZJ, Stannard SR, Mündel T (2010) Human thermoregulatory behavior during rest and exercise - a prospective review. Physiol Behav 99:269–275

77. Schlader ZJ, Prange HD, Mickleborough TD, Stager JM (2009) Characteristics of the control of human thermoregulatory behavior. Physiol Behav 98:557–562

78. Fukazawa T, Havenith G (2009) Differences in comfort perception in relation to local and whole body skin wettedness. Eur J Appl Physiol 106:15–24

79. Hensel H (1981) Thermoreception and temperature regulation. Academic Press, Ann Arbor, MI

80. Gagge AP, Stolwijk JA, Hardy J (1967) Comfort and thermal sensations and associated physiological responses at various ambient temperatures. Environ Res 1:1–20

81. Nakamura M, Yoda T, Crawshaw LI, Kasuga M, Uchida Y, Tokizawa K, Nagashima K, Kanosue K (2013) Relative importance of different surface regions for thermal comfort in humans. Eur J Appl Physiol 113:63–76

82. Winter EM, Abt G, Brookes FBC, et al (2016) Misuse of "power" and other mechanical terms in sport and exercise science research. J Strength Cond Res 30:292–300

83. Kenny GP, Webb P, Ducharme MB, Reardon FD, Jay O (2008) Calorimetric measurement of postexercise net heat loss and residual body heat storage. Med Sci Sports Exerc 40:1629–1636

84. Brotherhood JR (2008) Heat stress and strain in exercise and sport. J Sci Med Sport 11:6–19

85. Gagnon D, Jay O, Kenny GP (2013) The evaporative requirement for heat balance determines whole-body sweat rate during exercise under conditions permitting full evaporation. J Physiol 591:2925–2935

86. Marino FE, Mbambo Z, Kortekaas E, Wilson G, Lambert MI, Noakes TD, Dennis SC (2000) Advantages of smaller body mass during distance running in warm, humid environments. Pflügers Arch Eur J Physiol 441:359–367

87. Cheung SS, McLellan TM, Tenaglia S (2000) The thermophysiology of uncompensable heat stress. physiological manipulations and individual characteristics. Sport Med 29:329–359

88. González-Alonso J (2012) Human thermoregulation and the cardiovascular system. Exp Physiol 97:340–346

89. Hellsten Y, Nyberg M, Jensen LG, Mortensen SP (2012) Vasodilator interactions in skeletal muscle blood flow regulation. J Physiol 24:6297–6305

90. Joyner MJ, Casey DP (2015) Regulation of increased blood flow (hyperemia) to muscles during exercise: a hierarchy of competing physiological needs. Physiol Rev 95:549–601

91. González-Alonso J, Crandall CG, Johnson JM (2008) The cardiovascular challenge of exercising in the heat. J Physiol 586:45–53

92. Ekblom B, Hermansen L (2013) Cardiac output in athletes. J Appl Physiol 25:619–625

93. Taylor NAS (2014) Human heat adaptation. Compr Physiol 4:325–365

94. Rowell LB (1974) Human cardiovascular adjustments to exercise and thermal-stress. Physiol Rev 54:75–159

95. Johnson JM, Minson CT, Kellogg DL (2014) Cutaneous vasodilator and vasoconstrictor mechanisms in temperature regulation. Compr Physiol 4:33–89

96. Shibasaki M, Secher NH, Johnson JM, Crandall CG (2005) Central command and the cutaneous vascular response to isometric exercise in heated humans. J Physiol 565:667–673

97. Roddie IC (2003) Classical perspectives: Sympathetic vasodilation in human skin. J Physiol 548:336–337

98. Johnson JM, Minson CT, Kellogg DL (2015) Human cardiovascular responses to passive heat stress. Compr Physiol 5:17–43

99. Flouris AD, Cheung SS (2009) Influence of thermal balance on cold-induced vasodilation. J Appl Physiol 106:1264–1271

100. Flouris AD, Westwood DA, Mekjavic IB, Cheung SS (2008) Effect of body temperature on cold induced vasodilation. Eur J Appl Physiol 104:491–499

101. Johnson JM, Park MK (1982) Effect of heat stress on cutaneous vascular responses to the initiation of exercise. J Appl Physiol 53:744–749

102. Johnson JM (1992) Exercise and the cutaneous circulation. Exerc Sport Sci Rev 20:59–97

103. Benzinger TH (1959) On physical heat regulation and the sense of temperature in man. Proc Natl Acad Sci U S A 45:645–659

104. Shibasaki M, Wilson TE, Crandall CG (2006) Neural control and mechanisms of eccrine sweating during heat stress and exercise. J Appl Physiol 100:1692–1701

105. Gray H (1918) Fig. 940. In: Anat. Hum. Body. http://www.bartleby.com/107/illus940.html. Accessed 1 Aug 2017

106. Quinton PM (2007) Cystic Fibrosis: lessons from the sweat gland. Physiology 22:212–225

107. Webb P (1992) Temperatures of skin, subcutaneous tissue, muscle and core in resting men in cold, comfortable and hot conditions. Eur J Appl Physiol 64:471–476

108. González-Alonso J, Teller C, Andersen SL, Jensen FB, Hyldig T, Nielsen B (1999) Influence of body temperature on the development of fatigue during prolonged exercise in the heat. J Appl Physiol 86:1032–1039

109. Pearson J, Low D, Stöhr E (2011) Hemodynamic responses to heat stress in the resting and exercising human leg: insight into the effect of temperature on skeletal muscle blood flow. Am J Physiol Regul Integr Comp Physiol 300:R663–R673

110. Chiesa ST, Trangmar SJ, Kalsi KK, Rakobowchuk M, Banker DS, Lotlikar MD, Ali L, González-Alonso J (2015) Local temperature-sensitive mechanisms are important mediators of limb tissue hyperemia in the heat-stressed human at rest and during small muscle mass exercise. Am J Physiol Hear Circ Physiol 309:H369–H380

111. Kenefick RW, Cheuvront SN, Sawka MN (2007) Thermoregulatory function during the marathon. Sport Med 37:312–315

112. Wingo JE, Low DA, Keller DM, Brothers RM, Shibasaki M, Crandall CG (2010) Skin blood flow and local temperature independently modify sweat rate during passive heat stress in humans. J Appl Physiol 109:1301–1306

113. Smith CJ, Havenith G (2011) Body mapping of sweating patterns in male athletes in mild exercise-induced hyperthermia. Eur J Appl Physiol 111:1391–1404

114. Sawka MN, Burke LM, Eichner ER, Maughan RJ, Montain SJ, Stachenfeld NS (2007) American College of Sports Medicine position stand. Exercise and fluid replacement. Med Sci Sports Exerc 39:377–390

115. Galloway SDR, Maughan RJ (1997) Effects of ambient temperature on the capacity to perform prolonged cycle exercise in man. Med Sci Sports Exerc 29:1240–1249

116. Starkie RL, Hargreaves M, Lambert DL, Proietto J, Febbraio MA (1999) Effect of temperature on muscle metabolism during submaximal exercise in humans. Exp Physiol 84:775–784

117. Febbraio MA (2001) Alterations in energy metabolism during exercise and heat stress. Sport Med 31:47–59

118. González-Alonso J, Calbet JA (2003) Reductions in systemic and skeletal muscle blood flow and oxygen delivery limit maximal aerobic capacity in humans. Circulation 107:824–830

