Body temperature manipulation and exercise performance in athletically trained males

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Body Temperature Manipulation and Exercise Performance in Athletically Trained Males

by

Stephen H. Faulkner

A Doctoral Thesis submitted in partial fulfilment of the requirements for the award of

Doctor of Philosophy of Loughborough University

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ABSTRACT
Exercise or activity in high ambient temperatures offers a particular challenge to the thermoregulatory system. It is likely that mechanisms such as sweat evaporation alone are not sufficient for maintaining body temperature within a safe limit (~36.5-38.5°C) and below 40°C, which may result in impaired physiological function and performance. Exogenous cooling may be of benefit prior to, during and after events that place increased thermal strain due to increased metabolic heat production and elevated environmental temperatures upon the thermoregulatory system. Conversely, in situations where it is not possible to maintain body temperature via either continued physical activity or elevated ambient temperatures, exogenous heating may be required in order to allow optimal physiological performance. Few studies have directly aligned cooling devices with data detailing effective target regions for cooling to allow a pre-cooling garment to be of minimal weight but maximal cooling efficiency. Conversely, no study has considered the effect of muscle temperature maintenance during rest periods on subsequent power-based activities.

The aim of this thesis was to determine ways in which body temperature manipulation is capable of improving exercise performance in both power and endurance-based events. It was hypothesised that the manipulation of body temperature will result in subsequent changes in body temperature that would improve performance. Specifically, the use of pre-cooling would result in a reduction of body temperature and improve endurance exercise performance. Conversely, maintaining $T_m$ following warm up completion would have a beneficial effect on sprint and power related performance.

Study one set out to determine differences in regional body heat loss in 12 individual anatomical zones using a water perfused suit. Data obtained from this initial study allowed for the specific targeting of regions that were identified as having high rates of heat loss in subsequent studies that focused on pre-cooling and performance. The anatomical regions identified as having high potential affinity for heat exchange with the surrounding environment and cooling devices were the hands, forearms, upper and lower back and torso. Subsequent studies demonstrated that cooling of these areas was capable of lowering thermal sensation and improving thermal comfort prior to and during exercise in moderate environmental conditions (24°C, 50% RH). In these moderate conditions, there was no statistically significant improvement in treadmill based self-paced 5000m running performance. However, in hot conditions (35°C 50% RH), the use of a cooling vest and sleeves did yield a significant improvement in cycling time trial performance, which equated to 4.8%. This leads to the suggestion that there may be a threshold ambient temperature, above which pre-cooling becomes an important tool in maximizing performance potential.

A parallel area of investigation, on the other side of the temperature spectrum, was the effect of muscle temperature manipulation on power-based exercise performance. The relationship between increased muscle temperature and power output is well established, however little is known about the effect of enforced rest or recovery between two bouts of exercise. Therefore, two studies were conducted to establish what affect a delay between warm up completion and exercise has on muscle temperature and subsequent sprint cycling performance. It was shown that with 30-minutes of rest between exercise bouts wearing tracksuit trousers, muscle temperature...
declined significantly (~1-1.5°C). This decline was attenuated with the use of external passive electrical heating during the recovery compared to recovery completed in tracksuit trousers alone. The attenuated decline in muscle temperature following the use of the heated trousers resulted in an improvement in sprint cycling performance (~9%), with the use of insulated trousers having no effect on any variables measured, all relative to wearing tracksuit trousers in the rest period. In a follow-up study, the effect of implementing the heated trousers during the warm up and in addition to the rest period had on muscle temperature increase and sprint performance. A secondary area of investigation in this study was to determine the linearity of muscle temperature decline following warm up cessation. This study demonstrated that there was no additional benefit of combining passive heating with an active warm up on either muscle temperature elevations or subsequent sprint performance compared to the active warm up alone. It was shown that when the no heating was used at any stage, muscle temperature declined exponentially. However, when the heated trousers were used during recovery and/or during warm up, muscle temperature levelled off at a higher value towards the end of the recovery period. This study was also able to show significant improvements in absolute, relative and mean power output following the use of the heated trousers in the warm up and recovery, or the recovery alone.

This thesis has identified ways in which body temperature may be manipulated in order to benefit both sprint and endurance exercise performance, using both pre-cooling and active heating. A novel concept for minimizing muscle temperature decline during periods of inactivity between different rounds of competition was shown to maximize sprint performance yielding significant improvements in peak and mean power outputs.

KEYWORDS: Thermoregulation, exercise performance, cycling, running, pacing strategy, muscle temperature, skin temperature, (active) clothing, heated clothing.
Statement

The work presented in this thesis was funded by the Environmental Ergonomics Research Centre, Loughborough Design School, Loughborough University and the adidas Innovation Team, Germany.

Study 1 was conducted jointly by the author and Mr D. Dodd. The author assisted the supervision of Mr D. Dodd as part of his dissertation work. The author designed the experiment and reanalysed the raw data for inclusion in this thesis.

Study 2 was conducted jointly by the author and Miss S. Maisey. The author assisted the supervision of Miss S. Maisey as part of her dissertation work. The author designed the experiment and reanalysed the raw data for inclusion in this thesis.

Study 3 was conducted jointly by the author and Miss J. Smith. The author assisted the supervision of Miss J. Smith as part of her dissertation work. The author designed the experiment and reanalysed the raw data for inclusion in this thesis.
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Publications

Journal articles


Conference Presentations


# Table of Contents

Chapter 1 .................................................................................................................. 1

Introduction and Literature Review ........................................................................ 1

1 Introduction .............................................................................................................. 1
   1.1 Heat Balance ...................................................................................................... 2
   1.2 Thermoregulatory Responses to Heat Stress .................................................... 4
      1.2.1 Behavioural Thermoregulation .................................................................. 4
      1.2.2 Physiological Thermoregulation .................................................................. 4
   1.3 Fatigue and Exercise Performance .................................................................... 8
      1.3.1 Cardiovascular model of fatigue .................................................................. 9
      1.3.2 Metabolic factors ......................................................................................... 10
      1.3.3 Core Temperature ....................................................................................... 11
      1.3.4 Skin Temperature ....................................................................................... 12
   1.4 Central Fatigue .................................................................................................. 13
      1.4.1 The Central Governor ................................................................................ 14
   1.5 Measuring Exercise Performance ...................................................................... 16
   1.6 Body Temperature Manipulation and Performance ........................................... 18
      1.6.1 Endurance Exercise - Cooling ................................................................... 18
      1.6.2 Cooling During competition ....................................................................... 21
      1.6.3 Cooling Post-Competition ......................................................................... 25
      1.6.4 Endurance versus Power Events .................................................................. 28
      1.6.5 Body Warming – Sprint and Power Events .................................................. 29
   1.7 Summary/Conclusions ...................................................................................... 33
   1.8 Aim ..................................................................................................................... 34

Chapter 2 .................................................................................................................... 35

Body Mapping of Variations in Heat Exchange at Different Anatomical Regions ........ 35

2 Chapter Summary ................................................................................................... 35
   2.1 Introduction ....................................................................................................... 35
      2.1.1 Aim ............................................................................................................. 37
      2.1.2 Hypothesis ................................................................................................. 37
   2.2 Methods ............................................................................................................ 38
      2.2.1 Participants ................................................................................................. 38
      2.2.2 Experimental Equipment ........................................................................... 38
      2.2.3 Measurements ........................................................................................... 39
      2.2.4 Perceptual measures .................................................................................. 41
      2.2.5 Experimental Procedure .......................................................................... 41
      2.2.6 Statistics ..................................................................................................... 42
   2.3 Results ............................................................................................................... 43
      2.3.1 Heat Exchange at different body zones ....................................................... 44
      2.3.2 Thermal Sensation ...................................................................................... 46
      2.3.3 Core Temperature ....................................................................................... 47
      2.3.4 Skin Temperature ....................................................................................... 48
      2.3.5 Heart Rate ................................................................................................ 50
   2.4 Discussion ........................................................................................................... 50
      2.4.1 Perceptual Changes .................................................................................... 53
      2.4.2 Study Limitations ....................................................................................... 54
      2.4.3 Conclusion ................................................................................................. 55

Chapter 3 .................................................................................................................... 56
Notation and Abbreviations

-ve = negative
+ve = positive
AWUP = Active warm up
ATP = Adenosine TriPhosphate
BF = Body fat (%) (\%)
C = convection (W.m\(^{-2}\))
CNS = Central Nervous System
CV = Coefficient of Variation
CWI = Cold-water Immersion
E = evaporation (W.m\(^{-2}\))
HWI = Hot water immersion
HR = Heart Rate
Hb = Haemoglobin
H\(_{b}\) = Body Heat Content
iEMG = integrated Electromyography
K = conduction (W.m\(^{-2}\))
L = Linear Factor
La = Lactate
M = metabolic rate (W.m\(^{-2}\))
MVC = Maximal Voluntary Contraction
PC = Pre-Cool
PPO = Peak Power Output (W)
PPs = Participants
PWUP = Passive warm up
R = radiation (W.m\(^{-2}\))
RH = Relative humidity (%)
RPE = Rate of Perceived Exertion
r.p.m = Revolutions Per Minute (rev.min\(^{-1}\))
rPPO = Relative Peak Power Output (W/kg)
S = heat storage (W.m\(^{-2}\))
SkBF = Skin Blood Flow
TT = Time Trial
T\(_{c}\) = Core temperature (°C)
$T_b =$ Body temperature ($^\circ$C)

$\bar{T}_b =$ Mean body temperature ($^\circ$C)

$T_{sk} =$ Skin temperature ($^\circ$C)

$\bar{T}_{sk} =$ Mean skin temperature ($^\circ$C)

$T_{bicep} =$ Skin temperature at the bicep ($^\circ$C)

$T_{calf} =$ Skin temperature at the calf ($^\circ$C)

$T_{chest} =$ Skin temperature at the chest ($^\circ$C)

$T_{forearm} =$ Skin temperature at the forearm ($^\circ$C)

$T_{hand} =$ Skin temperature at the hand ($^\circ$C)

$T_{head} =$ Skin temperature at the forehead ($^\circ$C)

$T_{scap} =$ Skin temperature at the scapula

$T_{thigh} =$ Skin temperature at the thigh

$T_r =$ rectal temperature ($^\circ$C)

TS = Thermal Sensation

TC = Thermal Comfort

$\dot{V}O_2 =$ Volume of oxygen uptake (L.min$^{-1}$)

$\dot{V}O_2_{max} =$ Maximal Volume of Oxygen Uptake (mL.kg.min$^{-1}$)

W = external work done (W.m$^2$)

WUP = Warm Up

$W_{max} =$ Watt max (W)
Chapter 1
Introduction and Literature Review

1 Introduction
Humans strive to maintain a stable internal environment with a deep body core temperature ($T_c$) in the range of 36.5-37.5°C (Brooks et al. 2005). Any dramatic changes in body temperature can have wide ranging ill-effects on human health and physical performance, ranging from dehydration (Maughan and Shirreffs 2004) to heat stroke (American College of Sports Medicine et al. 2007) and even death (Maron et al. 2009). In response to exercise, as metabolic demand and heat production increases, there will be a 1-3°C increase in $T_c$, with a 3°C rise usually only occurring with very heavy exercise in warm conditions. Elevations in $T_c$ above 40°C are associated with severe heat stress and in exceptional circumstances can result in permanent brain damage if $T_c$ is not rapidly reduced via exogenous cooling routines.

Exercise or activity in high ambient temperatures offers a particular challenge to the thermoregulatory system. It is likely that mechanisms such as sweat evaporation alone are not sufficient for maintaining deep body core temperature within a functional working range (~36-40°C) and may result in impaired physiological function and performance. As such, artificial cooling may be of benefit prior to, during and after events that place additional thermal strain upon the thermoregulatory system. Conversely, in situations where it is not possible to maintain body temperature via either continued physical activity or elevated ambient temperatures, exogenous heating may be required in order to allow optimal physiological performance.

This thesis will focus on the differing ways in which body temperature can be manipulated in order to be of benefit to both endurance and power or sprint based activities. This chapter will review the general environmental and individual factors that influence the control of body temperature, along with methods frequently used in an attempt to artificially manipulate body temperature.
1.1 Heat Balance

A rise in overall body temperature ($T_b$) is associated with an increase in metabolic rate as a result of exercise and often leads to an increase in core temperature as the rate of heat storage also increases. Heat is lost or gained from environmental interaction by several processes; conduction, convection, radiation and evaporation and can be calculated using the heat balance equation (Parsons 2003):

$$M - W = E + R + C + K + S \quad [1.1]$$

Where:
- $M =$ metabolic rate (W.m$^{-2}$)
- $W =$ external work done (W.m$^{-2}$)
- $E =$ evaporation (W.m$^{-2}$)
- $R =$ radiation (W.m$^{-2}$)
- $C =$ convection (W.m$^{-2}$)
- $K =$ conduction (W.m$^{-2}$)
- $S =$ heat storage (W.m$^{-2}$)

The build up of heat in the body arises from biochemical reactions and alterations in metabolism within the body that release heat as a by-product. For example, the breakdown and formation of ATP required to fuel muscle contraction results in the release of considerable heat to the surrounding tissue. This heat production can account for up to 75% of the total energy expenditure during exercise (Brooks et al. 2005). With such an increase in metabolic heat production linked to increased physical activity, it is of paramount importance that excess heat can be dissipated in order to maintain $T_c$. As heat builds up within the body, the hypothalamus will trigger vasodilation of the blood vessels near the skin in order to increase skin blood flow, which can increase up to 8 L.min$^{-1}$ or 60% of total cardiac output during heat stress (Kenney and Johnson 1992b). This is because blood acts as an effective transporter of heat via convection from deep within the body to the skin surface. As skin blood flow increases, skin temperature ($T_{sk}$) will also gradually increase, and under conditions where $T_{sk}$ exceeds the ambient temperature ($T_a$), the body will lose heat via conduction, convection and radiation.
Conduction is the transfer of heat from the body to another object with which it is in direct contact, where heat moves along a thermal gradient (Brooks et al. 2005). For example, if you take hold of a piece of metal and it feels cold, this is due to the fact that skin temperature is higher than that of the metal and a thermal gradient exists. This is also dependent on the latent heat of an object, with a higher latent heat giving rise greater heat transfer. Convection is the transfer of heat to or from air or water (Brooks et al. 2005), and is the principle most widely taken advantage of when designing cooling apparatus for athletes (Marino 2002, Marino and Noakes 2009, Duffield and Marino 2007). Convection relies on the principle that once a given medium (either air or water) become heated the medium will expand, and because its weight remains unchanged it becomes less dense, allowing it to rise. The surrounding more dense, cooler fluid or gas then moves to replace the heated medium and the cycle is repeated resulting in a convection current, thus maintaining the thermal gradient and allowing heat transfer to continue. Where there is an incidence of forced convection due to a pumping effect, such as occurs in the circulatory system, or as in wind causing forced convection over the skin, then the rate of convective heat transfer will increase with the flow. Under conditions where $T_a$ is in excess of $T_{sk}$, then the effectiveness of convection as a means of cooling is reversed due to the reversal of the heat gradient, and the body will gain heat from the environment.