119. Dill DB, Edwards HT, Bauer PS, Levenson EJ (1931) Physical performance in relation to external temperature. Arbeitsphysiologie 4:508–518

120. Nielsen BYB, Hales JRS, Strange S, Juel N (1993) Thermoregulatory adaptations. J Physiol 460:467–485

121. Tatterson AJ, Hahn AG, Martin DT, Febbraio MA (2000) Effect of heat stress on physiological responses and exercise performance in elite cyclists. J Sci Med Sport 3:186–193

122. Tucker R, Rauch L, Harley YXR, Noakes TD (2004) Impaired exercise performance in the heat is associated with an anticipatory reduction in skeletal muscle recruitment. Pflugers Arch 448:422–30

123. Ely MR, Cheuvront SN, Roberts WO, Montain SJ (2007) Impact of weather on marathon-running performance. Med Sci Sports Exerc 39:487–493

124. Nielsen B, Strange S, Christensen NJ, Warberg J, Saltin B (1997) Acute and adaptive responses in humans to exercise in a warm, humid environment. Pflugers Arch Eur J Physiol Arch Eur J Physiol 434:49–56

125. Thomas MM, Cheung SS, Elder GC, Sleivert GG (2006) Voluntary muscle activation is impaired by core temperature rather than local muscle temperature. J Appl Physiol 100:1361–1369

126. Racinais S, Oksa J (2010) Temperature and neuromuscular function. Scand J Med Sci Sports 20:1–18

127. Cheung SS (2007) Hyperthermia and voluntary exhaustion: integrating models and future challenges. Appl Physiol Nutr Metab 32:808–817

128. Nybo L, Nielsen B (2001) Hyperthermia and central fatigue during prolonged exercise in humans Hyperthermia and central fatigue during prolonged exercise in humans. J Appl Physiol 91:1055–1060

129. Morrison S, Sleivert GC, Cheung SS (2004) Passive hyperthermia reduces voluntary activation and isometric force production. Eur J Appl Physiol 91:729–736

130. Nybo L, Nielsen B (2001) Middle cerebral artery blood velocity is reduced with hyperthermia during prolonged exercise in humans. J Physiol 534:279–286

131. Nybo L, González-Alonso J (2015) Critical core temperature: a hypothesis too simplistic to explain hyperthermia-induced fatigue. Scand J Med Sci Sports 25:4–5

132. Racinais S, Périard JD, Karlsen A, Nybo L (2015) Effect of heat and heat acclimatization on cycling time trial performance and pacing. Med Sci Sports Exerc 47:601–606

133. Watson P, Hasegawa H, Roelands B, Piacentini MF, Looverie R, Meeusen R (2005) Acute dopamine/noradrenaline reuptake inhibition enhances human exercise performance in warm, but not temperate conditions. J Physiol 565:873–883

134. Cheuvront SN, Kenefick RW, Montain SJ, Sawka MN (2010) Mechanisms of aerobic performance impairment with heat stress and dehydration. J Appl Physiol 109:1989–1995

135. Wingo JE, Lafrenz AJ, Ganio MS, Edwards GL, Cureton KJ (2005) Cardiovascular drift is related to reduced maximal oxygen uptake during heat stress. Med Sci Sports Exerc 37:248–255

136. Lorenzo S, Halliwill JR, Sawka MN, Minson CT (2010) Heat acclimation improves exercise performance. J Appl Physiol 109:1140–1147

137. Nybo L, Jensen T, Nielsen B, González-Alonso J (2001) Effects of marked hyperthermia with and without dehydration on VO2 kinetics during intense exercise. J Appl Physiol 90:1057–1064

138. Périard JD, Cramer MN, Chapman PG, Caillaud C, Thompson MW (2011) Cardiovascular strain impairs prolonged self-paced exercise in the heat. Exp Physiol 96:134–144

139. Périard JD, Caillaud C, Thompson MW (2012) The role of aerobic fitness and exercise intensity on endurance performance in uncompensable heat stress conditions. Eur J Appl Physiol 112:1989–1899

140. Marcora SM (2008) Do we really need a central governor to explain brain regulation of

exercise performance? Eur J Appl Physiol 104:929–931

141. Marcora SM, Staiano W (2010) The limit to exercise tolerance in humans: Mind over muscle? Eur J Appl Physiol 109:763–770

142. Pageaux B, Marcora SM, Rozand V, Lepers R (2015) Mental fatigue induced by prolonged self-regulation does not exacerbate central fatigue during subsequent whole-body endurance exercise. Front Hum Neurosci 9:1–12

143. Noakes TD, Peltonen JE, Rusko HK (2001) Evidence that a central governor regulates exercise performance during acute hypoxia and hyperoxia. J Exp Biol 204:3225–3234

144. Noakes TD (2012) Fatigue is a brain-derived emotion that regulates the exercise behavior to ensure the protection of whole body homeostasis. Front Physiol 3:1–13

145. Noakes TD (2000) Physiological models to understand exercise fatigue and the adaptations that predict or enhance athletic performance. Scand J Med Sci Sport 10:123–145

146. Tucker R (2009) The anticipatory regulation of performance: the physiological basis for pacing strategies and the development of a perception-based model for exercise performance. Br J Sports Med 43:392–400

147. Amann M (2011) Central and peripheral fatigue: interaction during cycling exercise in humans. Med Sci Sports Exerc 43:2039–2045

148. Schlader ZJ, Simmons SE, Stannard SR, Mündel T (2011) The independent roles of temperature and thermal perception in the control of human thermoregulatory behavior. Physiol Behav 103:217–224

149. Flouris AD, Schlader ZJ (2015) Human behavioral thermoregulation during exercise in the heat. Scand J Med Sci Sports 25:52–64

150. Casa DJ, Mcdermott BP, Lee EC, Yeargin SW, Armstrong LF, Maresh CM (2007) Cold water immersion: the gold standard for exertional heatstroke treatment. Exerc Sport Sci Rev 35:141–149

151. Wegmann M, Faude O, Poppendieck W, Hecksteden A, Fröhlich M, Meyer T (2012) Pre-cooling and sports performance: a meta-analytical review. Sports Med 42:545–564

152. Cotter JD, Sleivert GG, Roberts WS, Febbraio MA (2001) Effect of pre-cooling, with and without thigh cooling, on strain and endurance exercise performance in the heat. Comp Biochem Physiol - Mol Integr Physiol 128:667–677

153. Duffield R, Green R, Castle P, Maxwell N (2010) Precooling can prevent the reduction of self-paced exercise intensity in the heat. Med Sci Sports Exerc 42:577–584

154. Siegel R, Laursen PB (2012) Keeping your cool. Possible mechanisms for enhanced exercise performance in the heat with internal cooling methods. Sport Med 42:89–98

155. Burdon C, O’connor H, Gifford J, Shirreffs S, Chapman P, Johnson N (2010) Effect of drink temperature on core temperature and endurance cycling performance in warm, humid conditions. J Sports Sci 28:1147–1156

156. Duffield R, Steinbacher G, Fairchild T (2009) The use of mixed-method, part-body pre-cooling procedures for team-sport athletes training in the heat. J Strength Cond Res 23:2524–2532

157. Kay D, Taaffe DR, Marino FE (1999) Whole-body pre-cooling and heat storage during self-paced cycling performance in warm humid conditions. J Sports Sci 17:937–944

158. Poppendieck W, Faude O, Wegmann M, Meyer T (2013) Cooling and performance recovery of trained athletes: A meta-analytical review. Int J Sports Physiol Perform 8:227–242

159. Jones PR, Barton C, Morrissey D, Maffulli N, Hemmings S (2012) Pre-cooling for endurance exercise performance in the heat: a systematic review. BMC Med 10:166

160. Booth JD, Wilsmore BR, MacDonald AD, Zeyl A, Storlien LH, Taylor NAS (2004) Intramuscular temperatures during exercise in the heat following pre-cooling and pre-heating. J Therm Biol 29:709–715

161. James CA, Richardson AJ, Watt PW, Gibson OR, Maxwell NS (2015) Physiological responses to incremental exercise in the heat following internal and external precooling. Scand J Med Sci Sports 25:190–199

162. Hasegawa H, Takatori T, Komura T, Yamasaki M (2006) Combined effects of pre-cooling and water ingestion on thermoregulation and physical capacity during exercise in a hot environment. J Sports Sci 24:3–9

163. Lee JKW, Shirreffs SM, Maughan RJ (2008) Cold drink ingestion improves exercise endurance capacity in the heat. Med Sci Sport Exerc 40:1637–1644

164. Schulze E, Daanen H, Levels K, Casadio JR, Kilding AE, Siegel R, Laursen PB (2015) Effect of thermal state and thermal comfort on cycling performance in the heat. Int J Sports Physiol Perform 10:655–663

165. Riera F, Trong T, Rinaldi K, Hue O (2016) Precooling does not enhance the effect on performance of midcooling with ice-slush/menthol. Int J Sports Med 37:1025–1031

166. Tyler CJ, Sunderland C (2011) Neck cooling and running performance in the heat: single versus repeated application. Med Sci Sports Exerc 2388–2395

167. Tyler CJ, Wild P, Sunderland C (2010) Practical neck cooling and time-trial running performance in a hot environment. Eur J Appl Physiol 110:1063–1074

168. Tyler CJ, Sunderland C (2011) Cooling the neck region during exercise in the heat. J Athl Train 46:61–68

169. Kenny GP, Schissler AR, Stapleton J, Piamonte M, Binder K, Lynn A, Lan CQ, Hardcastle SG (2011) Ice cooling vest on tolerance for exercise under uncompensable heat stress. J Occup Environ Hyg 8:484–491

170. Luomala MJ, Oksa J, Salmi JA, Linnamo V, Holmér I, Smolander J, Dugué B (2012) Adding a cooling vest during cycling improves performance in warm and humid conditions. J Therm Biol 37:47–55

171. Eijsvogels T, Bongers C, Veltmeijer M, Moen M, Hopman M (2014) Cooling during exercise in temperate conditions: impact on performance and thermoregulation. Int J Sports Med 35:840–846

172. Hostler D, Reis SE, Bednez JC, Kerin S, Suyama J (2010) Comparison of active cooling devices with passive cooling for rehabilitation of firefighters performing exercise in thermal protective clothing: a report from the Fireground Rehab Evaluation (FIRE) trial. Prehosp Emerg Care 14:300–309

173. Song W, Wang F (2016) The hybrid personal cooling system (PCS) could effectively reduce the heat strain while exercising in a hot and moderate humid environment. Ergonomics 59:1009–1018

174. Bomalaski SH, Chen YT, Constable SH (1995) Continuous and intermittent personal microclimate cooling strategies. Aviat Space Environ Med 66:745–750

175. Caldwell JN, Patterson MJ, Taylor NAS (2012) Exertional thermal strain, protective clothing and auxiliary cooling in dry heat: evidence for physiological but not cognitive impairment. Eur J Appl Physiol 112:3597–3606

176. Glitz KJ, Seibel U, Rohde U, Gorges W, Witzki A, Piekarski C, Leyk D (2015) Reducing heat stress under thermal insulation in protective clothing: microclimate cooling by a “physiological” method. Ergonomics 58:1461–1469

177. Vernieuw CR, Stephenson LA, Kolka MA (2007) Thermal comfort and sensation in men wearing a cooling system controlled by skin temperature. Hum Factors 49:1033–1044

178. Davey SL, Barwood MJ, Tipton MJ (2013) Thermal perceptions and skin temperatures during continuous and intermittent ventilation of the torso throughout and after exercise in the heat. Eur J Appl Physiol 113:2723–2735

179. Teunissen LPJ, Wang L-C, Chou S-N, Huang C, Jou G-T, Daanen HAM (2014) Evaluation of two cooling systems under a firefighter coverall. Appl Ergon 45:1433–1438

180. Chinevere TD, Cadarette BS, Goodman DA, Ely BR, Cheuvront SN, Sawka MN (2008) Efficacy of body ventilation system for reducing strain in warm and hot climates. Eur J Appl Physiol 103:307–314

181. Bain B, Vallerand AL (1992) Limb blood flow while wearing aircrew chemical defense ensembles in the heat with and without auxiliary cooling. Aviat Space Environ Med 63:267–272

182. Kim J-H, Coca A, Williams WJ, Roberge RJ (2011) Effects of liquid cooling garments on recovery and performance time in individuals performing strenuous work wearing a firefighter ensemble. J Occup Environ Hyg 8:409–416

183. Walker T, Zupan M, McGreggor J, Cantwell A, Norris T (2009) Is performance of intermittent intense exercise enhanced by use of a commercial palm cooling device? J Strength Cond Res 23:2666–2672

184. Riggs CE, Johnson DJ, Konopka BJ, Kilgour RD (1981) Exercise heart rate response to facial cooling. Eur J Appl Physiol Occup Physiol 47:323–330

185. Greenleaf JE, Van Beaumont W, Brock PJ, Montgomery LD, Morse JT, Shvartz E, Kravik S (1980) Fluid-electrolyte shifts and thermoregulation: rest and work in heat with head cooling. Aviat Space Environ Med 51:747–753

186. Watanuki S (1993) Effects of head cooling on cardiovascular and body temperature responses during submaximal exercise. Ann Physiol Anthropol 12:327–333

187. Ansley L, Marvin G, Sharma A, Kendall MJ, Jones DA, Bridge MW (2008) The effects of head cooling on endurance and neuroendocrine responses to exercise in warm conditions. Physiol Res 57:863–872

188. Quirion A, Boisvert P, Brisson GR, DeCarufel D, Laurencelle L, Dulac S, Vogelaere P, Therminarias A (1989) Effects of selective cooling of the facial area on physiological

and metabolic output during graded maximal or prolonged submaximal exercise. Int J Biometeorol 33:82–84

189. Armada-da-Silva PAS, Woods J, Jones DA (2004) The effect of passive heating and face cooling on perceived exertion during exercise in the heat. Eur J Appl Physiol 91:563–571

190. Brisson GR, Boisvert P, Péronnet F, Quirion A, Senécal L (1989) Face cooling-induced reduction of plasma prolactin response to exercise as part of an integrated response to thermal stress. Eur J Appl Physiol Occup Physiol 58:816–820