Evaporation is an extremely efficient and effective way of removing heat from the body; it has been demonstrated that when 1g of sweat changes from water to vapour the latent heat of vaporization is 2.4 kJ.g$^{-1}$ (Nagata 1978), meaning that the body loses 2.4 kJ of heat for each gram of water evaporated. Under conditions of elevated ambient temperature and high exercise intensity, it is not uncommon for athletes to reach a sweat rate of 1.5-2.0 L.hr$^{-1}$, and this can rise to in excess of 2.5 L.hr$^{-1}$ in hot conditions (Sawka and Montain 2000), accounting for up to 2.4 kJ.g$^{-1}$.hr$^{-1}$ of heat dissipation through sweating and evaporation.

Sweat production is only an effective method of cooling under conditions of low humidity, where the vapour content of the air is low compared to that at the skin surface, thus creating a vapour pressure gradient and allowing for vapour transfer from the skin surface to the surrounding atmosphere. However, under hot and humid conditions, where the moisture content of the air is elevated, then the vapour pressure
gradient becomes reduced, making the rate of vapour transfer, and thus cooling, much slower and less effective.

Finally, heat can be lost or gained as a consequence of electromagnetic waves, which is known as radiation. The sun acts as the greatest source of radiation, and the degree to which the body is covered with clothing and the body’s position in relation to the sun, or source of radiation overhead will influence the rate of heat transfer. Heat exchange as a result of radiation is continuous; it is the net effect of total radiation, which will influence body temperature. For example, in cloudy conditions, if overall skin temperature is greater than that of the surrounding environment, more heat will radiate from the body than to it, resulting in a net loss of heat.

If the above mechanisms for heat dissipation become overwhelmed, then thermal load will increase and if allowed to do so unabated will eventually result in heat injury.

1.2 Thermoregulatory Responses to Heat Stress
In order to maintain heat balance, the body has a number of mechanisms that have developed to achieve this. Broadly, these can be split into two categories: i) behavioural and ii) physiological.

1.2.1 Behavioural Thermoregulation
Behavioural thermoregulation is a thermoregulatory response which is driven by conscious responses to changes in thermal conditions, such as taking shelter, adding or removing clothing, changing posture or other procedures to keep the body within a thermally acceptable range (Parsons 2003). To a large extent, behavioural thermoregulation is a learned response to differing thermal stimuli. Prior experiences are used to determine an appropriate response to a change in thermal stimulus in order to maintain thermal comfort.

1.2.2 Physiological Thermoregulation
Physiological thermoregulation consists of a number of internal systems that provide different degrees of feedback detailing changes in both external and internal
temperature. It is widely accepted that the central thermal controller is located in the hypothalamus, which receives a variety of sensory feedback from peripheral thermoreceptors. When the hypothalamus is damaged, the body’s ability to thermoregulate appears to be severely impaired, resulting in an increased $T_c$ and hyperthermia (He et al. 1999), with hyperthermia defined as a $T_c$ in excess of 38.5°C. It is likely that this is as a result of a malfunction in the feedback loop to the hypothalamus, and a subsequent disruption to correction of error signals received regarding the need for heat loss or heat generation. Therefore, it would appear that for effective control of body temperature to occur, there is a requirement for both central and peripheral feedback in order to maintain a stable $T_c$.

1.2.2.1 **Cardiovascular and Circulatory Responses**

During exposure to a hot environment, one way in which the body is able to maintain a stable $T_c$ is via vasodilatation. During exercise in the heat, the temperature gradient between the body core and skin is reduced. Therefore, in order to maintain body temperature within an acceptable range, an increase in skin blood flow (SkBF) must occur. Reductions in perfusion of the internal organs will assist in SkBF redistribution, but in order to maintain cardiac output an increase in heart rate will occur. When warm blood from the deeper tissues reaches the skin surface and travels through the superficial veins and tissues, heat exchange occurs with the cooler surrounding environment and heat is liberated, with the now cooled blood returning to the core. The rate at which this occurs is dependent on the rate of skin blood flow and the temperature gradient between the skin and the surrounding environment. However, under circumstances where there is also an increased demand for metabolic activity in the muscles, which itself requires elevated blood flow and causes further heat production, there is a degree of conflict concerning the distribution of blood flow. Under these conditions, where elevated muscle activity results in greater metabolic heat production, it is logical that there is an increase in SkBF via vasodilation, however, with the onset of exercise, there is an initial period of vasoconstriction of the peripheral blood vessels as blood is directed to working skeletal muscle. After this period of vasoconstriction, as $T_c$ begins to rise, vasodilation occurs in an effort to dissipate the excess heat production (Kenney and
Johnson 1992a), with reported SkBF of up to 6 to 8 L.min^{-1}, or approximately 60% of cardiac output under hyperthermic conditions (Hashim and Tadepalli 1995).

The mechanism by which blood flow is controlled, largely concerns the body’s centre for temperature control, which lies within the hypothalamus and maintains $T_c$ by a negative feedback loop (Charkoudian 2003) (Figure 1.1), and is reliant on information derived from thermoreceptors located within the skin, nervous system, abdominal cavity and blood vessels (Brooks et al. 2005). Under conditions where thermoreceptors detect increasing temperature, the anterior portion of the hypothalamus becomes active, stimulating increased sweat production and as a result elevated evaporative heat loss. Furthermore, vasoconstrictor tone is removed from the blood vessels close to the skin, resulting in increased surface blood flow and a loss of heat through the skin (Brooks et al. 2005).

**Figure 1.1:** The hypothalamic control of body temperature occurs via a negative feedback loop. Changes in peripheral or central temperature are sensed by thermoreceptors and relayed back to the hypothalamus, which is then able to correct these changes by activation of vasodilation and sweating if temperature is too high, or vasoconstriction and thermogenesis if too low.
The baroreflex has an important role in the regulation of skin and muscle blood flow. Baroreceptors sense changes in blood pressure and provide impulses to the cardiovascular control centre to reduce sympathetic activity and stimulate vasodilation if blood pressure is too high. When blood pressure is low, there is a reduction in baroreceptor activity, causing vasoconstriction, and an elevation in blood pressure. During hyperthermia, baroreflex control of blood vessel diameter is of great importance in maintaining blood pressure, as up to 60% of total cardiac output is redirected towards the skin surface (Brooks et al. 2005).

1.2.2.2 Metabolic Responses
During exercise, one of the major limiting factors is the availability of carbohydrate (CHO), fat and to some extent protein to fuel muscular contractions. This is particularly true in endurance-based activity. As an individual begins to deplete their fuel reserves without consuming additional CHO, overall performance will begin to decline, and fatigue will occur more rapidly. Until relatively recently, the majority of research has focused on the interaction between metabolism and exercise under moderate ambient conditions, and it is only in the last 20 years that the influence of environmental extremes have started to be considered. Exercise under conditions of high ambient temperatures elicits heat stress, which appears to favour carbohydrate oxidation and glycogenolysis (Febbraio 2001). The first to show this were Fink et al., (1975) who reported that during 60 minutes of intermittent exercise completed in either 41˚C or 9˚C, there was an increase in glycogen metabolism in hot compared to cool ambient conditions (Fink et al. 1975). Furthermore, they showed that there was an associated decline in triglyceride use in hot compared to cold conditions. Despite this, at the point of fatigue total carbohydrate oxidation is less and muscle glycogen content higher compared with the same exercise without heat stress (Marino 2002, Mundel 2008). Therefore, in hot conditions, ambient temperature, thermal strain and heat storage are likely to be a greater limiting factor on exercise performance than nutritional demand alone, owing to the elevated metabolic cost of exercise at a given intensity in hot environmental conditions.
1.3 Fatigue and Exercise Performance

Fatigue is defined as the reversible reduction in force- or power-generating capacity of the neuromuscular system (Bigland-Ritchie *et al.*, 1983, Fitts and Holloszy, 1976, both cited in (Amann and Calbet 2008)). Exercise in the heat (>30˚C) poses extra significant thermal strain on the body’s thermoregulatory mechanisms, and it is well established that hot conditions markedly impair performance relative to cool conditions (3-20˚C) (Tucker 2008, Galloway and Maughan 1997). The importance of how exercise in a warm environment influences performance is not only of pertinence to elite sport, but also in situations where individuals are exposed to high temperatures as a requirement of their employment, such as fire-fighters and military personnel. However, the understanding of how changes in ambient temperature influence performance is still somewhat limited. For example, in a theoretical study conducted prior to the 1996 Atlanta Olympics, it was predicted via manipulation of the heat balance equation, using average conditions for the time of year, that the fastest time for the marathon would be in excess of 3 hours 20 minutes (Nielsen 1996). Despite this, the winning time was only marginally slower than the athlete’s original Olympic qualifying time. Regardless of this relatively small influence of heat on performance, in the realms of elite sport, small differences can make the difference between a gold medal and not making an Olympic final. As such, any information regarding ways in which this decline in performance may be offset is important in maximising elite performance.

The vast majority of recent work that has focused on the performance effects of exercise in the heat, is largely in agreement that increased environmental temperature causes a significant decline in performance (Maughan and Shirreffs 2004, Gonzalez-Alonso *et al.* 1999, Maughan *et al.* 2007). However, many of the early studies used performance measures with limited real world application. Of the fifteen studies summarised by Quod *et al.*, (Quod *et al.* 2006), only one used a real world performance measure, in the form of the time taken to complete a self paced 5km run (Arngrimsson *et al.* 2004). Of the remaining studies, the performance measure was often the time taken to reach volitional fatigue, or the quantity of work done in a predetermined time frame. The benefits and limitations of each type of performance test will be discussed in a later section.
A recent study by Crewe et al., demonstrated that the time to volitional fatigue was inversely related to changes in ambient and rectal temperature (Crewe et al. 2008), with fatigue occurring more rapidly under warm compared to cool conditions. However, under conditions where an athlete has the ability to self-select or self-pace a performance in response to physiological changes during exercise, the mechanisms resulting in fatigue may be somewhat different. Duffield and colleagues (Duffield and Marino 2007, Duffield 2008) have suggested that pacing strategies during exercise are selected in such a way to allow for completion of the required task prior to failure due to fatigue. In addition, Tatterson and colleagues have reported that power output in elite cyclists completing a self-paced 30-minute time trial was 6.5% lower in 32°C compared to 23°C. They suggest that power output was selected in response to an increased rate in the rise of $T_c$ (Tatterson et al. 2000).

It is clear from the current body of literature that exercise and physical performance can be severely hampered in the heat. However, there is still much debate as to exactly which mechanisms are key in maintaining body temperature during exercise and how performance is affected.

### 1.3.1 Cardiovascular model of fatigue

The classical view of fatigue is that it is caused by peripheral failure of cardiovascular and metabolic systems to meet the continuing demands of exercise. The cardiovascular model of fatigue suggests that exercise is limited by the capacity of an individual’s heart to supply working muscles with enough blood, and thus oxygen, before outstripping oxygen availability. Therefore, according to this model of fatigue, it is $O_2$ delivery (blood flow $\times$ arterial $O_2$ content) to the muscles that is the main limiting factor in endurance exercise. Once the heart reaches its maximum capacity or maximal cardiac output, then blood flow, and thus oxygen, to the muscles reaches a plateau and begins to fall behind demand. At this point, anaerobic metabolism is induced which results in the accumulation of a number of metabolites which contribute to fatigue. As such, the primary purpose of training is to improve the body’s maximum capacity to transport and consume oxygen ($VO_2\max$), and in
particular the percentage of $\dot{V}O_2\text{max}$ at which an athlete reaches their anaerobic threshold to delay the onset of anaerobic metabolism. However, although $O_2$ delivery has a large influence on exercise performance and endurance capacity, more recently other potential limiters such as core temperature, skin temperature and metabolic factors, have received more focus on how they may limit and/or determine performance and exercise capacity.

1.3.2 Metabolic factors
Metabolic fatigue becomes more apparent during exercise of long duration (>2 hours), where muscle and liver glycogen depletion have been shown to be a limiting factor in exercise duration (Costill et al. 1973), with ingestion of CHO prior to (Hawley et al. 1997) or during exercise (Coyle et al. 1986) delaying the onset of fatigue and improving exercise performance. Glycogen availability as a limiter of exercise performance and endurance has been supported by a number of studies which report that subjects who reach exhaustion during prolonged exercise develop very low levels of muscle glycogen (Burke et al. 2000, Jeukendrup 2011). However, glycogen availability cannot explain why fatigue occurs during short duration exercise, where there are still sufficient supplies of muscle glycogen to fuel muscle contractions at the point of fatigue (Marino 2002).

It has been suggested that another limiting factor, which may influence short-term exercise duration and fatigue is the rate at which ATP can be cyclically used and resynthesized. However, the major limit of ATP availability as a regulator of exercise is that if ATP becomes depleted, then skeletal muscle should enter a state of rigor (Noakes 1997). Despite this, with skeletal muscle at or very near the point of fatigue ATP concentration has been shown to be reduced by only 25-80% of resting values depending on fibre type (Karatzafiri et al. 2001a), indicating that there should still be sufficient supply of ATP to maintain contractions. Therefore, it appears unlikely that the availability of ATP is a key determinant in limiting exercise performance and/or endurance. Instead, it would appear that muscle ATP concentrations are defended in order to prevent the development of skeletal muscle rigor (Noakes 2000).
The accumulation and build up of lactate and hydrogen ions (H\(^+\)) have also received a large degree of support in causing local muscular fatigue, owing to the high correlation between their accumulation and the occurrence of fatigue during short duration exercise. Lactate and H\(^+\) accumulate as a result of anaerobic glycolysis, and the dissociation of lactic acid into lactate and H\(^+\) results in a decrease in pH. It has been suggested that a reduction in pH may slow down the rate of glycolysis, and thus reduce ATP availability and limit muscle contraction (Brooks et al. 2005).