191. Wingo JE, Cureton KJ (2006) Body cooling attenuates the decrease in maximal oxygen uptake associated with cardiovascular drift during heat stress. Eur J Appl Physiol 98:97–104

192. Mündel T, King J, Collacott E, Jones DA (2006) Drink temperature influences fluid intake and endurance capacity in men during exercise in a hot, dry environment. Exp Physiol 91:925–933

193. Gisolfi C V, Copping JR (1974) Thermal effects of prolonged treadmill exercise in the heat. Med Sci Sports 6:108–113

194. Heled Y, Epstein Y, Moran DS (2004) Heat strain attenuation while wearing NBC clothing: dry-ice vest compared to water spray. Aviat Space Environ Med 75:391–396

195. Barwood MJ, Corbett J, Thomas K, Twentyman P (2015) Relieving thermal discomfort: Effects of sprayed L-menthol on perception, performance, and time trial cycling in the heat. Scand J Med Sci Sports 25:211–218

196. Stevens CJ, Best R (2016) Menthol: a fresh ergogenic aid for athletic performance. Sport Med 47:1–8

197. Barwood MJ, Corbett J, White DK (2014) Spraying with 0.20% L-menthol does not enhance 5 km running performance in the heat in untrained runners. J Sports Med Phys Fitness 54:595–604

198. Barwood MJM, Corbett J, White D, James J (2012) Early change in thermal perception is not a driver of anticipatory exercise pacing in the heat. Br J Sports Med 46:936–942

199. Lovejoy CO, Simpson SW, White TD, Asfaw B, Suwa G (2009) Careful Climbing in the Miocene: The Forelimbs of Ardipithecus ramidus and Humans Are Primitive. Science (80-) 326:70e1-70e8

200. Boulant JA, Hardy JD (1974) The effect of spinal and skin temperatures on the firing rate and thermosensitivity of preoptic neurones. J Physiol 240:639–660

201. Gray H (1918) Fig. 815. In: Anat. Hum. Body. http://www.bartleby.com/107/illus815.html. Accessed 1 Aug 2017

202. Daanen HAM (2003) Finger cold-induced vasodilation: a review. Eur J Appl Physiol 89:411–426

203. Flouris AD, Cheung SS (2010) On the origins of cold-induced vasodilation. Eur J Appl Physiol 108:1281–1282

204. Jessen C (2010) Interaction of Body Temperatures in Control of Thermoregulatory Effector Mechanisms. Compr Physiol. doi: 10.1002/cphy.cp040107

205. Caldwell JN, Matsuda-Nakamura M, Taylor NAS (2014) Three-dimensional interactions of mean body and local skin temperatures in the control of hand and foot blood flows. Eur J Appl Physiol 114:1679–1689

206. Taylor NAS (2015) Overwhelming physiological regulation through personal protection. J Strength Cond Res 29:S111–S118

207. Goosey-Tolfrey V, Swainson M, Boyd C, Atkinson G, Tolfrey K (2008) The effectiveness of hand cooling at reducing exercise-induced hyperthermia and improving distance-race performance in wheelchair and able-bodied athletes. J Appl Physiol 105:37–43

208. Scheadler CM, Saunders NW, Hanson NJ, Devor ST (2013) Palm Cooling Does not Improve Running Performance. Int J Sports Med 34:732–735

209. Selkirk GA, McLellan TM, Wong J (2004) Active versus passive cooling during work in warm environments while wearing firefighting protective clothing. J Occup Environ Hyg 1:521–531

210. Barwood MJ, Davey S, House JR, Tipton MJ (2009) Post-exercise cooling techniques in hot, humid conditions. Eur J Appl Physiol 107:385–396

211. Price M, Thake D, O'Doherty A (2007) Effects of hand cooling on intermittent exercise performance in the heat. Environ Ergon Proc 12th Int Conf Environ Ergon 389–392

212. Barr D, Reilly T, Gregson W (2011) The impact of different cooling modalities on the physiological responses in firefighters during strenuous work performed in high environmental temperatures. Eur J Appl Physiol 111:959–967

213. Giesbrecht GG, Jamieson C, Cahill F (2007) Cooling hyperthermic firefighters by immersing forearms and hands in 10°c and 20°c water. Aviat Sp Environ Med 78:561–567

214. Khomenok GA, Hadid A, Preiss-Bloom O, Yanovich R, Erlich T, Ron-Tal O, Peled A, Epstein Y, Moran DS (2008) Hand immersion in cold water alleviating physiological strain and increasing tolerance to uncompensable heat stress. Eur J Appl Physiol 104:303–309

215. Allsopp AJ, Poole KA (1991) The effect of hand immersion on body temperature when wearing impermeable clothing. J R Nav Med Serv 77:41–47

216. House and J.A.S.Groom JR (1998) The alleviation of heat strain using water-perfused forearm cuffs. Environ Med 255–258

217. Savage RJ, Lord C, Larsen BL, Knight TL, Langridge PD, Aisbett B (2014) Firefighter feedback during active cooling: A useful tool for heat stress management? J Therm Biol 46:66–71

218. House JR, Holmes C, Allsopp AJ (1997) Prevention of heat strain by immersing the hands and forearms in water. J R Nav Med Serv 83:26–30

219. Amorim FT, Yamada PM, Robergs RA, Schneider SM (2010) Palm cooling does not reduce heat strain during exercise in a hot, dry environment. Appl Physiol Nutr Metab 35:480–489

220. Kuennen MR, Gillum TL, Amorim FT, Kwon YS, Schneider SM (2010) Palm cooling to reduce heat strain in subjects during simulated armoured vehicle transport. Eur J Appl Physiol 108:1217–23

221. Grahn DA, Dillon JL, Heller HC (2009) Heat loss through the glabrous skin surfaces of heavily insulated, heat-stressed individuals. J Biomech Eng 131:71005-1-71005–7

222. Zhang Y, Bishop P a, Casaru C, Davis JK (2009) A new hand-cooling device to enhance firefighter heat strain recovery. J Occup Environ Hyg 6:283–288

223. Casa DJ, DeMartini JK, Bergeron MF, et al (2015) National Athletic Trainers' Association Position Statement: Exertional Heat Illnesses. J Athl Train 50:986–1000

224. Parkin JM, Carey MF, Zhao S, Febbraio MA (1999) Effect of ambient temperature on human skeletal muscle metabolism during fatiguing submaximal exercise. J Appl Physiol 86:902–908

225. Ely BR, Cheuvront SN, Kenefick RW, Sawka MN (2010) Aerobic performance is degraded, despite modest hyperthermia, in hot environments. Med Sci Sports Exerc 42:135–141

226. Levels K, de Koning J, Broekhuijzen I, Zwaan T, Foster C, Daanen H (2014) Effects of radiant heat exposure on pacing pattern during a 15-km cycling time trial. J Sports Sci 32:845–852

227. Schlader ZJ, Perry BG, Jusoh MRC, Hodges LD, Stannard SR, Mündel T (2013) Human temperature regulation when given the opportunity to behave. Eur J Appl Physiol 113:1291–1301

228. Morante SM, Brotherhood JR (2008) Thermoregulatory responses during competitive singles tennis. Br J Sports Med 42:736–741

229. DeGroot DW, Gallimore RP, Thompson SM, Kenefick RW (2013) Extremity cooling for heat stress mitigation in military and occupational settings. J Therm Biol 38:305–310

230. Seals DR (2013) Translational physiology: from molecules to public health. J Physiol 591:3457–3469

231. Liberati A, Altman DG, Tetzlaff J, Mulrow C, Gøtzsche PC, John PA (2009) The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions explanation and elaboration. Br Med J 339:b2700

232. Higgins JPT, Altman DG, Gotzsche PC, Juni P, Moher D, Oxman AD, Savovic J, Schulz KF, Weeks L, Sterne JAC (2011) The Cochrane Collaboration's tool for assessing risk of bias in randomised trials. BMJ 343:d5928–d5928

233. Burdon CA, Hoon MW, Johnson NA, Chapman PG, O'Connor HT (2013) The effect of ice slushy ingestion and mouthwash on thermoregulation and endurance performance in the heat. Int J Sport Nutr Exerc Metab 23:458–469

234. Burdon CA, Ruell P, Johnson N, Chapman P, O'Brien S, O'Connor HT (2015) The effect of ice-slushy consumption on plasma vasoactive intestinal peptide during prolonged exercise in the heat. J Therm Biol 47:59–62

235. Lee JKW, Maughan RJ, Shirreffs SM (2008) The influence of serial feeding of drinks at different temperatures on thermoregulatory responses during cycling. J Sports Sci 26:583–590

236. Lee JKW, Koh ACH, Koh SXT, Liu GJX, Nio AQX, Fan PWP (2014) Neck cooling and cognitive performance following exercise-induced hyperthermia. Eur J Appl Physiol 114:375–384

237. Minniti A, Tyler CJ, Sunderland C (2011) Effects of a cooling collar on affect, ratings of perceived exertion, and running performance in the heat. Eur J Sport Sci 11:419–429

238. Morris NB, Coombs G, Jay O (2016) Ice Slurry Ingestion Leads to a Lower Net Heat Loss during Exercise in the Heat. Med Sci Sport Exerc 48:114–122

239. Bulbulian R, Shapiro R, Murphy M, Levenhagen D (1999) Effectiveness of a commercial head-neck cooling device. J Strength Cond Res 13:198–205

240. Carvalho M, de Andrade M, Ramos G, Maia-Lima A, Pereira E, Mendes T, Marins J, Amorim F, Garcia E (2015) The temperature of water ingested ad libitum does not influence performance during a 40-km self-paced cycling trial in the heat. J Sports Med Phys Fitness 55:1473–1479

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

242. Young AJ, Sawka MN, Epstein Y, Decristofano B, Pandolf KB (1987) Cooling different body surfaces during upper and lower body exercise. J Appl Physiol 63:1218–1223

243. Ruddock AD, Tew GA, Purvis AJ (2014) Reliability of intestinal temperature using an ingestible telemetry pill system during exercise in a hot environment. J Strength Cond Res 28:861–869

244. Nybo L, Rasmussen P, Sawka MN (2014) Performance in the heat-physiological factors of importance for hyperthermia-induced fatigue. Compr Physiol 4:657–689

245. Gagnon D, Kenny GP (2012) Does sex have an independent effect on thermoeffector responses during exercise in the heat? J Physiol 590:5963–5973

246. Armstrong LE, Casa DJ, Millard-Stafford M, Moran DS, Pyne SW, Roberts WO (2007) American College of Sports Medicine position stand. Exertional heat illness during training and competition. Med Sci Sports Exerc 39:556–572

247. Domitrovich JW, Cuddy JS, Ruby BC (2010) Core-temperature sensor ingestion timing and measurement variability. J Athl Train 45:594–600

248. Gant N, Atkinson G, Williams C (2006) The validity and reliability of intestinal temperature during intermittent running. Med Sci Sports Exerc 38:1926–1931

249. Kolka MA, Levine L, Stephenson LOUA (1997) Use of an ingestible telemetry sensor to measure core temperature under chemical protective clothing. J Therm 22:343–349

250. Leicht AS, Sinclair WH, Patterson MJ, Rudzki S, Tulppo MP, Fogarty AL, Winter S (2009) Influence of postexercise cooling techniques on heart rate variability in men. Exp Physiol 94:695–703

251. Schlader ZJ, Raman A, Morton RH, Stannard SR, Mündel T (2011) Exercise modality modulates body temperature regulation during exercise in uncompensable heat stress. Eur J Appl Physiol 111:757–766

252. Manfredini R, Manfredini F, Fersini C, Conconi F (1998) Circadian rhythms, athletic performance, and jet lag. Br J Sports Med 32:101–106

253. Nielsen R, Gavhed DCE, Nilsson H (1989) Thermal function of a clothing ensemble during work: dependency on inner clothing layer fit. Ergonomics 32:1581–1594

254. Hunt AP, Stewart IB (2008) Calibration of an ingestible temperature sensor. Physiol

Meas 29:N71–N78

255. Colin J, Timbal J, Houdas Y, Boutelier C, Guieu JD (1971) Computation of mean body temperature from rectal and skin temperatures. J Appl Physiol 31:484–489

256. Hopkins WG (2004) How to interpret changes in an athletic performance test. Sportscience 8:1–7

257. Jette M, Quenneville J, Thoden J, Livingstone S (1995) Reproducibility of body temperature response to standardized test conditions when assessing clothing. Ergonomics 38:1057–1066

258. van Nieuwenhoven MA, Brouns F, Brummer RJ (1999) The effect of physical exercise on parameters of gastrointestinal function. Neurogastroenterol Motil 11:431–439

259. Grayson J, Durotoye AO (1971) Effect of environment on temperatures in the viscera of the dog. Int J Biometeorol 15:176–180

260. Challis G, Kolb J (2010) Agreement between an ingestible telemetric sensor0001.pdf. Clin J Sport Med 20:53–57

261. Morante SM, Brotherhood JR (2008) Autonomic and behavioural thermoregulation in tennis. Br J Sports Med 42:679–685

262. Minett GM, Duffield R, Marino FE, Portus M (2011) Volume-Dependent Response of Pre-Cooling For Intermittent-Sprint Exercise in the Heat. Med Sci Sports Exerc 43:1760–1769

263. Duffield R, Marino FE (2007) Effects of pre-cooling procedures on intermittent-sprint exercise performance in warm conditions. Eur J Appl Physiol 100:727–735

264. Siegel R, Maté J, Brearley MB, Watson G, Nosaka K, Laursen PB (2009) Ice slurry ingestion increases core temperature capacity and running time in the heat. Med Sci Sports Exerc 42:717–725

265. Marino FE (2002) Methods, advantages, and limitations of body cooling for exercise performance. Br J Sports Med 36:89–94

266. Livingstone SD, Nolan RW, Cattroll SW (1989) Heat loss caused by immersing the hands in water. Aviat Sp Environ Med 60:1166–1171

267. Allsopp AJ, Pool KA (1991) The effect of hand immersion on body temperature when wearing impermeable clothing. J R Nav Med Serv 77:41–47

268. Egaña M, O'Riordan D, Warmington SA (2010) Exercise performance and V̇2 kinetics during upright and recumbent high-intensity cycling exercise. Eur J Appl Physiol 110:39–47

269. Egaña M, Columb D, O'Donnell S (2013) Effect of low recumbent angle on cycling performance, fatigue, and V??O2 kinetics. Med Sci Sports Exerc 45:663–673