1.3.3 Core Temperature
The heat generated as a result of increased physical activity can elevate core temperature to levels that would immobilise an individual if achieved by environmental heat stress alone (Asmussen and Boje 1945). Furthermore, it is well documented that endurance capacity is impaired in hot versus temperate climates (Galloway and Maughan 1997, Tatterson et al. 2000, Febbraio et al. 1994) and that initial core temperature may also act as a key determinant of exercise performance (Gonzalez-Alonso et al. 1999, Booth et al. 1997, Olschewski and Bruck 1988). One common feature of much of the available literature is that fatigue usually occurs at a T\(_c\) of between 38-40°C (Gonzalez-Alonso et al. 1999, Nielsen et al. 1997), which reflects the likely existence of a “critical” threshold of body core temperature, beyond which fatigue will occur. Support for this notion comes from Nielsen et al., who studied the effect of heat acclimatization on endurance performance (Nielsen et al. 1993). It was noted that following 9-12 days of exercise based acclimatization in the heat resulted in a 32 minute improvement in time to reach volitional exhaustion, but despite this apparent acclimatization, fatigue still occurred at a T\(_c\) of ~39.7°C. When the relative humidity increases, there is a marked reduction in the improvement in performance, however, fatigue still occurs at a T\(_c\) of approximately 40°C (Nielsen et al. 1997) with the earlier onset of fatigue occurring more rapidly in progressively more humid environments as a result of increased rate of T\(_c\) elevation (Watson et al. 2011). However, the increase in relative humidity will reduce the vapour gradient between the skin and the environment, hindering sweat evaporation and leading to an increase in skin temperature.
In the widely cited paper by González-Alonso, it was demonstrated that despite differing initial core temperatures, fatigue always occurred at a $T_c$ of ~40°C during prolonged exercise in an uncompensable hot environment (Gonzalez-Alonso et al. 1999). In addition, they demonstrated that time to exhaustion was inversely related to the initial $T_c$ at the onset of exercise and directly related to the rate of heat storage; i.e. a higher initial $T_c$ and/or greater rate of heat storage resulted in faster fatigue. These reported finding have lead to the continued study of core temperature as a limiter of endurance exercise, and has spawned a number of new practices by the elite endurance athlete prior to competition, most notably pre-cooling (see later section). These changes are based on the belief that a lower $T_c$ at the onset of exercise will allow an athlete to complete a given distance in a faster time due to an increase in heat storage capacity and potential for elevated work rate, owing to a lower initial core temperature.

Despite the large body of evidence which supports the notion of a critical limiting core temperature of ~40°C, there is evidence to suggest that this may not be the case in all populations. A recent study has demonstrated that in well-trained endurance athletes, a $T_c$ in excess of 40°C, and in some instances as high as 42°C, has been reported at the end of competition, without any of the documented complications usually associated with such high core temperatures. (Ely et al. 2009). Ely et al., have shown that in both cool (~13°C) and warm (~27°C) ambient conditions, when $T_c$ is >40°C in the last 600m of a simulated 8km running race, there was no difference in finishing speed compared to when $T_c$ was below 40°C (Ely et al. 2009).

Consequently, it perhaps seems unlikely that $T_c$ alone is the sole regulator or exercise performance and endurance capacity, rather it is more likely that $T_c$ along with feedback from other peripheral regions, such as the skin and muscle, are used to alter pacing strategies and regulate the onset of fatigue.

1.3.4 Skin Temperature
During prolonged exercise, one of the main avenues for heat loss is via the skin. As exercise continues, blood flow to the skin surface increases in an attempt to dissipate heat from the working muscle and the body core. It has recently been suggested that
skin temperature itself may be a regulator of exercise intensity (Schlader et al. 2011, Schlader et al. 2010b, Jay and Kenny 2009, Sawka et al. 2012). During exercise in the heat, exercise intensity was significantly lower compared to exercise intensity evident in cooler ambient conditions before any differences in \( T_c \), metabolism or heart rate become apparent, although \( T_{sk} \) was consistently elevated throughout exercise (Tatterson et al. 2000, Tucker et al. 2004). However, there are inherent difficulties in attempting to separate the effects of \( T_c \) and \( T_{sk} \) from one another. Using either an exercise protocol or whole body water immersion to elicit changes in \( T_{sk} \) is likely to increase both \( T_c \) and \( T_{sk} \) simultaneously, therefore not enabling researchers to directly assess the impact of elevated \( T_{sk} \). In a novel study, Schlader et al., used a water perfused suit to manipulate skin temperature during self paced cycling exercise (Schlader et al. 2011). \( T_{sk} \) was either cold (29.4°C) or hot (35.2°C) at the onset of exercise, and the suit was used to manipulate \( T_{sk} \) during the exercise task so that it went from cold to hot or \textit{vice versa}. The magnitude of change was similar in both conditions, as was the overall mean skin temperature. They reported that when \( T_{sk} \) went from hot to cold, power output was significantly lower through the course of the trial than compared to cold to hot \( T_{sk} \), despite no differences in \( T_c \) (Schlader et al. 2011). These results suggest that \( T_{sk} \) is capable of influencing the initial selection of exercise intensity and subsequent pacing strategy, which will obviously have an impact upon performance. Therefore, it appears possible that afferent feedback from the skin’s thermoreceptors, coupled with perceptual changes in thermal sensation and comfort, may in someway help to provide information regarding overall thermal strain and regulate initial intensity selection.

1.4 Central Fatigue

During exercise in hot ambient temperatures (>33°C), fatigue is often associated with the attainment of a critical core temperature of approximately 40°C, muscle temperature of ~41°C and skin temperature of ~37°C (Gonzalez-Alonso et al. 1999, Nybo and Nielsen 2001) despite differing rates of heat storage and initial \( T_c \) (Gonzalez-Alonso et al. 1999). However, the use of imposed work-loads to assess fatigue does not account for what processes occur during exercise where individuals are freely able to adjust their pace or intensity which occurs during the majority, if not all sporting situations.
In free-paced activity, the decline in performance and associated fatigue in high temperatures is suggested to result from failure of the CNS to activate sufficient skeletal muscle to maintain sufficient contractile force, resulting in sub-optimal muscle contraction. This idea has become known as central fatigue (Nybo and Nielsen 2001, Nybo and Secher 2004). Nybo and Nielsen were among the first to demonstrate that hyperthermia is directly associated with a decline in prolonged maximal voluntary contraction (MVC) (Nybo and Nielsen 2001). They reported that following exercise induced hyperthermia, both muscle activation (measured by electromyography, EMG) and force production of the knee extensors was significantly lower than when compared to exercise completed in a thermoneutral environment. Furthermore, they also ascertained that the percentage of voluntary activation, as determined by superimposed electrical stimulation of the femoral nerve, was also significantly lower (54% of MVC) at the end of the hyperthermic trial compared to controls (82% of MVC). As they demonstrated that a reduction in force production was associated with a reduction in EMG activity, they concluded that the reduction was closely linked to a decline in central activation. The role of hyperthermia in causing a decline in MVC is supported by Todd et al., who demonstrated that muscle fatigue during a 2 minute MVC was greater following hyperthermia (Todd et al. 2005). They showed that stimulation of the motor cortex by transcranial stimulation resulted in a greater increase in superimposed muscle twitch following hyperthermia than in normothermic controls, indicating that central drive is likely to be influenced by hyperthermia (Todd et al. 2005).

1.4.1 The Central Governor

The use of a feed-forward mechanism in response to afferent feedback from different sources and the subsequent adjustment in skeletal muscle recruitment has been termed the “central governor” (Noakes et al. 2004) and is suggested to regulate self-paced exercise. In the central governor model, it is suggested that the CNS controls mechanisms that strive to maintain homeostasis both at rest and during all forms of exercise and activity. Furthermore, it is proposed that the sensation of fatigue is not a direct consequence of metabolite accumulation in the periphery, but is an interpretation of the effect of the current level of activity on future exercise capacity and the implications for maintaining homeostasis (Tucker et al. 2004).
Figure 1.2: Hypothetical model of the CNS as a limiter of exercise performance. The CNS receives afferent information from a number of central and peripheral sources, and integrates them to form a moving threshold for exercise duration and intensity to protect the physiological integrity of the organism. (Adapted from Kayser, 2003)

Following the suggestion that hyperthermia does cause a reduction in central activation of the working muscles, leading to lower force production and possibly impaired exercise performance, Tucker et al., considered how high ambient temperatures during dynamic exercise may affect skeletal muscle recruitment (Tucker et al. 2004). Participants completed a 20km self-paced cycling time trial on two occasions in hot (35°C) or cool (15°C) ambient conditions. Measurements for $T_c$, power output and quadriceps muscle activity via electromyography (EMG) were taken. They reported that in the hot condition, $T_c$ was significantly elevated compared to cool at the end of the 20km trial. They also demonstrated that power output and EMG activity began to decline earlier in the hot trial, despite similar values for heart rate and RPE between conditions. The authors suggest that as changes in power output and EMG activity occur before there are any abnormal changes in $T_c$, heart rate or perceived effort, that this is evidence for centrally controlled anticipatory regulation of muscle recruitment and power output to limit heat production in order to maintain thermal homeostasis during exercise in the heat (Tucker et al. 2004).
idea opposes the idea of a critical limiting core temperature, as the results indicate that exercise in the heat is limited by central regulation of heat production and gain in order to avoid catastrophic fatigue occurring whilst maximizing the overall performance. Furthermore, if a threshold of a critical core temperature does exist, then it would be expected that if there is a relationship between increasing $T_c$ and declining performance, it would not be possible to increase performance and complete a “sprint finish.” Instead, a sprint finish or “end spurt” is a characteristic of most endurance races and is often associated with high (>39.2°C) core temperatures (Tucker et al. 2004).

Rather than a critical core temperature leading to central fatigue (Gonzalez-Alonso et al. 1999, Nybo and Nielsen 2001), the rate of heat storage is suggested to be of importance during exercise in the heat. The study discussed above by Tucker et al., indicates that the rate of heat storage might provide afferent feedback to the CNS from a number of sources including thermoreceptors in the skin, heart and muscles (figure 1.2 (Kayser 2003)) to allow mediation of heat gain under differing environmental conditions. This is a speculation that has received empirical support from some authors. Marino et al., showed that the rate of heat storage during running in the heat was closely correlated to body mass, with lighter runners producing and storing less heat for the same given intensity and out performing heavier runners (Marino et al. 2000). In a subsequent study, Tucker and colleagues demonstrated that a reduction in power output during exercise in hot conditions was associated with a significantly higher rate of heat storage at the onset of exercise. This led them to conclude that the initial rate of heat storage provides afferent feedback which regulates exercise intensity and therefore heat storage during the remainder of the exercise bout (Tucker et al. 2006b). However, the role of heat storage as a regulator of exercise intensity is a contentious issue (Jay and Kenny 2009) and warrants further investigation.

1.5 Measuring Exercise Performance

In the literature to date, there is a wide variety of both laboratory and field based performance test protocols used, ranging from intermittent sprints (Duffield and Marino 2007, Bishop and Maxwell 2009), run time to fatigue (Uckert and Joch 2007,
Webster et al. 2005) time to complete a set distance (Arngrimsson et al. 2004), intermittent cycling (Vaile et al. 2008a) and cycling time trial performance (Quod et al. 2008, Hajoglou et al. 2005). This makes direct comparison between studies difficult, as there is no standard method measuring performance. Furthermore, there is often a lack of ecological validity, meaning that application of results gained in a laboratory environment may not be applicable in the field, which is often the primary aim of sports science and exercise physiology related research.

Intermittent sprint protocols are designed to be successful at mimicking the complex sporting and physiological requirements of team sports such as soccer and rugby, however, their use as a measure of actual “game performance” is limited, as there is often no measure of skill, which is a large pre-determining factor of soccer performance, independent of physical fitness. Before the use of such intermittent sprint protocols becomes more widespread, the validity and reliability of including skill performance within these simulations needs to be confirmed (Currell and Jeukendrup 2008).

Time to exhaustion is a common method for ascertaining performance changes, with a longer time to fatigue indicating an improved or elevated performance. This type of test is performed at a fixed intensity of an individual’s $VO_2$ max or maximal power output ($W_{max}$) until exhaustion occurs. In contrast, a time-trial performance allows for simulation of variable intensities which are evident during time-trial events such as cycling (Palmer et al. 1994), and provide a good physiological simulation of actual performance and correlate well with actual performance (Currell and Jeukendrup 2008). In terms of application to a professional sports environment, the results of studies involving time to exhaustion tests may have limited relevance, as there are very few, if any, situations in sport that require athletes to continue until complete physical fatigue. Amongst competitive runners, it has been reported that compared to time to fatigue tests, laboratory trials simulating time trial performance (e.g. 5000m run) were perceived to be similar to actual competition performance with no significant differences in measured physiological parameters (Foster et al. 1993). This suggests that either a running or cycling-based time trial protocol may be the most effective for measuring performance changes.
It is clear that in order to gain a valid measure of performance, the performance test used must closely replicate the actual performance, both in terms of environmental conditions and the actual task to be completed. It is of great importance that studies wishing to make claims concerning changes in exercise performance consider the ecological validity of the tests employed.

1.6 Body Temperature Manipulation and Performance

1.6.1 Endurance Exercise - Cooling

If the rate at which $T_c$ increases is a potential limiter of performance (Marino 2002), whether that be via attainment of a critical core temperature (Nielsen et al. 1993) or adjustment of pacing strategies in response to a rising $T_c$ (Kay et al. 1999), then it is likely that any way in which core temperature can be lowered prior to, or during competition will have a possible performance enhancing effect. In the literature to date, there has been wide spread use of varying techniques and methodologies for pre-cooling, ranging from cold air exposure (Lee and Haymes 1995, Hessemer et al. 1984), the wearing of ice vests (Hunter et al. 2006, Price et al. 2009) and water perfused suits (Daanen et al. 2006) to whole body water immersion (Booth et al. 1997, Booth et al. 2001), with the majority reporting a lowering of $T_c$ and improved performance outcomes (table 1.1). For the most part, the athlete is required to be subjected to the cooling device for up to 60 minutes in order for a significant drop in $T_c$ to occur, prior to the commencement of an event-specific warm up. Hunter and colleagues demonstrated that when wearing an ice-vest during a warm up for 60 minutes prior to competition, $T_c$ was significantly reduced throughout a cross-country run, and remained reduced immediately post race when compared to control subjects (Hunter et al. 2006). Recently Price et al., reported similar results following the use of an ice vest prior to soccer competition, with the effect of reducing heat storage for more than 60 minutes of intermittent exercise in the heat (Price et al. 2009). These results suggest that the effects of pre-cooling via the use of an ice-vest is an effective means of delaying an increase in $T_c$ associated with heavy exercise, and may lead to an improvement in performance, although this was not directly measured in this study due to differing race distances.
Most of the work to date attributes the apparent improvement in performance to a reduction in metabolic and thermal strain (Arngrimsson et al. 2004, Lee and Haymes 1995), or via a change in the centrally mediated control of muscle recruitment and activation resulting from a change in the thermal conditions (Tucker et al. 2004). However, the exact mechanisms by which pre-cooling exerts its effect remain largely unknown.

Pre-cooling appears to have a limited influence on performance lasting more than 30-40 minutes (Marino 2002). However, there has been some evidence to suggest that pre-cooling may be beneficial for intermittent, sprint like exercise (Duffield and Marino 2007, Castle et al. 2006). Booth et al., (Booth et al. 1997) demonstrated that pre-cooling of runners via cold-water immersion, resulted in an increased 30 minute run performance in an ambient temperature of 32°C. In addition, pre-cooling lowered $T_c$ and $T_{sk}$ prior to exercise, with the effect lasting approximately 20 minutes, along with reduced mean body temperature throughout exercise. In addition, the influence of pre-cooling on running performance in the heat has been considered (Uckert and Joch 2007). Athletes were required to wear an ice-cooling vest with a temperature of 0-5°C for 20 minutes, prior to completing an incremental running test in warm ambient conditions (30-32°C). They reported that the use of the cooling vest significantly improved time to fatigue compared to controls with no pre-cooling.
Table 1.1: Summary of recent studies considering the effects of pre-cooling on endurance exercise. RH = Relative humidity; MPO = mean power output; VO$_2$ max = maximal oxygen consumption

<table>
<thead>
<tr>
<th>Authors</th>
<th>Pre-Cooling Procedure</th>
<th>Exercise</th>
<th>Ambient Conditions</th>
<th>Performance Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Booth et al., (1997)</td>
<td>60 min whole body water immersion</td>
<td>30 min self-paced run</td>
<td>31.6°C 60% RH</td>
<td>4% increase in distance run</td>
</tr>
<tr>
<td>Kay et al., (1999)</td>
<td>~60 min whole body immersion in 26°C water</td>
<td>30 min self-paced cycling</td>
<td>31.4°C 60% RH</td>
<td>6% increase in cycling distance</td>
</tr>
<tr>
<td>Arngrimsson et al., (2004)</td>
<td>Ice vest during a run warm up</td>
<td>5km running race</td>
<td>32°C 50% RH</td>
<td>1% improvement in run time</td>
</tr>
<tr>
<td>Webster et al., (2005)</td>
<td>Ice vest during 25 minute warm up</td>
<td>10 min at 70% VO$_2$ max and 95% VO$_2$ max to fatigue</td>
<td>37°C 50% RH</td>
<td>49s increase in time to fatigue at 95% VO$_2$ max</td>
</tr>
<tr>
<td>Uckert and Joch (2007)</td>
<td>20 min ice vest before warm up</td>
<td>GXT to volitional fatigue</td>
<td>~31°C 50% RH</td>
<td>7% improvement in time to fatigue</td>
</tr>
<tr>
<td>Duffield et al., (2010)</td>
<td>20 min lower body water immersion</td>
<td>40 min self-paced cycling time trial</td>
<td>33°C 50% RH</td>
<td>11% improvement in MPO</td>
</tr>
<tr>
<td>Ross et al., (2011)</td>
<td>Mixed method pre-cool ice slushy drink and cold towel</td>
<td>Self paced cycling TT</td>
<td>32-35°C 50-60% RH</td>
<td>3% increase in MPO; 1.6% improvement in performance time</td>
</tr>
</tbody>
</table>

Furthermore, the completion of a warm up procedure in warm ambient conditions appeared to have a detrimental effect on performance when compared to both control and pre-cooling conditions. In support of the work of Uckert and Joch, Webster and colleagues have demonstrated that the use of a cooling vest prior to and during a warm up, resulted in improved perceptions of comfort, reduced $T_{sk}$ and $T_c$, and increased time to fatigue in endurance trained runners (Webster et al. 2005).
Despite these findings, there is much uncertainty about which methods provide the most effective performance improvement. Quod et al., demonstrated that cycling time trial performance was no different following pre-cooling using a jacket with a phase change material (PCM) sewn onto the inside lining, compared to non-cooled controls (Quod et al. 2008). However, when pre-cooling using the jacket was combined with water immersion, time trial performance was improved by 1.8% over control and jacket pre-cooling only. However, the difference in results reported by Quod et al., may be a result of the type of cooling jacket used. Their jacket was designed using PCMs, which changed from solid to liquid form at 20˚C, and may have resulted in a smaller thermal gradient between the skin and the external environment, compared to an ice cooled jacket at 0-5˚C.

At present, there are a number of limitations associated with application of pre-cooling during athletic competition. One of the major limitations is that a number of the methods used to date require external power sources and/or water tanks that can be very cumbersome. Furthermore, it is debateable as to whether or not any pre-cooling device has enough of an effect to offset any increases in heat storage due to the increased metabolic demand as a result of carrying the device, some of which can weigh in excess of 4kg, particularly in weight bearing exercise, such as running. However, the majority of research does point towards a performance enhancing effect as a result of pre-cooling, and further research needs to be done to clarify the most effective methodology for athlete cooling away from the laboratory, and in the competitive arena.

1.6.2 Cooling During competition.
To date, it appears that a lowering of body temperature prior to exercise does have a beneficial effect on subsequent performance. However, what remains to be studied in any depth are ways in which cooling techniques could be used during competition, without an adverse affect on performance due to their size or weight. Two recent investigations (House et al. 2009, Stapleton et al. 2009) have demonstrated that the wearing of a cooling vest during exercise results in a tendency for reduced $T_c$, both during and after completion of an exercise protocol in a warm environment. These two studies suggest that if an effective design for a non-intrusive cooling garment for
use in competition can be developed, it may further enhance the performance boosting benefits of athlete cooling during competition in warm ambient conditions.

In the modern sporting environment, it is common for athletic endeavour to occur during hot conditions and, as discussed in the previous section, this can have severe detrimental effects on performance and personal health if the body becomes excessively hyperthermic ($T_c > 39.5^\circ C$). In analyses conducted during team sport competition, it was evident that the distance covered during the second half of a game of soccer was significantly impaired when the game was played in the heat and $T_c$ was above 39°C (Reilly 1997, Mohr et al. 2003), providing direct data from a competitive situation that performance is hampered in the heat. If it is possible for pre-cooling treatments to delay the onset of heat-induced fatigue, then it follows that cooling during competition, for example half time in a soccer game, should elicit similar physiological and psychological benefits, resulting in improved performance. To date, there is only limited data on the effectiveness of intermittent cooling and its influence on performance.

One of the early studies to explore the possibility of “half-time cooling,” found that the use of a cooling jacket for 10 minutes did not result in an improvement in a variety of physiological measures, including blood lactate and heart rate, or concentration and physical performance, despite improved ratings of thermal sensation (Duffield et al. 2003). Despite this, researchers have continued to strive to search for ways in which cooling during an event may influence subsequent performance. In one of the first studies to do such, 10 minutes of cooling via the wearing of an ice-jacket was administered between two 30 minute exercise bouts (Hornery et al. 2005). They reported a reduced perception of exertion following cooling, and a tendency towards improved aerobic performance and reduced rectal temperature (~0.2-0.5°C). However, due to the impossibility of blinding participants to a change in treatment, it is not possible to rule out any possible placebo effect, which is likely to have been a large contributing factor in the results only approaching significance. A further issue with this study was the performance measure used; in the first 30-minute period, participants completed sub-maximal exercise and were then exposed to cooling. Following cooling they completed a further 20 minutes sub-maximal exercise and then completed a 10 minute maximal exertion to enable
measurement of any performance changes. The use of a repeated intermittent sprint protocol, rather than phases of sub-maximal exercise, during both exercise periods may have resulted in greater changes in performance.

Recently, in an attempt to discover the influence of athlete cooling mid competition on heat storage, Price et al., have reported that pre-cooling in combination with half-time cooling administered using an ice vest during a simulated soccer game, had the effect of reducing overall heat storage during the trials (Price et al. 2009). Furthermore, heat storage in the first 5 minutes of the second half of intermittent sprint exercise was lower than pre-cooling alone and non-cooled controls. These results lead to the suggestion that during intermittent sprint events a combination of both pre-cooling and where possible half-time cooling may offer the best way of reducing the thermal strain associated with intermittent, high intensity exercise in the heat.

One of the main issues with the above studies is that the time required for cooling exposure may not necessarily fit with most half time intervals, which generally last only 10-15 minutes. In an attempt to discover the necessary parameters for shorter cold exposure, Pfeiffer and co-workers exposed participants to 5 minutes of cold-water (14°C) immersion (Peiffer et al. 2008). They reported that such a short exposure was sufficient to cause a 0.5°C lowering of $T_c$, and that following cooling, power output was significantly increased, resulting in a faster time to completion of a 4km cycling time trial. These results suggest that short-term cooling via cold water immersion may be sufficient to improve performance, providing that there is a significant drop in $T_c$, which may need to be as much as 0.5°C.

A further way to maximise cooling during short half time intervals may be by direct cooling of the extremities (hands and feet) via cold-water immersion, which would allow for maximal cooling time and minimal disruption to preparation for the second half of a game. Several recent studies have reported cooling of the extremities to be a beneficial way to reduce core temperature (Goosey-Tolfrey et al. 2008, Zhang et al. 2009, Hagobian et al. 2004, Hsu et al. 2005, Grahn et al. 2008, Khomenok et al. 2008, Allsopp and Poole 1991, House et al. 1997). House and colleagues demonstrated that in hyperthermic individuals, hand immersion in 10°C, 20°C or 30°C water, resulted in
a significant decline in core temperature within 20 minutes and a cooling power of between 113 Watts (30˚C) and 334 Watts (10˚C, (House et al. 1997)), which is far greater than is achieved via the use of air cooled vests (17-50W, (Shapiro et al. 1982)), liquid cooled vests (15-65W, (Shapiro et al. 1982, Cadarette et al. 1990)) and of garments incorporating phase change materials (32-55W, (Bennett et al. 1995)). Furthermore, there is evidence to suggest that this type of peripheral cooling of the hands and feet may result in a boost in exercise performance (Goosey-Tolfrey et al. 2008, Hsu et al. 2005, Grahn et al. 2008). However, much of these data have been obtained from disabled athletes with spinal cord injuries (SCI), which may limit its able-bodied application, as SCI patients have a compromised thermoregulatory system. This is due to the reduction in autonomic control below the region of spinal injury, causing a reduction in sweating capacity (Randall et al. 1966), and limiting blood flow to body segments associated with control from below the spinal injury (Theisen et al. 2000), limiting heat loss as a consequence of redirection of blood flow to the skin surface. Any effects of peripheral cooling may exaggerate the physiological benefit of cooling strategies in disabled compared to able-bodied athletes (Hagobian et al. 2004).

The possible influence of hand and foot cooling on athletic performance warrants further investigation; with particular focus on whether the improvements reported in spinal cord injured athletes are in any way replicated in able-bodied athletes.

There is some anecdotal evidence to suggest that ethanol based cooling liquids may improve the thermal perception of athletes competing in the heat. When certain alcohols, for example menthol, come into contact with the body, it is possible that the cold receptors located in the skin become activated on exposure, resulting in a cooling sensation similar to spraying cold-water onto the face (Mundel and Jones 2009, Eccles et al. 1990). Another potential mechanism underlying alcohol cooling is the increased rate of evaporation associated with alcohol. It has been shown that in the presence of ethanol, the evaporation rate of water increased compared to water alone (Liu et al. 2008), thus offering support for the use of alcohol based liquids to enhance athlete cooling. However, the reduction of athlete perception of heat stress may have serious implications for non-elite athletes who are subjected to less stringent physiological monitoring during training and competition. This may lead to a rapid
rise in $T_c$ and an overriding of the hypothalamic “safety switch,” potentially leading to heat related complications.

During the Beijing Olympics, Team New Zealand regularly used clothing that had been pre-soaked in an alcohol-based coolant prior to competition, with players reporting a perceived cooling effect as a result. A recently published paper has offered empirical support of a possible role for alcohol-based products as a way of improving thermal comfort. Mundel and Jones (Mundel and Jones 2009) have shown that regular swilling of a menthol solution during endurance exercise resulted in increased athlete performance and a reduction in cardiopulmonary ratings of perceived exertion. They suggest that this is a consequence of a change in thermal sensation resulting in an increase in exercise capacity, ventilation and reduced sense of effort. Conversely, it has been demonstrated that the use of spray of either 0.2% or 0.05% menthol concentration administration had no effect on mean skin temperature, mean body temperature, skin blood flow, heart rate, or thermal comfort, however the spray did result in participants reportedly feeling cooler (Gillis et al. 2010). Currently there are limited data that considers the influence of alcohol on rates of sweat evaporation and cooling during exercise in the heat, and the use of alcohol-based sprays as a mechanism of cooling in sport remains equivocal.

From the limited data available, it is clear that a reduction in heat strain caused by exercise is capable of boosting exercise performance. Methods and techniques should be developed which facilitate this in a competitive arena, with minimal impingement on athlete preparation or the laws of a given event.

1.6.3 Cooling Post-Competition

In the modern sporting theatre, it is not uncommon for athletes to have multiple rounds of competition or games interspersed over a very short period of time, particularly in events such as track cycling, athletics, and during football and rugby tournaments. The limited time available for athletes to fully recover between competitions and training sessions, has led to the use of post-competition cooling procedures to speed up the recovery process, and boost performance in subsequent exercise bouts (Barnett 2006), in particular those reliant on muscle power (Leeder et
Recent data suggest that if there is no or limited recovery of pre exercise body temperature, then there will be a drop in subsequent performance (Kenefick et al. 2009). These results clearly suggest that post exercise cooling (i.e. following completion of an event or training session) can have performance enhancing effects on subsequent performance.

There have been a number of papers which have considered the ways in which post exercise cooling may influence recovery, however, there is still relatively little information about the physiological mechanisms underpinning the process of recovery (Cochrane 2004). One of the major processes during the recovery process is the removal of lactic acid, which accumulates during training and competition to varying degrees, depending on the intensity of exercise. Initially, it was widely believed that local cooling of muscle following exercise may expedite the removal of lactate. However, there is much conflicting evidence on how cooling may influence metabolite removal (Vaile et al. 2008a, Hornery et al. 2005, Cochrane 2004). The exact process is complex and multifactorial as it depends on a number of factors such as local blood flow, buffering by HCO$_3^-$, shuttle of lactate from muscle to blood, and the rate of conversion of lactate to pyruvate in the muscle, heart and liver (McArdale et al. 2001).

One of the first to consider the effects of post exercise cooling on subsequent athlete performance were Vaile and colleagues (Vaile et al. 2008a). They looked at the effect of whole-body cooling via 15 minutes of continual or cyclical cold water immersion followed by 40 minutes of passive recovery after maximal cycling in 34°C on a following 15-minute bout of exercise at 75% of peak power output. Following all methods of cold-water immersion, the group reported that there was no difference in total work done when compared to the initial exercise bout, whereas those completing an active recovery at 40% $W_{\text{max}}$ experienced a significant decline in total work done. These results suggest that cold-water immersion may assist in maintaining performance, when there is a limited recovery time in-between exercise bouts. The authors suggest that the mechanisms by which post-cooling works in this instance, are similar to those of pre-cooling, namely by increasing heat storage capacity and a reduced strain on both the metabolic and cardiovascular systems (Lee and Haymes 1995). However, it is difficult to ascertain from the Vaile study if the decline in total
work done in the active recovery group was due to the lack of a cold-water immersion recovery, or as a result of fatigue from the passive recovery exercise.

In a ensuing study the same group looked at ways in which cold and warm water treatments may alleviate the signs and symptoms of delayed onset muscle soreness (DOMS) (Vaile et al. 2008b). In concurrence with their previous results, they reported that cold-water therapy led to significant enhancement of squat-jump performance and isometric force recovery for up to 72 hours post exercise, compared to passive recovery alone. In addition, they showed that hot water immersion was also effective for the recovery of isometric force, but had no effect on the other markers of recovery such as creatine kinase, perception of muscle pain and IL-6.