270. Hettinga FJ, De Koning JJ, de Vrijer A, Wüst RCI, Daanen H a M, Foster C (2007) The effect of ambient temperature on gross-efficiency in cycling. Eur J Appl Physiol 101:465–71

271. JOHNSON JM (1998) Physical training and the control of skin blood flow. Med Sci Sport Exerc 30:382–386

272. Borg GAV (1982) Psychophysical bases of perceived exertion. Med Sci Sport Exerc 14:377–381

273. Razminia M, Trivedi A, Molnar J, Elbzour M, Guerrero M, Salem Y, Ahmed A, Khosla S, Lubell DL (2004) Validation of a new formula for mean arterial pressure calculation: the new formula is superior to the standard formula. Catheter Cardiovasc Interv 63:419–425

274. Ekenvall L, Lindblad LE, Norbeck O, Etzell BM (1988) Alpha-adrenoceptors and cold-induced vasoconstriction in human finger skin. Am J Physiol Hear Circ Physiol 255:H1000-1003

275. Roddie IC, Shepherd JT, Whelan RF (1957) The contribution of constrictor and dilator nerves to the skin vasodilation during body heating. J Physiol 136:489–497

276. Cheung SS, Sleivert GG (2004) Multiple triggers for hyperthermic fatigue and exhaustion. Exerc Sport Sci Rev 32:100–106

277. Tyler CJ, Reeve T, Hodges GJ, Cheung SS (2016) The Effects of Heat Adaptation on Physiology, Perception and Exercise Performance in the Heat: A Meta-Analysis. Sport Med 46:1699–1724

278. Tan PMS, Lee JKW (2015) The role of fluid temperature and form on endurance performance in the heat. Scand J Med Sci Sports 25:39–51

279. Adams WM, Hosokawa Y, Adams EL, Belval LN, Huggins RA, Casa DJ (2016) Reduction in body temperature using hand cooling versus passive rest after exercise in the heat. J Sci Med Sport 19:936–940

280. Ruddock AD, Tew GA, Purvis AJ (2017) Effect of hand cooling on body temperature, cardiovascular and perceptual responses during recumbent cycling in a hot environment. J Sports Sci 35:1466–1474

281. Digestive system diagram. https://commons.wikimedia.org/wiki/File:Digestive_system_diagram_en.svg. Accessed 1 Aug 2017

282. Bain AR, Lesperance NC, Jay O (2012) Body heat storage during physical activity is lower with hot fluid ingestion under conditions that permit full evaporation. Acta Physiol 206:98–108

283. Parkin JM, Carey MF, Zhao S, Febbraio MA (1999) Effect of ambient temperature on human skeletal muscle metabolism during fatiguing submaximal exercise. J Appl Physiol 86:902–908

284. Gosling CM, Gabbe BJ, McGivern J, Forbes AB (2008) The incidence of heat casualties in sprint triathlon: The tale of two Melbourne race events. J Sci Med Sport 11:52–57

285. Atkinson G, Batterham AM (2015) True and false interindividual differences in the physiological response to an intervention. Exp Physiol 100:577–588

286. Hopkins WG (2015) Individual responses made easy. J Appl Physiol 118:144–1446

287. Borg G (1998) Borg´s perceived exertion and pain scales. Hum Kinet 104

288. Gray H (1918) Fig. 1032. In: Anat. Hum. Body. http://www.bartleby.com/107/illus1032.html. Accessed 27 Jul 2017

Appendicies

Appendix 1: Ethics approval letter study 1

Faculty of Health and Wellbeing Research Ethics Committee

Report Form

Principal Investigator: Alan Ruddock

Title: Reliability of cardiopulmonary, systemic circulatory and body temperature responses during recumbent cycling in a hot environment.

Checklist:

Application form	✓
Informed consent form	✓
Participant information sheet	✓
Risk assessment form	✓
Pre-screening form	✓
Pre-screening form (under 18)	n/a
Collaboration evidence/support	n/a
CRB Disclosure certificate	n/a

Recommendation:

Acceptable: ☑

Not acceptable, see comments: ☐

Acceptable, but see comments: ☐

Comments:

Signature : .... Date: 26.05.11

David Binney

Chair, Sport and Exercise Research Ethics Review Group

Please remember that an up-to-date project file must be maintained for the duration of the project and afterwards. The project file might be inspected at any time.

Note: *Approval applies until the anticipated date of completion unless there are changes to the procedures, in which case another application should be made.*

Name of Supervisor : Alison Purvis

Appendix 2: Ethics approval letter study 3

Faculty of Health and Wellbeing Research Ethics Committee

Sport and Exercise Research Ethics Review Group

Report Form

Principal Investigator: Alan Ruddock

Title: Effects of hand cooling on cardiopulmonary, systemic circulatory and body temperature responses during recumbent cycling in a hot environment.

Checklist:

Application form	✓
Informed consent form	✓
Participant information sheet	✓
Risk assessment form	✓
Pre-screening form	✓
Pre-screening form (under 18)	n/a
Collaboration evidence/support	n/a
CRB Disclosure certificate	n/a

Recommendation:

Acceptable: ✓

Not acceptable, see comments:

Acceptable, but see comments:

Comments:

Thank you for providing an amended Risk Assessment form as requested.

Your application is now Acceptable and you may commence your study.

Signature : Date: 16.10.12

David Binney

Chair, Sport and Exercise Research Ethics Review Group

Please remember that an up-to-date project file must be maintained for the duration of the project and afterwards. The project file might be inspected at any time.

Note: *Approval applies until the anticipated date of completion unless there are changes to the procedures, in which case another application should be made.*

Name of Supervisor : Alison Purvis

Appendix 3: Ethics approval letter study 4

Sheffield Hallam University

RESEARCH ETHICS REVIEWER'S FEEDBACK FORM (SHUREC3)

Principal investigator: Alan Ruddock **Reference number:**

Other investigators:

Title of project:

Effect of hand cooling gloves on perceptual, cardiovascular and body temperature responses during exercise in a hot environment

In my judgement the application should be (tick one box):

☒ Approved

☐ Approved with attention to the items listed below (1). Please email the details of how the issues have been addressed to the FREC and provide confirmation from the supervisor that the issues have been addressed for student projects.

☐ Referred back to the applicant for a full resubmission to address all the conditions listed below (1)

☐ Not approved for the reasons listed below (2)

1. The following issues need to be addressed:

Appendix 4: Informed consent form study 1

Sheffield Hallam University

Faculty of Health and Wellbeing Research Ethics Committee

Sport and Exercise Research Ethics Review Group

INFORMED CONSENT FORM	
TITLE OF PROJECT: Reliability of cardiopulmonary, systemic circulatory and body temperature responses during recumbent cycling in a hot environment.	
The participant should complete the whole of this sheet himself/herself	
Have you read the Participant Information Sheet?	YES/NO
Have you had an opportunity to ask questions and discuss this study?	YES/NO
Have you received satisfactory answers to all of your questions?	YES/NO
Have you received enough information about the study?	YES/NO

To whom have you spoken? .... Do you understand that you are free to withdraw from the study: • at any time • without having to give a reason for withdrawing • and without affecting your future medical care	YES/NO
Have you had sufficient time to consider the nature of this project?	YES/NO
Do you agree to take part in this study?	YES/NO
Signed .... Date .... (NAME IN BLOCK LETTERS)..	
Signature of Parent / Guardian in the case of a minor	

Appendix 5: Informed consent form study 3

Sheffield Hallam University

Faculty of Health and Wellbeing Research Ethics Committee

Sport and Exercise Research Ethics Review Group

INFORMED CONSENT FORM	
TITLE OF PROJECT: Effects of hand cooling on cardiopulmonary, systemic circulatory and body temperature responses during recumbent cycling in a hot environment	
The participant should complete the whole of this sheet himself/herself	
Have you read the Participant Information Sheet?	YES/NO
Have you had an opportunity to ask questions and discuss this study?	YES/NO
Have you received satisfactory answers to all of your questions?	YES/NO

Have you received enough information about the study?	YES/NO
To whom have you spoken? .... Do you understand that you are free to withdraw from the study: • at any time • without having to give a reason for withdrawing • and without affecting your future medical care	YES/NO
Have you had sufficient time to consider the nature of this project?	YES/NO
Do you agree to take part in this study?	YES/NO
Signed .... Date ....……….. (NAME IN BLOCK LETTERS)...…………………….	
Signature of Parent / Guardian in the case of a minor	

PTO

Appendix 6: Informed consent form study 4

Sheffield Hallam University

Faculty of Health and Wellbeing Research Ethics Committee

Sport and Exercise Research Ethics Review Group

INFORMED CONSENT FORM	
TITLE OF PROJECT: Effect of hand cooling gloves on perceptual, cardiovascular and body temperature responses during exercise in a hot environment	
The participant should complete the whole of this sheet himself/herself	
Have you read the Participant Information Sheet?	YES/NO
Have you had an opportunity to ask questions and discuss this study?	YES/NO
Have you received satisfactory answers to all of your questions?	YES/NO
Have you received enough information about the study?	YES/NO

To whom have you spoken? .... Do you understand that you are free to withdraw from the study: • at any time • without having to give a reason for withdrawing • and without affecting your future medical care	YES/NO
Have you had sufficient time to consider the nature of this project?	YES/NO
Do you agree to take part in this study?	YES/NO
Signed .... Date ....………… (NAME IN BLOCK LETTERS)...……………………	
Signature of Parent / Guardian in the case of a minor	

PTO

I hereby give consent for the photographic recording made of me on.......................
to be published in an appropriate journal or textbook. It is understood that I have the right to withdraw consent at any time prior to publication but that once the images are in the public domain there may be no opportunity for the effective withdrawal of consent.

Signed .... Date ....

Signature of Parent / Guardian in the case of a minor

....

Appendix 7: Participant information sheet study 1

Sheffield Hallam University

Faculty of Health and Wellbeing Research Ethics Committee

Sport and Exercise Research Ethics Review Group

Participant Information Sheet

Project Title	Reliability of cardiopulmonary, systemic circulatory and body temperature responses during recumbent cycling in a hot environment

Supervisor/Director of Studies	Alison Purvis

Principal Investigator	Alan Ruddock

Principal Investigator telephone/mobile number	07515690009/01142254439

Purpose of Study and Brief Description of Procedures

(Not a legal explanation but a simple statement)

It is well known that it is harder to exercise in hot rather than cool environments. Consequently, researchers are looking at ways to aid cooling of the body so athlete's bodies can maintain performance.

This study is the first in a series of studies attempting to find a practical method of cooling the body during exercise. In this particular study we are investigating whether the physiological responses of the heart, muscles, skin blood circulation and body temperature to exercising in a hot environment are the same on two identical situations on different days.

This study requires you to visit the research centre at Sheffield Hallam University on three occasions.

During visit one, on arrival to the laboratory you will be asked to undertake 10-min of light exercise whereby you will try out the exercise equipment before the test. This is to ensure you are comfortable with recumbent cycling (seated in a chair). Following the initial 10-min you will be asked to complete a maximal exertion test. This is a standard test to assess your fitness. Please be aware that this test is a maximal test and it is likely you will experience severe physical discomfort, tiredness, dizziness and sickness. **The tests involve giving maximum effort** to ensure your results are a true reflection of your ability.

Following this test you will be given one hour of rest before entering a hot room. The conditions in this room will be set to the same temperature as visits 2 and 3 (35°C 50% humidity). You will be asked to perform 30-mins of light exercise on the same recumbent cycle. The purpose of this part of the visit to ensure that you are used to exercising in a hot room.

On visits two and three you will be asked to cycle for up to 60-mins in the hot room. Your physiological responses will be monitored at regular intervals using instruments that are placed on top of your skin. Your internal body temperature will be monitored using a small pill which will transmit signals to a recorder. You will be asked to swallow the pill at least 4 hours before you visit the laboratory to ensure it is within your gut. The purpose of these two visits is to investigate whether your physiological responses are the same on different days.

To achieve reliable (similar physiological responses on different days) results you should be in a **fully rested state**. It is advised that you do not undertake stressful training 24-hours prior to the tests as this will impact upon the results. On the day of testing you should **have at least 8 hours sleep** the night before. **Do not consume energy drinks, caffeine or alcohol** on the day of testing. **Do not eat anything 2 hours before the test** but make sure you arrive at the Laboratory in a **fully hydrated state.**

Please bring your trainers, exercise kit (preferably a light vest and shorts), something to keep warm after the test and a towel and soap for a shower if required.

<u>If you feel that BEFORE or DURING the test that you do not want to take part or carry on, you are free to stop the tests at any time you wish.</u>

Please note that you have the right to withdraw from the investigation at any time, without giving a reason for withdrawing and without affecting your future medical care.

All information you provide (telephone numbers, email address, medical information, testing results) or any concerns you express regarding the study with be held with the strictest confidentiality.

If you have any concerns or wish to gain additional information relating to this study please contact Alan Ruddock who is responsible for the investigation or Alison Purvis at Sheffield Hallam University who is supervising this study.

If necessary continue overleaf

It has been made clear to me that, should I feel that these Regulations are being infringed or that my interests are otherwise being ignored, neglected or denied, I should inform Mr David Binney, Chair of the Faculty of Health and Wellbeing Research Ethics Committee (Tel: 0114 225 5679) who will undertake to investigate my complaint.

Appendix 8: Participant information sheet study 3

Sheffield Hallam University

Faculty of Health and Wellbeing Research Ethics Committee

Sport and Exercise Research Ethics Review Group

Participant Information Sheet

Project Title	Effects of hand temperature on cardiopulmonary, systemic circulatory and body temperature responses during recumbent cycling in a hot environment

Supervisor/Director of Studies	Alison Purvis

Principal Investigator	Alan Ruddock

Principal Investigator telephone/mobile number	07515690009/01142254439

Purpose of Study and Brief Description of Procedures

(Not a legal explanation but a simple statement)

It is well known that it is harder to exercise in hot rather than cool environments. Consequently, researchers are looking at ways to aid cooling of the body so athlete's bodies can maintain performance.

This study is the second in a series of studies attempting to find a practical method of cooling the body during exercise. In this particular study we are investigating whether the physiological responses of the heart, muscles, skin blood circulation and body temperature to exercising in a hot environment are different when we use cooling or not.