However, one of the major practical limitations of these studies is the way in which these methods could be applied effectively in a competitive situation. Post-exercise cooling appears to have a beneficial effect on subsequent performance, but the availability of cold-water tanks at the site of competition will impede its widespread use in the athletic arena. It would be of benefit to consider alternative ways in which cooling could be administered, either using cooling vests/jackets, or by targeting specific areas of the body, such as the head, hands and feet to bring about a reduction in body temperature in such a way that could be administered at half-time intervals or between closely scheduled bouts of exercise.

Despite the limited data currently available regarding post exercise cooling and recovery, there are some reports that post-cooling may be detrimental to long term adaptation and performance (Leeder et al. 2011, Yamane et al. 2006). Yamane et al., (Yamane et al. 2006) have reported that individuals exposed to cold-water immersion post exercise showed impaired physiological adaptation to training, when compared to individuals who underwent no post exercise cooling. They suggest that local exercise induced hyperthermia is a key stimulant of some of the physiological adaptations that occur as a result of training, and that active cooling will reduce any training effect. Furthermore, Crowe et al., (Crowe et al. 2007) report that cold-water cooling in-between two bouts of 30 seconds maximal cycling as part of a sixty minute recovery procedure, resulted in a decline in peak power output during the second cycling task. It is possible that the decline in peak power was due to less than optimal
temperature of the muscles following cooling, which may have resulted in impaired nerve conduction velocity and thus contraction frequency (Peiffer et al. 2009). In this instance, where elevated muscle temperature is of greater importance for performance, it may be that exposure to hot water may be a beneficial way of enhancing recovery and maintaining performance levels (Vaile et al. 2008b).

To date, there is much conflicting evidence as to the effectiveness of post exercise cooling on recovery and subsequent performance. Although there is some evidence that cooling may have a performance enhancing effect when repeated exercise is of short duration and within a short time of the previous session, which is often required during track cycling competitions and track and field. In spite of this, it is possible that the exposure time to cooling will influence recovery, as long term (>30 minutes), chronic exposure to cold-water (~5˚C) as used by Yamane et al., results in reduced adaptive capacity to physical training. Furthermore, there is little or no empirical information about long-term (i.e. >24 hours) recovery and the ability to complete training and or competition at high work rates, with current beliefs based largely on anecdotal evidence. Clearly the field of pre- and post-exercise cooling as an ergogenic tool is a potentially fruitful area for future research and warrants further investigation.

### 1.6.4 Endurance versus Power Events

As already discussed in detail in this chapter, performance in endurance events is impaired when the thermal load placed on the human body becomes too great, and to prevent the possibility of physiological damage, a slowing in pace must occur to prevent whole body hyperthermia. Therefore, in these instances, where over-heating can lead to a decline in performance, keeping an athlete cool is of paramount importance.

Power and sprint based activities lie on the other side of the temperature spectrum. In these instances elevations in local muscle temperature (i.e. agonistic muscle groups) become of more importance. For peak muscular power and therefore performance to be achieved, the muscle must first be warmed by several degrees centigrade to achieve the best contractile conditions. That is not to say that whole body temperature will not become a limiting factor in
determining performance, but in purely power based activities which last only a matter of seconds - such as sprint track cycling, powerlifting or the 100m - there is not likely to be sufficient time to develop a level of hyperthermia that will be detrimental to performance, as is the case in many endurance events. Consequently, it may be that passively adding heat will be of benefit to power and sprint based performance.

1.6.5 Body Warming – Sprint and Power Events
It has become common practice to complete a warm up prior to exercise to maximize performance potential. Muscle temperature has a significant role to play in determining the power produced by skeletal muscle, with elevations in $T_m$ resulting in higher power output (figure 1.3). Much of the available literature suggests that events and sports that are of short duration (<5 minutes) and are more heavily reliant on high levels of power production, are more likely to benefit from increases in $T_m$ (Asmussen and Boje 1945, Hajoglou et al. 2005) Whereas in endurance based activities, performance may be potentially impaired if the warm up results in depleted glycogen stores (Genovely and Stamford 1982, Bergstrom et al. 1967) and an increase in thermoregulatory strain (Marino 2004, Drust et al. 2005). Therefore, it appears that the use of extensive passive heating, may be of most benefit for short duration activities.

Increasing $T_m$, either passively or actively has been shown to cause an increase in skeletal muscle power output (Asmussen and Boje 1945, Bergh and Ekbom 1979, Davies and Young 1983, Sargeant 1987, Frankenfield 2010, Racinais et al. 2005). Bergh and Ekbom were one of the first to demonstrate a clear link between changes in $T_m$ and maximal strength and power output in humans. They demonstrated that maximal strength and power output had a positive thermal dependence on changes in $T_m$ and reported a 5% improvement in vertical jump performance as $T_m$ increased (Bergh and Ekbom 1979).

It is well established that changes in $T_m$ result in a shift in the force velocity curve, which in turn will alter power output (De Ruiter and De Haan 2000, Ranatunga 1984, Bottinelli et al. 1996). With an increase in muscle temperature, there is an associated
increase in maximum velocity of shortening of muscle fibres ($V_{max}$) and force produced, which causes a concurrent increase in power output (figure 1.3).

During short duration maximal activity, both type I and type II muscle fibres are metabolically (Karatzafiri et al. 2001b) and mechanically (Beelen et al. 1995) active, with each fibre type having a different relative contribution to power output. It is therefore important to consider how alterations in temperature may change with different fibre types. Studies in both rat (Ranatunga 1984) and human (Sargeant and Rademaker 1996) skeletal muscle have demonstrated that power output of type I fibres has a greater temperature dependence than in type II fibres. It is has been suggested that this is due to a difference in optimal $V_{max}$ of type I and type II muscle fibres (Sargeant and Rademaker 1996). Sargeant has shown that the effect of temperature on skeletal muscle is velocity dependent. At low contraction velocities an increase in $T_m$ only related to a 2% per °C improvement in power output, whereas at a higher velocity, this increased to 10% per °C (Sargeant 1987). This is most likely because of the type II fibres contracting nearer to their optimal $V_{max}$, resulting in an increase in power output rather than a temperature affect. The influence of $T_m$ improving the contraction velocity of muscle has some support in the literature. Gray et al., (Gray et al. 2006) demonstrated that following passive heating of the legs, there was a 22% increase in maximal pedal rate and 18% improvement in power output during sprint cycling. However, they also report that in contrast to previous studies, the magnitude of temperature dependent increase in power output was positively correlated to the percentage of type II fibres.
Figure 1.3: Schematic representation of the alteration in the force and power velocity relationships. With increased $T_m$, there is an increase in maximal power and velocity of shortening, with peak force remaining unchanged.

There is limited evidence for the effectiveness of a passive warm up as a means of improving performance, however, they have become a well-accepted practice with many athletes (Bishop 2003a), with the majority of effects been ascribed to temperature mediated mechanisms (Asmussen and Boje 1945) and psychological preparedness. In the literature to date, it appears that a warm up designed to increase $T_m$ has more benefit in short to medium term events of less than 5 minutes in duration, and in particular in sprint events which require faster contraction velocities (Davies and Young 1983, Brown et al. 2008, Mohr et al. 2004).

In contrast, as a dramatic rise in $T_c (>\sim 2.5^\circ C)$ during endurance exercise is associated with a decline in performance, it is logical that a warm up of too high an intensity may result in a rapid rise in $T_c$, which may influence pacing strategy (Wittekind et al. 2009, Noakes et al. 2005), particularly in hot ambient conditions. In addition, it is possible that a long or overly intense warm up (~75% VO$_{2\text{max}}$) (Bishop et al. 2001) may lead to early depletion of glycogen stores which is associated with fatigue (Bishop 2003a). However, this is likely to be of less importance during exercise in the
heat, where fatigue has been shown to develop whilst there are still adequate stores of muscle glycogen (Marino 2002).

Despite the contrasting evidence in support for the effectiveness of warms ups, the use of athlete warming during intermittent exercise and half-time periods in team games has started to be investigated. This is of interest as in intermittent type activities such as football and rugby, where increases in $T_m$ will improve muscle function for periods of high intensity sprinting. It is likely that during half time, the elevation in $T_m$ gained from the initial warm up is lost due to inactivity and athletes need to “re-warm” prior to the start of the second half. It has been reported that in the second half of soccer games, players and officials cover less ground (Duffield, unpublished observation) (Reilly 1997) and perform less high intensity running (Mohr et al. 2003) in the early part of the second half compared to the first half. It is possible that this may be due to a lack of a warm-up in preparation for the second half as a way of re-warming following a loss of $T_m$ during the half-time interval. Recently, Mohr et al., (Mohr et al. 2004) examined the effects of a half-time “re-warm-up” on second half sprint performance. They reported that the half-time interval led to a drop in $T_m$ and $T_c$ and that in the group who underwent passive recovery (i.e. no re-warm), sprint performance declined as expected. The decline in $T_m$ was approximately 2°C, which has been suggested to be the degree to which $T_m$ must be elevated to have a performance enhancing effect (Cochrane 2004). Furthermore, they conclusively demonstrated that the re-warm was able to attenuate the drop off in $T_m$, $T_c$ and sprint performance. However, there is a paucity of data documenting the $T_m$ change in response to an enforced rest or inactivity between exercise bouts, or warm-up and performance execution, and the exact effect this has on sprint-based activities.

It is possible that the increase in sprint performance following a warming of skeletal muscle is due to increased muscle fibre conduction velocity and anaerobic ATP turnover. This speculation was recently confirmed by Gray et al., who reported that elevated $T_m$ (~37.5°C) prior to sprint exercise lead to increased muscle fibre conduction velocity, power output and pedalling cadence, which was associated with reduced residual muscle phosphocreatine following sprints proceeded by muscle warming (Gray et al. 2006). These data offer clear empirical support for the notion
that increased muscle temperature via a warm-up is beneficial for sprint-based performance. For sprint and power events of less than 10s duration, a boost in anaerobic ATP utilisation, should benefit performance, by increasing the release of potential energy from the breakdown of ATP to power more frequent and faster muscle contractions.

In the face of evidence in support of increasing $T_m$ prior to short-term exercise under normal ambient conditions, the effect of a passive warm up prior to endurance exercise in the heat is less clear-cut. As previously discussed, there is evidence for a critical cut off point of approximately 40°C, after which fatigue will occur (Gonzalez-Alonso et al. 1999), it therefore follows that completing a passive warm up designed to raise $T_m$ and $T_c$ prior to endurance exercise in the heat, may in fact be counter productive towards performances increases.

It may be that the observed decline in performance is due to a change in athlete pacing in order to delay the onset of fatigue (Noakes et al. 2005) and via a reduction in heat storage capacity (Bishop 2003a). Although the benefits of a passive warm up on endurance performance appear limited, the same cannot be said for an active warm up, although this is less likely to be as a result of temperature mediation and more closely liked to an elevated VO$_2$ at the onset of exercise.

### 1.7 Summary/Conclusions

From the extensive literature review presented, the following conclusions can be drawn:

- Humans strive to maintain their core body temperature at approximately 37°C at rest, and fluctuations only occur within very narrow limits, where heat balance exists between the surrounding environment and the body.
- During exercise, core body temperature regulation occurs at a higher temperature, often referred to as a set-point shift relative to the workload.
- The centre for thermoregulatory control is located within the hypothalamus, with thermoregulatory activity (physiological and behavioural) determined via a combination of peripheral and central feedback.
• The interaction between changes in core temperature and exercise performance have received large supporting evidence in having a regulatory effect on performance. It is widely accepted that pace is regulated via changes in core temperature in order to prevent core temperature rising above ~40°C.

• More recent evidence suggests that core temperature may not be the key determinant of endurance exercise performance, with the suggestion that peripheral feedback regarding changes in skin temperature may play a more important role in determining pacing strategies and performance.

• Both whole body and local skin and muscle temperature have differing effects on endurance and power based activities, with elevations in temperature being more desirable for short term power based events, but potentially detrimental to endurance events.

• Pre-cooling is an effective method for reducing thermal strain prior to exercise in the heat, however many laboratory based methods are impractical for field application and new methodologies are required.

• The role of passive/artificial heating on sprint performance has received limited research focus.

• Elevations in muscle temperature are key to power based activities such as sprinting, with sub-optimal muscle temperature resulting in impaired muscle power output due to changes in the force velocity relationship.

• There is a particular paucity of data concerning muscle temperature changes in the period between warm up completion and performance execution and the effect of declining muscle temperature on subsequent performance.

1.8 Aim

It is the aim of this thesis to determine ways in which body temperature manipulation, both heating and cooling, is capable of improving exercise performance in both power and endurance based events, using novel and competition applicable methodologies. Specific hypotheses will be presented in the following experimental chapters after a more detailed discussion relevant to the specific research question.
Chapter 2

Body Mapping of Variations in Heat Exchange at Different Anatomical Regions.

2 Chapter Summary

This chapter investigates the regional variation in heat loss that may be evident for different anatomical regions in athletic males using a high density, water-perfused suit. It was hypothesised that regions of low adiposity and high vascularisation would demonstrate the highest rates of heat loss in response to cooling. Participants underwent systematic cycles of cooling (7.5°C) and rewarming (33°C) of 12 individual body parts. Water temperature was closely regulated so that the flow to all zones was the same temperature, while the cooled zone received cold-water flow. Data were corrected to allow for heat exchange from the connective tubing with the surrounding environment. Results show that different regions experience different rates of heat loss, with the forearms, hands, feet and upper back experiencing the highest rates of heat loss. This is attributed to the low distribution of body fat in these regions, coupled with high vascularisation resulting in these regions demonstrating the highest rates of heat loss.

2.1 Introduction

Many types of sports performance are adversely affected by elevations in environmental temperature, causing an increase in physiological thermal stress (Galloway and Maughan 1997). Studies have shown that this can be overcome with the use of pre-cooling (Duffield et al. 2010, Ross et al. 2010) and in particular ice vests (Arngrimsson et al. 2004, Bogerd et al. 2010, Luomala et al. 2012). Despite this, no study has considered differences in regional heat exchange throughout the body in order to maximize the efficiency of clothing used for cooling.
The methodology of cooling used will have an important effect on the rate of cooling and overall heat flux. Different mediums have different heat transfer coefficients, with water possessing a higher heat transfer coefficient than air. This means that water has a greater ability for thermal transfer via conduction from the body than air alone. Therefore, the use of water as a medium for heat transfer allows for a greater transfer of heat before a loss in the thermal gradient occurs. However, it is also important to consider the temperature of the cooling medium used. Too low a temperature is likely to lead to vasoconstriction, resulting in a decline in peripheral blood flow (House and Tipton 2002). This will have the effect of increasing central blood volume and as a result elevate core temperature as warm blood is redistributed to the body core.

Body composition varies greatly between genders and ethnic origins (Anderson 1999). However, there are still a great deal of compositional differences between individuals of the same gender and race. These divergences are largely attributed to differences in the deposition of adipose tissue, musculature, body surface area, vascularisation of a given area and body weight (Anderson 1999) which all have close influence on thermal conductivity in response to changes in both internal and external environments. Higher percentages of body fat content will result in a reduction in the conductivity of heat within the body, and result in a build up of stored heat and elevated core temperature in warm ambient conditions. Whereas leaner individuals will not have such a large barrier to internal thermal conductivity, and thus experience less thermal strain at a given metabolic rate in the same environmental conditions.

Much of the literature to date concerning the field of individual cooling has primarily focused on methods which involve large areas of the body being covered by a cooling garment or immersed in cold water, in order to maximise heat exchange. There is relatively little information about how regional rates of heat exchange vary throughout the human body. Any regional differences in heat exchange are likely to play an important role in optimising garments designed to protect individuals from inhospitable environments and maximising physical and cognitive performance. A recent study using a multi-zoned water perfused suit clearly demonstrates that there are significant regional differences in the rate of heat exchange, with the thigh, torso, shoulder, calf and forearm eliciting the greatest amount of heat transfer to cooled water (Koscheyev et al. 2002). Furthermore, there is clear evidence to suggest that
changes in skin temperature (T_{sk}) are not uniform throughout the body when exposed to cool air (~15.5°C), with the hands and feet reaching temperatures as low as 23 and 21.5°C respectively, and the neck remaining relatively stable at ~33°C (Huizenga et al. 2004). This suggests that heat exchange, and indeed thermal sensation and thermal comfort are also likely to widely fluctuate from body region to region during cooling.

The control of body temperature is of vital importance in a wide range of scenarios, from keeping fire-fighters cool, maintaining astronaut’s warmth during space flight and optimizing athlete temperature prior to sports performance. It has been demonstrated that certain areas are likely to allow for greater levels of heat exchange, (Koscheyev et al. 2002, Koscheyev et al. 2006), and as such these areas may be targeted for more effective control of body temperature during periods of exposure to environmental extremes.

Taken together, these studies suggest that there are regional differences in heat exchange throughout the body, and that applying cooling to one or more of these locations may, at the very least be able to attenuate or even reverse rises in core temperature (T_{c}) and improve thermal perception and exercise performance. It is of value to investigate exactly which areas are the most effective regions for cooling and how this may influence performance.

### 2.1.1 Aim

The aim of this study is to demonstrate how heat exchange and local thermal sensation at regionalised anatomical zones responds to changes in temperature, via the manipulation of inlet water temperature flowing through a water perfused suit.

### 2.1.2 Hypothesis

It was hypothesized that individual zones would demonstrate differing rates of heat exchange, with regions of high vascularization and low adipose tissue coverage demonstrating the highest rates of heat exchange.
2.2 Methods

2.2.1 Participants
Ten Caucasian male participants participated in this investigation age (mean, SD) 23.4 ± 3.2 years; height 182.2 ± 6.1 cm; weight 80.3 ± 8.1 kg; body surface area 2.02 ± 0.13 m²; body fat content 8.8 ± 3.9%. All were non-smokers, free of any prescription and non-prescription medication and participated in regular physical activity. The Loughborough University Ethical Advisory Committee approved all procedures, and participants gave their written informed consent (Appendix A).

2.2.2 Experimental Equipment
Water was circulated through a customised, high density, medical grade PVC tubing water perfused Lycra suit (Med Eng, Canada). The water perfused suit (WPS) was worn over underpants and a thin all-in-one suit to maintain hygiene. Over the top of the suit, a compression layer was worn to ensure uniform contact between the suit and the body. The WPS covered all of the body surface area apart from the face. The tubing system allowed for the division of the suit into 12 independent anatomical regions: head, torso, upper back, lower back, upper arms, forearms, hands, front thigh, rear thigh, buttocks, lower legs and feet (figure 2.1). As a result, it was possible to manipulate temperature at a required zone whilst maintaining the water temperature supplied to the remaining zones. The garment was made of a cotton/Lycra fabric, with the PVC tubing sewn onto the fabric. The internal diameter of the tubing was 2.5 mm, and the total length of tubing within the suit totalled 131.6 m. In total, the suit covered an area of 1.70 m².

Two water baths (TLC-15, TLC-30, Tamson Instruments, Netherlands) provided cooling and warming of the water supplied to individual zones, with each zone on a closed-circuit loop. One water bath was used for cooling (7.5°C) and the other for warming (33°C). In addition, an industrial water chiller (TAE EVO M10, Industrial Cooling Systems Technology, UK) was used to help maintain the water temperature at 7.5°C. The chiller was set at 5°C to allow for heat gain through the system prior to reaching the temperature controlled water baths as a result of environmental heat exchange, due to the exposed non-insulated tubing. During cooling, the cool tank was
connected to the tubing inlet/outlet for the required zone, with the remaining zones connected to the warming tank. Water flow rate within each zone was monitored using manually adjustable flow control meters maintained at 300 mL.min\(^{-1}\) (Cole Parmer, UK) giving a total suit flow rate of 3.6 L.min\(^{-1}\). Thermistors (PT100) located at the point of the inlet/outlet of each zone monitored water temperature as it entered and returned from the suit. Water temperature was monitored and recorded using DASYLab (National Instruments Ireland Resources Ltd.) and displayed on a computer monitor.

![Figure 2.1: A schematic representation of the individual zones within the Water Perfused Suit. A) head, torso, upper arms, forearms, hands, front thigh, lower leg feet; B) head, upper back, lower back, upper arms, forearms, hands, buttocks, rear thigh, lower legs and feet.](image)

### 2.2.3 Measurements

Participants’ height (Seca, Birmingham, UK) and weight (ID1 Multi Range, Sartorius, Goettingen, DE) was recorded. Body fat content was calculated with skinfold callipers (Harpenden, HaB Intl Ltd, Warwickshire, UK) using the 7 site skinfold method as described by Jackson and Pollock and weighted for the athletic population.
Body surface area was calculated using the DuBois formula (Du Bois and Du Bois 1989).

The temperature of the circulating water in each body zone was measured at the point of the tubing inlet/outlet to allow the calculation of heat flux evident as a result of the cooled water and absorption by the body and loss to the environment. The quantities of conductive heat exchange were calculated using the following formula:

\[
Q_w = \frac{(m_w \cdot \Delta T)}{(C_p \cdot area)} \quad \text{[W.m}^{-2}\text{]} \quad \text{[2.1]}
\]

where:
- \(Q_w\) = Heat flux (W.m\(^{-2}\))
- \(m_w\) = water flow rate (g.sec\(^{-1}\))
- \(\Delta T\) = corrected change in water temperature (°C)
- \(C_p\) = Specific heat of water (J.g\(^{-1}\).°C\(^{-1}\))
- \(area\) = area of zone (m\(^2\))

In order to account for heat exchange that occurred as a result of the connective tubing, the heat exchange to the environment per meter of tubing was calculated. This was achieved by firstly running 10°C water through a known length of connective tubing and recording the difference between inlet and outlet temperature to allow for the calculation of heat exchange with the environment per meter of the tubing. Secondly, to determine the heat exchange with the surrounding environment, the whole suit was connected, covered with a duvet for additional insulation to replicate the experimental trials and filled with insulative padding to minimise heat exchange between different zones. 10°C water was then run through the suit for 30 minutes to allow for equilibrium of heat exchange to occur. Heat exchange at each individual zone was then calculated. This allowed for the calculation of the exact heat exchange value for each zone (figure 2.2). The corrected value was then used in the above equation for the calculation of heat exchange with the body.
To monitor changes in core temperature ($T_c$), rectal temperature was monitored and recorded throughout experimentation as an indicator of any changes in $T_c$. Participants inserted a rectal thermistor (Grant Instruments Ltd, Cambridge, UK) 10cm beyond the anal sphincter. Local skin temperature ($T_{sk}$) was measured using calibrated thermistors (manufacturer reported accuracy of ± 0.3°C, Grant Instruments Ltd, Cambridge, UK) placed at the following sites on the body: forehead, neck superior to C4, chest, the lateral aspect of the upper arm midway along the humerus, the lateral aspect of the forearm midway along the radius, the dorsal surface of the hand, 10cm lateral to the umbilicus, mid surface of the scapula spine, lateral to L4/5, muscle belly of rectus femoris and biceps femoris, the widest diameter of the gastrocnemius and midway along the 3rd metatarsal of the foot. Temperatures were recorded at 10s intervals using a Grant Squirrel 2020 data logger (Grant Instruments Ltd, Cambridge, UK). Thermistors were calibrated using water immersion in a thermostatic circulator water bath (GD120 R1, Grant Instruments, UK) at 7x5 minute stable plateau temperatures (10°C, 15°C, 20°C, 25°C, 30°C, 35°C and 40°C). The measurement of the thermistors was referenced against a calibrated certified reference thermometer. Following calibration, thermistors were within 0.1 °C of the reference thermometer. Heart rate was recorded at 5-minute intervals using a commercially available heart rate monitor (RS 800 Polar, Kempele, Finland).

2.2.4 Perceptual measures
Thermal sensation was recorded at 5-minute intervals using a 21-point scale ranging from extremely cold (-10), neutral (0) to extremely hot (10) (Appendix B (ASHRAE 1997). Thermal sensation was recorded in the last 60 seconds of each cooling and warming phase, with participants giving two scores - the first for local thermal sensation for the area being manipulated, and the second for overall thermal sensation.

2.2.5 Experimental Procedure
Experimental sessions were all conducted in a room with air temperature of 21.9 ± 1.2°C and humidity of 37.4 ± 2.5%. Participants were studied at rest whilst lying supine on an examination bed and covered with a duvet for insulation to reduce environmental heat loss. Eleven body zones were assessed for their rate of conductive
heat exchange, these were: head, torso, upper back, lower back, upper arms, forearms, hands, front thighs, rear thighs, lower legs and feet. Participants underwent a 10 minute period of thermal stabilisation during which time all zones of the WPS were connected to an inlet temperature of 33°C and $T_{sk}$ at all sites was within the range of 32-33°C. Each zone was then serially exposed to a cycle of 5-minutes of cooling at 10°C and 5 minutes re-warming at 33°C. The order of heating and cooling of zones was balanced to reduce any influence of prior warming and cooling from one zone to the next.

2.2.6 Statistics
Preliminary analysis was conducted to ensure that there was no violation of the assumptions of the normality of distribution using the Shapiro-Wilk test. The mean and SD were calculated for all data. Repeated Measures Analysis of Variance (ANOVA) was used for analysis of differences in heat exchange between different anatomical zones. Where significant differences were identified, post-hoc two way paired samples t-tests with Bonferroni correction for multiple comparisons were conducted. The relationships between variables were assessed using a Pearson product-moment correlation coefficient. In all instances the accepted level of statistical significance was set a priori to $p < 0.05$, and the null hypothesis accepted or rejected accordingly. Where greater levels of significance were found, they are reported accordingly. Data presented as mean ± SD.
2.3 Results

Tests for normality of distribution showed that all heat exchange data were normally distributed (p = 0.282). Figure 2.2 shows the differences in calculated heat exchange that actually occurred within the suit, allowing for the heat loss occurring from the external supply tubing. At 7 of the 11 zones, there was a significant effect of heat loss through the system on the total calculated heat loss (p<0.05). For the remaining 4 zones, although there was a trend towards overestimation of heat loss, there were no significant differences between the initial value and the final corrected value. There was a positive correlation between cooling power (W.m\(^{-2}\)) and external tubing length (r=0.6 p<0.05, figure 2.3). There were no significant correlations for either \(\Delta\) water temperature and tube length (r = 0.5 p=0.118) or cooling (W) and tube length (r = 0.4 p = 0.122). Table 2.1 shows the mean changes in water temperature as calculated from the difference in outlet minus inlet temperature for water suit. The corrected heat

![Figure 2.2: The difference between calculated values of heat loss between corrected and uncorrected values. Values were obtained by subtracting heat exchange values from the empty WPS from those obtained from the experimental trials. * = p<0.05; ** = p<0.01, *** = p<0.0005. N =10. Data presented as mean ± SD](image)
flux is shown for each individual anatomical zone ± S.D, with the inlet water temperature maintained at 10.0 ± 1.9°C throughout the course of experimentation.

Figure 2.3: The correlation between cooling power and external tube length, p<0.05

2.3.1 Heat Exchange at different body zones
The change in overall heat flux for each body segment during cooling is shown in figure 2.4. The greatest amount of heat transferred from the body to the cooled water was from the hands (724.3 ± 75.8 W.m⁻²), foot (658.9 ± 173.7 W.m⁻²) forearms (644.0 ± 215.9 W.m⁻²), and upper back (637.6 ± 87.1 W.m⁻²). The least amount of heat exchange occurred at the head and torso (230.5 ± 49.4 W.m⁻² and 361.7 ± 176.1 W.m⁻² respectively). There was a significant main effect of zones on heat exchange (p < 0.001). Post-hoc analysis showed that significant mean differences between the head and hands (p < 0.005) and front thigh and hands (p < 0.05, figure 2.4).
Table 2.1: Mean heat flux for different body zones. Surface is area of each zone, length corresponds to the length of tubing within a given zone, external tubing corresponds to the length of tubing that is open to the environment between the suit and the heater, internal suit tubing is the total length of tubing within each zone, $\Delta T$ is the change in inlet versus outlet water temperature, and mean heat loss is the cooling power of each zone.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Surface area (m$^2$)</th>
<th>External Tubing (m)</th>
<th>Internal Tubing (m)</th>
<th>Mean Flow Rate (mL.min$^{-1}$)</th>
<th>Mean $\Delta T$ ($^\circ$C)</th>
<th>Uncorrected Mean Heat Loss (W.m$^{-2}$)</th>
<th>Corrected Mean Heat Loss (W.m$^{-2}$)</th>
</tr>
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<tbody>
<tr>
<td>1. Head</td>
<td>0.099</td>
<td>3.70</td>
<td>7.46</td>
<td>279.4 ± 61.7</td>
<td>2.4 ± 0.2</td>
<td>528.0 ± 49.4</td>
<td>327 ± 87.3</td>
</tr>
<tr>
<td>2. Torso</td>
<td>0.210</td>
<td>3.60</td>
<td>18.65</td>
<td>280.5 ± 33.4</td>
<td>4.1 ± 1.6</td>
<td>435.1 ± 176.1</td>
<td>357.2 ± 184.9</td>
</tr>
<tr>
<td>3. Upper Back</td>
<td>0.124</td>
<td>3.56</td>
<td>10.39</td>
<td>279.5 ± 56.2</td>
<td>4.4 ± 0.4</td>
<td>721.9 ± 87.1</td>
<td>534.8 ± 132.9</td>
</tr>
<tr>
<td>4. Lower Back</td>
<td>0.110</td>
<td>3.62</td>
<td>9.20</td>
<td>289.0 ± 31.4</td>
<td>2.1 ± 0.7</td>
<td>452.4 ± 221.0</td>
<td>295.7 ± 249.5</td>
</tr>
<tr>
<td>5. Upper Arm</td>
<td>0.180</td>
<td>3.82</td>
<td>13.06</td>
<td>287.0 ± 31.3</td>
<td>4.8 ± 1.2</td>
<td>601.5 ± 198.7</td>
<td>498.1 ± 220.5</td>
</tr>
<tr>
<td>6. Forearm</td>
<td>0.106</td>
<td>3.67</td>
<td>8.58</td>
<td>287.0 ± 31.3</td>
<td>4.7 ± 0.9</td>
<td>960.6 ± 215.9</td>
<td>789.6 ± 235.6</td>
</tr>
<tr>
<td>7. Hands</td>
<td>0.084</td>
<td>3.91</td>
<td>5.08</td>
<td>284.5 ± 47.3</td>
<td>4.7 ± 0.3</td>
<td>1173.3 ± 75.8</td>
<td>876.1 ± 121.4</td>
</tr>
<tr>
<td>8. Front Thigh</td>
<td>0.224</td>
<td>3.85</td>
<td>17.77</td>
<td>280.0 ± 46.4</td>
<td>7.8 ± 0.8</td>
<td>723.0 ± 82.0</td>
<td>636.7 ± 89.5</td>
</tr>
<tr>
<td>9. Rear Thigh</td>
<td>0.116</td>
<td>3.86</td>
<td>10.33</td>
<td>280.0 ± 46.43</td>
<td>4.2 ± 1.7</td>
<td>813.5 ± 355.5</td>
<td>603.9 ± 372.5</td>
</tr>
<tr>
<td>10. Lower Leg</td>
<td>0.188</td>
<td>3.71</td>
<td>9.50</td>
<td>279.0 ± 56.3</td>
<td>5.6 ± 0.8</td>
<td>591.3 ± 129.4</td>
<td>499.4 ± 126.8</td>
</tr>
<tr>
<td>11. Foot</td>
<td>0.135</td>
<td>3.93</td>
<td>11.91</td>
<td>287.5 ± 31.7</td>
<td>5.6 ± 0.6</td>
<td>906.4 ± 173.7</td>
<td>751.1 ± 197.1</td>
</tr>
<tr>
<td>Total</td>
<td>1.576</td>
<td>41.23</td>
<td>121.93</td>
<td>283.0 ± 43.0</td>
<td>4.6 ± 0.9</td>
<td>718.8 ± 160.4</td>
<td>560.9 ± 183.5</td>
</tr>
</tbody>
</table>