This study requires you to visit the research centre at Sheffield Hallam University on four occasions.

During visit one, on arrival to the laboratory you will be asked to undertake 10-min of light exercise whereby you will try out the exercise equipment before the test. This is to ensure you are comfortable with recumbent cycling (seated in a chair). Following the initial 10-min you will be asked to complete a maximal exertion test. This is a standard test to assess your fitness. Please be aware that this test is a maximal test and it is likely you will experience severe physical discomfort, tiredness, dizziness and sickness. **The tests involve giving maximum effort** to ensure your results are a true reflection of your ability.

Following this test you will be given one hour of rest before entering a hot room. The conditions in this room will be set to the same temperature as visits 2, 3 and 4 (35°C 50% humidity). You will be asked to perform 30-mins of light exercise on the same recumbent cycle. The purpose of this part of the visit to ensure that you are used to exercising in a hot room.

On visits two, three and four you will be asked to cycle for up to 60-mins in the hot room. During exercise you will be asked to place both your hands in two buckets (one each for right and left hands) of water for the duration of the test. Your physiological responses will be monitored at regular intervals using instruments that are placed on top of your skin. Your internal body temperature will be monitored using a small pill which will transmit signals to a recorder. You will be asked to swallow the pill at least 6 hours before you visit the laboratory to ensure it is within your gut.

To achieve reliable (similar physiological responses on different days) results you should be in a **fully rested state**. It is advised that you do not undertake stressful training 24-hours prior to the tests as this will impact upon the results. On the day of testing you should **have at least 8 hours sleep** the night before. **Do not consume energy drinks, caffeine or alcohol** on the day of testing. **Do not eat anything 2 hours before the test** but make sure you arrive at the Laboratory in a **fully hydrated state.**

Please bring your trainers, exercise kit (preferably a light vest and shorts), something to keep warm after the test and a towel and soap for a shower if required.

<u>If you feel that BEFORE or DURING the test that you do not want to take part or carry on, you are free to stop the tests at any time you wish.</u>

Please note that you have the right to withdraw from the investigation at any time, without giving a reason for withdrawing and without affecting your future medical care.

All information you provide (telephone numbers, email address, medical information, testing results) or any concerns you express regarding the study with be held with the strictest confidentiality.

If you have any concerns or wish to gain additional information relating to this study please contact Alan Ruddock who is responsible for the investigation or Alison Purvis at Sheffield Hallam University who is supervising this study.

If necessary continue overleaf

It has been made clear to me that, should I feel that these Regulations are being infringed or that my interests are otherwise being ignored, neglected or denied, I should inform Mr David Binney, Chair of the Faculty of Health and Wellbeing Research Ethics Committee (Tel: 0114 225 5679) who will undertake to investigate my complaint.

Appendix 9: Participant information sheet study 4

Faculty of Health and Wellbeing Research Ethics Committee

Sport and Exercise Research Ethics Review Group

Participant Information Sheet

Project Title	Effect of hand cooling gloves on perceptual, cardiovascular and bo temperature responses during exercise in a hot environment

Supervisor/Director of Studies	Alison Purvis

Principal Investigator	Alan Ruddock

Principal Investigator telephone/mobile number	07515690009/01142254439

Purpose of Study and Brief Description of Procedures

(Not a legal explanation but a simple statement)

It is well known that it is harder to exercise in hot rather than cool environments. Consequently, researchers are looking at ways to aid cooling of the body so athlete's bodies can maintain performance.

This study is the third in a series of studies attempting to find a practical method of cooling the body during exercise. In this particular study we are investigating whether the physiological responses of the heart, muscles, skin blood circulation and body temperature to exercising in a hot environment are different when we use cooling or not.

This study requires you to visit the research centre at Sheffield Hallam University on three occasions.

During visit one, on arrival to the laboratory you will be asked to undertake 10-min of light exercise whereby you will try out the exercise equipment before the test. This is to ensure you are comfortable with cycling. Following the initial 10-min you will be asked to complete a maximal exertion test. This is a standard test to assess your fitness. Please be aware that this test is a maximal test and it is likely you will experience severe physical discomfort, tiredness, dizziness and sickness. **The tests involve giving maximum effort** to ensure your results are a true reflection of your ability.

Following this test you will be given one hour of rest before entering a hot room. The conditions in this room will be set to the same temperature as visits 2 and 3 (35°C 50% humidity). You will be asked to perform 30-mins of light exercise on the same cycle. The purpose of this part of the visit to ensure that you are used to exercising in a hot room.

On visits two and three you will be asked to cycle for up to 60-mins in the hot room. During exercise you will be asked to place both your hands in special gloves for the duration of the test. Your physiological responses will be monitored at regular intervals using instruments that are placed on top of your skin. We will also ask you to provide a small urine sample so we can check your hydration status. Your internal body temperature will be monitored using a small pill which will transmit signals to a recorder. You will be asked to swallow the pill at least 6 hours before you visit the laboratory to ensure it is within your gut.

To achieve reliable (similar physiological responses on different days) results you should be in a **fully rested state**. It is advised that you do not undertake stressful training 24-hours prior to the tests as this will impact upon the results. On the day of testing you should **have at least 8 hours sleep** the night before. **Do not consume energy drinks, caffeine or alcohol** on the day of testing. **Do not eat anything 2 hours before the test** but make sure you arrive at the Laboratory in a **fully hydrated state.**

Please bring your trainers, exercise kit (preferably a light vest and shorts), something to keep warm after the test and a towel and soap for a shower if required.

<u>If you feel that BEFORE or DURING the test that you do not want to take part or carry on, you are free to</u>

<u>stop the tests at any time you wish.</u>

Please note that you have the right to withdraw from the investigation at any time, without giving a reason for withdrawing and without affecting your future medical care.

All information you provide (telephone numbers, email address, medical information, testing results) or any concerns you express regarding the study with be held with the strictest confidentiality.

If you have any concerns or wish to gain additional information relating to this study please contact Alan Ruddock who is responsible for the investigation or Alison Purvis at Sheffield Hallam University who is supervising this study.

If necessary continue overleaf

It has been made clear to me that, should I feel that these Regulations are being infringed or that my interests are otherwise being ignored, neglected or denied, I should inform Mr David Binney, Chair of the Faculty of Health and Wellbeing Research Ethics Committee (Tel: 0114 225 5679) who will undertake to investigate my complaint.

Appendix 10: Borg perceived exertion scale

6 - No exertion at all

7 - Extremely light

8 -

9 - Very light

10

11 - Light

12

13 - Somewhat hard

14

15 - Hard (Heavy)

16 -

17 - Very hard

18

19 - Extremely hard

20 - Maximal exertion

Appendix 11: Thermal perception scale

1= Very Cold

2 = Cold

3 = Cool

4 = Slightly Cool

5 = Comfortable

6 = Slightly Warm

7 = Warm

8 = Hot

9 = Very Hot

Appendix 12: Thermal Sensation Scale (Parsons, 2014)

Hot - 7

Warm - 6

Slightly warm - 5

Neutral - 4

Slightly cool - 3

Cool - 2

Cold - 1

Appendix 13: Thermal Comfort Scale (Parsons, 2014)

Comfortable - 1

Slightly uncomfortable - 2

Uncomfortable - 3

Very uncomfortable - 4