* = $p<0.05$; ** = $p<0.01$, *** = $p<0.0005$ between corrected and uncorrected values. Superscript denoted significant difference compared to numbered zone ($p<0.05$).
2.3.2 Thermal Sensation

Each body zone was highly sensitive to temperature change, and the cooling of a body segment resulted in a significant change in thermal sensation compared to that experienced by the body as a whole (p < 0.005, figure 2.4). Differences in thermal sensation were significant for all body zones (p < 0.05). There was a small but significant correlation between heat flux and thermal sensation (r = 0.231, p < 0.05, figure 2.5). There was no relationship between local thermal sensations on whole body thermal sensation, following 5 minutes of cooling.

![Figure 2.4: Thermal sensation during cooling for each body zone’s sensation and whole body sensation. Measures were taken in the last 60 seconds of each cooling phase. Local represents the area undergoing cooling. Overall represents the overall thermal sensation during cooling of the corresponding anatomical zone. * = p<0.05, ** = p<0.01 denotes significant difference between overall and local thermal sensation. N =10. Data presented as mean ± SD](image-url)
2.3.3 Core Temperature

Throughout the experimental trial, there was a significant gradual decline in core temperature (p < 0.001; figure 2.6). There was no significant difference in mean $T_c$ between each zone following 5 minutes of cooling exposure (head $36.7 \pm 0.2 ^\circ$C, torso $36.8 \pm 0.2 ^\circ$C, upper arm $36.8 \pm 0.3 ^\circ$C, forearm $36.9 \pm 0.3 ^\circ$C, hands $36.8 \pm 0.3 ^\circ$C, upper back $36.8 \pm 0.3 ^\circ$C, lower back $36.7 \pm 0.2 ^\circ$C, front thigh $36.8 \pm 0.2 ^\circ$C, rear thigh $36.8 \pm 0.2 ^\circ$C, lower leg $36.8 \pm 0.3 ^\circ$C and foot $36.7 \pm 0.2 ^\circ$C). Changes in rectal temperature in response to individual zone cooling were not calculated due to the slow change in rectal measurement of $T_c$ in response to peripheral cooling.
Figure 2.6: The mean decline in core temperature as measured by a rectal probe throughout the course of the trial. * $p < 0.05$. $N = 9$. Data presented as mean ± SD

2.3.4 Skin Temperature

Nine of the eleven sites at which $T_{sk}$ was measured, demonstrated a significant decline in $T_{sk}$ from T0 to T5 during their cooling phase (figure 2.7, $p < 0.005$), however for both the head and neck, there was no significant change in $T_{sk}$ during cooling.
Figure 2.7: Fluctuation in skin temperature at different anatomical zones during the cooling and re-warming cycle individually performed at each zone. Blue solid line indicates cooling period. Red solid line indicates re-warming. Compared to 0:00 † = p<0.05; * = p<0.0005. n=10. Data presented as mean ± SD.
2.3.5 Heart Rate
There were no significant changes in heart rate as a result of cooling, either throughout the duration of the trial, or during cooling at any single body zone Mean heart rate during cooling was $59.7 \pm 1.2 \text{ bpm}^{-1}$ and $60.5 \pm 1.5 \text{ bpm}^{-1}$ during heating.

2.4 Discussion
The aim of this study was to determine how heat exchange and local thermal sensation at regionalised anatomical zones responded to changes in temperature, via the manipulation of inlet water temperature flowing through a water perfused suit. The results demonstrate that different body zones have very different rates of heat loss when cold water is moved over the skin surface through a water-perfused suit. The most powerful areas for extracting heat were the hands, forearms, upper back and the feet, all areas which are highly vascularised and of low density adipose tissue (Brooks et al. 2005), thus allowing us to accept our initial hypothesis. The results differ slightly from those of Koscheyev et al., (Koscheyev et al. 2002) who reported that the hands were a poor region for obtaining a high rate of heat flux. Furthermore, unlike previous studies, the data obtained in this study control for changes in flow rate of water through a particular zone, which has not been achieved before.

There are several differences between this and previous studies that have employed water perfused suits to study changes in thermal sensation and rates of heat exchange. Firstly, we were able closely control the flow of water to each body zone, to try and minimise any affect of flow rate on heat gain within the WPS. This improved control allows for greater accuracy in calculating the degree of heat loss a given zone. As the cooled water passes through each suit zone, and over a given body zone, it gains heat from the body via conductive heat exchange, and the rate at which this occurs is closely influenced by water flow rate. Flow rate is an important factor, as with lower flow rates, the warmed or cooled water remains in contact with a body zone for a longer period of time, thus reducing the thermal gradient between the body surface and the suit. Therefore, a higher flow rate through each zone is beneficial, as the warmed water is moved away from a zone more quickly and replaced with cool water, maintaining the thermal gradient between the two surfaces, and allowing heat exchange to occur effectively. Consequently where flow rates are lower, as often the
case in previous research, then there may be an underestimation of the rate of heat loss from the body.

The same is true of tube length. Within the WPS there were differing lengths of tubing both internally and externally, despite this flow rate was kept constant between zones. Therefore, the potential is that in zones with greater lengths of tubing, there was greater heat exchange with the environment, as the circulating water remained in the larger loops for longer. Theoretically, with longer tube lengths, the change in temperature may also increase, owing to the increased heat exchange with the surrounding environment. Indeed, this is evident from the present data, although the linearity of this increase is not as high as would be expected. It is possible that this is due to differences in the tubing arrangement and interference from neighbouring tubes impacting upon the tube’s heat loss, although care was taken to minimize this interference it is a possible explanation as to why there is not a greater degree of linearity between increases in tube length and heat loss. In order to maintain a given value for heat exchange between zones of differing tubing lengths, cooling power would need to be increased to overcome environmental heat exchange. In this instance, this would require alterations in inlet water temperature; with zones possessing longer tubing lengths having colder water inlet temperatures.

To overcome these issues, it would be necessary to adjust both flow rate and water inlet temperature for each individual zone, so that there is no difference between zones in the time it takes for the water to complete a circuit of a given zone. However, to achieve this would require very high flow rates in some of the larger zones (>1000 mL.min\(^{-1}\)), which would be beyond the pressure limits of some of the components of the system. Nevertheless, this is an important limitation to consider, as despite our improvements in using a higher flow rates to minimize some of the underestimation in heat loss, we have not completely achieved this, and these results still present an underestimation of actual convective heat loss.

The duration of cooling used in the present study is also shorter than used in previous studies. Pilot testing revealed that a cooling period of 10 minutes or more resulted in a minimal increase in cooling compared to the 5 minutes of cooling used presently. A further difference between this and the Koscheyev studies (Koscheyev et al. 2002,
Koscheyev et al. 2006) is the number and distribution of zones that were used, particularly the inclusion of the back, split into upper and lower, and the separation of the thighs into front and back. These differences in methodological approaches possibly allow for greater insight into the role of different anatomical regions into heat loss and thermal sensation.

Heat exchange from the body core to the surrounding environment is limited by the density of muscle and adipose tissue under the skin surface as well as by alterations in SkBF, all of which will impair heat exchange (Cooper and Trezek 1971). An increase in resistance to heat exchange via increases in vasoconstricted muscle (Rennie 1988), and therefore reduced skin surface blood flow (House et al. 1997), and fat (Rennie 1988, Nadel et al. 1974, Veicsteinas et al. 1982) will provide greater resistance to heat exchange with the environment and result in reduced heat loss. Consequently, areas such as the torso, abdomen, back and legs, which are all areas of high muscularity and fat deposition, demonstrate lower rates of heat exchange compared to leaner and more highly vascularised regions such as the hands and forearms.

One of the major challenges of cooling, particularly during physical activity is to overcome the conflict for blood flow between the skin and the working muscles. One way in which this may be achieved is via the specific targeting of regions with a high vascular density, which will allow for maximal conductive and convective heat loss with minimal resistance. Skin blood flow is an important factor in maintaining thermal homeostasis via the regulation of heat transfer from the body to the environment. During exposure to a warm environment, one way in which the body attempts to maintain a stable $T_c$ is via an increase in skin blood flow (SkBF), with maximal flow rates of 240 L.m$^{-2}$.hr$^{-1}$ having been reported (Nadel et al. 1979, Rowell 1974, Havenith 2001). An elevation in SkBF results in an increase in conductive, convective and radiative heat loss, via the transport of metabolic heat by the blood from the core to the skin, thus raises $T_{sk}$ and that way increasing heat loss to the environment. However, under circumstances where there is also increased metabolic activity in the muscles, which requires elevated blood flow and causes further heat production, then there is a degree of conflict concerning the distribution of blood flow between muscle and skin. This is evident during moderate exercise where skin blood flow is dramatically reduced to between 60 and 120 L.m$^{-2}$.hr$^{-1}$, depending on the level
of aerobic power production (Havenith 2001), with a higher level of aerobic power resulting in lower SkBF and a gradual increase in $T_c$. Therefore, it is important that the cooling applied is of sufficient intensity to minimize the effect elevated muscle activity has on SkBF, by maintaining skin vasodilation, blood flow and convective heat loss. It has been reported that the temperature range which will maintain vasodilatation and skin blood flow is in the region of ~15°C (House et al. 1997, Tipton et al. 1993).

Unexpectedly, core temperature underwent a steady decline throughout the trial. The suit used in the present study covered in excess of 70% of total body surface area, and although the largest zone of cooling only covered 10%, it is possible that the drop in $T_c$ occurred as a result of repeated cooling of short periods. Covering a large total body surface area may have a large cumulative effect on $T_c$ decline. Kume et al., suggest that there may be a threshold of 40% body surface area coverage for cooling to cause a decline in $T_c$ (Kume et al. 2009). They report that during exercise, increases in oesophageal and thigh temperatures were significantly elevated if less than 40% of total body surface area had been exposed to cooling. Alternatively, it may be that each individual area where cooling was applied was not large enough to trigger a large degree of peripheral vasoconstriction. This would result in a greater volume of circulating SkBF undergoing convective cooling with the cool skin surface, causing a reduction in $T_c$ as the cooled blood returns to the body core. A further possibility is that the ambient temperature of 21°C may have resulted in heat loss whilst at rest owing to the large thermal gradient in existence between body temperature and the surrounding environment. In future, similar studies should consider using a thermoneutral environmental temperature (~28°C) to counter this possibility.

### 2.4.1 Perceptual Changes

All zones were sensitive to changes in temperature, in that there was a clear change in reported temperature sensation following 5-minutes cooling. Cooling of the arms, thighs and torso all resulted in a reduction in whole body thermal sensation towards feeling “cool”. This is in agreement with previous research which demonstrates that the torso is a highly dominant influence on overall thermal sensation, whereas the
influence of the extremities such as the hands and feet on overall thermal sensation is considerably less despite large changes in $T_{sk}$ (Zhang et al. 2004). It is likely that the disparity in regional thermal comfort arose due to differences in the distribution of thermoreceptors over the skin's surface, with areas that are more sensitive to changes in temperature assumed to have a greater density of thermoreceptors (Strughold and Porz 1931, Hensel 1982). The arms, hands, thighs and feet demonstrated the greatest response in thermal sensitivity in the present study. This finding is in contrast to previous results, which suggest that regions closer to the trunk possess a higher density of cold sensitive areas, (Strughold and Porz 1931, Choi and Seol 2001). One possible reason why we have demonstrated a high level of thermal sensation in the hands and feet, which according to Strughold and Choi, possess a low density of cold spots, is down to the size of each individual zone. The hands and feet were two of the smaller zones within the WPS, and as discussed previously, the combination of a high flow rate and a small surface area may have caused a faster rate of cooling and greater thermal sensitivity response.

2.4.2 Study Limitations
There are some acknowledged limitations to the present study. The current study overlooks changes in skin blood flow in response to regional cooling. However, it is well documented that in response to skin cooling blood flow is redirected away from the skin in an attempt to maintain a stable core temperature (Bogerd et al. 2010, Johnson and Kellogg 2010, Havenith et al. 1995a, Stocks et al. 2004). It would be of interest to consider the effect that regionalised cooling has on rates of skin blood flow, both locally and to the skin as a whole. Secondly, the size of each zone may have an effect on heat exchange. It is possible that larger zones may require a higher rate of flow through the suit depending on their total area, rather than a standard flow rate. The water in larger zones will remain in that zone for a longer period of time than in smaller zones, this allowing more time for an increase in water temperature to occur via heat exchange with the body. As considered earlier in this discussion, a flow rate that was more relative to zone size would help prevent this situation arising. Thirdly, the tubing that supplied the suit with water was not insulated after the point of temperature measurement. This will have caused a difference in temperature between the recorded water temperature and actual water temperature, at both inlet and outlet.
points of the suit, although we did attempt to apply a correction to this. This may result in a systematic overestimation of the cooling power of the suit and each individual body segment.

These acknowledged problems commonly arise in studies using similarly designed water perfused suits (Koscheyev et al. 2002, Leon et al. 2004, Yoshida et al. 2005). These problems include differences in flow rate, a low total flow volume and the density of tubing in a given zone. We have tried to minimise these where possible and improve control for changes in flow rate that are inherent in zones of different sizes and tubing lengths.

2.4.3 Conclusion
In conclusion, these data demonstrate that the areas with the highest potential for heat loss are the forearms, hands, feet and upper back. This confirms that the highest rates of heat loss will be in areas consisting of low levels of adipose tissue and skeletal muscle, and are highly vascularised. This suggests that regions that may be targeted for heat removal should be characterised by low insulative capacity and a high relative volume of skin blood flow to assist in heat removal. In addition, as there were significant differences between the thermal sensations from zone to zone, it is important to consider this when applying a cooling protocol, as if thermal discomfort becomes a problem, it may have a detrimental effect on any subsequent task performance.
Chapter 3

Half-Time Cooling Using Hand and Forearm Immersion During Intermittent Exercise in The Heat

3 Chapter Summary
The study presented in this chapter aimed to determine the effect mid-event cooling has on subsequent running performance in the heat, using an intermittent protocol based on field hockey. Participants were requested to complete two 35-minute bouts of intermittent exercise in hot ambient conditions on a motorized treadmill. The first bout mimicked the intermittent nature of field hockey, with participants completing 35-minutes of intermittent exercise made up of periods of walking, jogging, sprinting and passive recovery. In the second bout, they completed 35 minutes of interval exercise split as 60 seconds of maximal self-paced running, immediately followed by 90-seconds active recovery, with the aim of covering as much distance as possible. In the intervening “half-time” period, participant immersed their hands and forearms in cold water (14˚C) for 10-minutes. The cooling placement was based on data obtained in study 1 (Chapter 2) with the hands and forearms having been demonstrated to be regions of high heat loss in response to skin surface cooling. Each participant completed two trials, one of which acted as the control with no immersion occurring. There was a positive effect on lowering thermal sensation following half time cooling. There was no significant improvement in the distance covered during the self-paced exercise component, although there was a trend towards greater distance being covered.

3.1 Introduction
In recent years, there has been a great deal of interest concerning ways in which body temperature may be manipulated in order to enhance physical performance. It is well accepted that there is a strong link between elevations in environmental temperature and a decline in performance and onset of fatigue (Maughan and Shirreffs 2004, Galloway and Maughan 1997), which is particularly evident during endurance events such as the marathon. This decline in performance has been suggested to be linked to
a critical limiting core temperature ($T_c$) of $\sim 40^\circ C$, beyond which physical fatigue will occur (Gonzalez-Alonso et al. 1999). It has been demonstrated that fatigue during exercise in the heat is independent of muscle glycogen content, as fatigue is reached when there are still sufficient supplies of muscle and liver glycogen to meet metabolic demand. However, fatigue always occurred once a core temperature of $\sim 40^\circ C$ was reached (Booth et al. 2001, Marino 2004). Following the discovery of a strong link between the attainment of a critical limiting $T_c$ and performance decline, there have been many attempts to curtail the effects of high ambient temperatures on core temperature and exercise performance. The rationale being that if performance is limited by approaching a certain core temperature, then lowering $T_c$ prior to exercise should have the affect of prolonging performance at a given intensity; this manoeuver has become known as pre-cooling.

There have been a number of different methods used in implementing pre-cooling, including cold air exposure (Lee and Haymes 1995), wearing ice vests (Arngrimsson et al. 2004, Webster et al. 2005, Quod et al. 2008, Price et al. 2009, Ross et al. 2010) and cold water immersion (Vaile et al. 2008a, Quod et al. 2008, Rowsell et al. 2009, Halson et al. 2008). The methods used in each instance vary widely, but there is a general agreement that cooling using the aforementioned methods can lower $T_c$ and contribute to improved exercise performance. It has been shown that the use of a ice vest prior to the completion of a 5000m run resulted in lower $T_c$, mean body temperature and heart rate during the warm up phase, and into the 5000m run (Arngrimsson et al. 2004). Furthermore, the authors report that time to complete the run was 1% faster following a warm up completed whilst wearing an ice vest.

There exists some uncertainty about the duration of any benefits arising from pre-cooling. In one study, pre-cooling effectively reduced $T_c$ and improved 5000m running performance, although the reduction in $T_c$ following pre-cooling did not last throughout the run (Arngrimsson et al. 2004). It may be that the effects of pre-cooling are able to have an influence during the first 30-40 minutes of continuous exercise (Marino 2002). Furthermore there are some authors who report pre-cooling having a beneficial effect during intermittent bouts of exercise (Castle et al. 2006). Additionally, many of the methods used to apply pre-cooling to date involve heavy and cumbersome equipment, and are often not very practical for application outside of
the laboratory. Indeed, the added weight of such items, such as cooling vests, can add up to 4kg in weight for the athlete to carry around during a warm up, with the metabolic cost of this possibly negating any effect of cooling if the cooling power is not sufficiently high. Clearly, there is still much debate about how athlete cooling may be applied in the most effective manner to achieve the greatest performance improvement in a way that can be easily applied in the field.

Much of the current literature attributes the alteration in performance following pre-cooling to a reduction in thermal and cardiovascular strain (Arngrimsson et al. 2004), or via changes in the central (Tucker et al. 2004, Ansley et al. 2004) and/or peripheral (Hettinga et al. 2006, Schlader et al. 2010a), recruitment and activation of skeletal muscle. Recently, it has been shown that voluntary muscle activation is impaired by elevated core temperature (Drust et al. 2005) and not necessarily local muscle temperature (Thomas et al. 2006). Thomas et al., attempted to isolate the effects of elevated $T_c$ on neuromuscular performance. Core temperature was first artificially raised to 39.5°C and then cooled to 37.9°C with the use of a water perfused suit, during which time the right leg was maintained at a thermoneutral temperature and the left leg was allowed to heat and cool. In the left, there was a greater decline in maximal isometric voluntary contraction, torque and maximal voluntary activation compared to the decline evident in the thermoneutral right leg during passive heating. Once cooling was initiated, there was a rapid decline in skin temperature, however torque and voluntary activation only returned to baseline values once $T_c$ was lowered towards resting levels (Thomas et al. 2006). These results indicate that changes in local skin temperature may be partially linked to changes in skeletal muscle activation, and that any elevation in local skin temperature and $T_c$ because of exercise will eventually result in impaired activation, and thus performance.

One theory which has received much interest to date is that changes in performance arise as a result in a change to athlete pacing strategy in response to changes in $T_c$. Noakes et al., suggest that a number of different physiological systems continually provide afferent feedback to a central governor, which in turn make alterations in skeletal muscle recruitment as a part of a continually changing pacing strategy (Noakes et al. 2005). Arngrimsson et al’s performance trial was terminated once runners had covered 5000m and not on attainment of a critical limiting temperature,
with indications that athletes had regulated their pacing strategy so they were near the point of exhaustion and critical limiting temperature on completion of the 5000m trial. This supports the idea that pacing strategy is altered during competition, to allow for completion of a given task, before hyperthermia causes fatigue and failure (Marino 2004). However, there remains uncertainty as to whether pacing strategies are altered as a result of central activation or peripheral fatigue (Perrey et al. 2010, Marcara 2010, Amann and Secher 2010).

During many team games, and in competitions that require repeated bouts of exercise with minimal recovery, there is evidence to suggest that incomplete recovery of thermal balance can have a negative effect on performance. It appears that pre-cooling prior to a single bout of exercise does have an ergogenic effect on performance, and there is recent data to suggest that intermittent or “half-time” cooling may be beneficial for repeated bouts of exercise (Vaile et al. 2008a, Hornery et al. 2005). Vaile et al., demonstrated that the use of cold-water immersion in between bouts of cycling was more effective at maintaining high intensity cycling performance than active recovery alone (Vaile et al. 2008a).

These results suggest that active cooling during a break in exercise activity may be able to reduce the thermal load experienced by athletes, and thus minimize the associated negative effects on performance. However, to date there are very few studies which consider a methodology which may be effectively applied during a competitive scenario.

3.1.1 Aim
The primary aim of this study was to determine whether a combined forearm and hand cooling intervention could have a beneficial effect on exercise performance in the heat, using a protocol designed to mimic the demands of field hockey.

3.1.2 Hypothesis
It was hypothesized that combined forearm and hand cooling via cold-water immersion would improve the distance covered in the second half of the simulated
game of hockey. Furthermore, we expect that participants will experience a reduction in perceived thermal sensation as a result of the cooling intervention.

3.2 Methods

3.2.1 Experimental Overview
In an environmental chamber maintained at 30.3 ± 1.4°C and 49.7 ± 1.8% relative humidity, eight male participants completed a 70-minute bout of exercise on a treadmill. The time was separated into two 35-minute periods, with the first designed to mimic the demands of field hockey and was at various intensities relative to each participant’s maximal oxygen uptake ($\dot{V}O_2$ max). The second bout was a self-paced bout of intermittent exercise, during which time participants were instructed to cover as much distance as possible. In between each exercise bout, participants underwent 10 minutes of hand and forearm immersion in cold water. All trials were balanced and took part at the same time of day with a minimum of 7 days between each trial.

3.2.2 Participants
Based on participant numbers in the pre-existing literature, eight elite male hockey players were recruited to take part in this study age (mean ± SD) 20.4 ± 1.7 years; height 181.2 ± 6.1 cm; weight 80.3 ± 7.3 kg; $\dot{V}O_2$ max 59.5 ± 7.7 mL.kg.min$^{-1}$. All participants were non-smokers and played national or international level representative field hockey. All participants gave their written informed consent. The Loughborough University Ethical Advisory Committee approved all procedures.

3.2.3 Preliminary Tests
Approximately 7 days prior to the first experimental trial, participants reported to the laboratory for a maximal oxygen uptake test (VO$_2$ max test). All tests were completed on a treadmill (HP Cosmos quasar, Germany) in moderate ambient conditions (23.7 ± 1.4°C). All VO$_2$ max tests were completed on the same treadmill. The test protocol required all participants to run at a constant self selected pace with gradient increasing
every 3 minutes (0° 3.5°, 6.0°, 8.5°, 11°, 13.5°, 16°) throughout the test until volitional fatigue. Running speeds equivalent to 75% and 95% VO\(_2\) max for each participant were calculated and derived from following formula (American College of Sports Medicine 2006):

\[
VO_2 \text{ max} = (0.2 \cdot S) + (0.9 \cdot S \cdot G) + 3.5 \quad \text{[mL.kg}^{-1}.\text{min}^{-1}\text{]} \quad [3.1]
\]

where:
S = speed (m.min\(^{-1}\))
G = percentage gradient as a fraction

These values were later used to formulate the intensity of the exercise bout which would be completed during the experimental trials.

### 3.2.4 Experimental Protocol

The experimental trials consisted of running in an environmental chamber maintained at ~30°C, with a relative humidity of ~50% and 10 minutes of combined forearm and hand immersion in water at 14.2 ± 1.2°C or a control condition with no immersion. For obvious reasons the participants could not be blinded to the conditions, but were unaware of the researchers’ hypothesis. It was assumed that the participants were not heat acclimatized, and the time period between trials was designed to minimize any effects of acclimation to the heat.

All participants reported to the laboratory on the morning of the trial having completed an overnight fast and refrained from strenuous exercise, alcohol and caffeine consumption for the previous 24 hours. To minimize the effect of pre-trial muscle glycogen content on exercise performance, participants completed a food diary and activity log in the 24 hours prior to the first trial, and were instructed to repeat the same diet prior to their second visit. On arrival at the laboratory participants voided and were weighed (Mettler ID1 Multi Range, Sartorius, Goettingen, DE). They then consumed a 500mL bolus of water to ensure adequate hydration. Participants were then fully instrumented with calibrated skin thermistors and self
inserted a rectal probe 10cm beyond the anal sphincter. They then moved to the environmental chamber.

3.2.5 Exercise Protocol
Participants first completed a 5-minute self-paced, steady state warm-up, which was then replicated on their second visit. They then underwent 5 minutes of static stretching to mimic pre-game activity. Following this period they then commenced the first 35-minute period (Part A). This consisted of seven, 5-minute continuous cycles of intermittent exercise completed on a treadmill at a gradient of 1%, based on values gained from GPS data (Sunderland et al, unpublished data) of male hockey players (Figure 3.2). A vertical bank of three fans (JS Humidifiers, Littlehampton, UK) was placed in front of the treadmill with the fans remaining (air velocity 3.5 ± 0.3 m.s\(^{-1}\)) on throughout the trial.

- 20s standing (0 km.hr\(^{-1}\))
- 75s walking (6 km.hr\(^{-1}\))
- 55s fast walking (7 km.hr\(^{-1}\))
- 100s jogging (75% \(\dot{V}O_2\) max, 12.6 ± 1.65 km.hr\(^{-1}\))
- 28s tempo (95% \(\dot{V}O_2\) max, 16.0 ± 2.15 km.hr\(^{-1}\))
- 5s increasing speed to sprint
- 12s sprint (20 km.hr\(^{-1}\))
- 5s decreasing speed to standing

Following the initial 35-minute exercise bout, participants were seated for 15 minutes, during which time they consumed a standardised volume of water (replicated from ad libitum consumption from visit 1). In the cooling condition, participants immersed their arms up to the level of the elbow in cold (14.2 ± 1.2 °C) water for 10 minutes (2-12 minutes of the half-time period, figure 3.1). In the remaining time, participants dried off their arms and consumed the remainder of the drink if needed. After 15 minutes, participants moved back to the treadmill for the second exercise period.
Figure 3.1: Participant undergoing forearm and hand immersion during half time cooling intervention. The forearms and hands were immersed up to the elbow in \(~14^\circ\text{C}\) water for 10 minutes

The second period (Part B) consisted of a self-paced bout of intermittent exercise, with 60 seconds of effort and 90 seconds of recovery. This cycle was completed 14 times to comprise the 35-minute half. Participants were only told to cover as much distance as they could in the time allowed, and received no further encouragement or information regarding time, heart rate or distance covered.
3.2.6 Measurements
Distance covered was manually recorded every 5-minutes. Skin thermistors (Grant Instruments Ltd., UK) were attached to four sites using Transpore™ Surgical Tape (3M Healthcare, St. Paul, Minnesota, USA) to the chest, arm, thigh and calf on the right side of the body to allow for the calculation of mean body temperature (Ramanathan 1964). A rectal probe (Grant Instruments Ltd., UK) was inserted 10cm beyond the anal sphincter for monitoring of core temperature ($T_c$). Heart rate was recorded throughout the trial using a heart rate monitor (RS800, Polar, Kempele, Fi). Thermal sensation (ASHRAE 1997) and the Rating of Perceived Exertion (RPE; Appendix B) (Borg 1982) were recorded every 5 minutes throughout the trial. Capillary blood lactate was measured using a Lactate Pro (Arkray, Shiga, Japan) at rest, following Part A, immediately post “half-time” and on completion of Part B (figure 3.3.2). Body heat content was calculated using the following equation (Havenith et al. 1995b):

![Figure 3.2: A schematic showing the outline of the experimental procedure, showing point at which physiological and performance measures were taken](image-url)
Heat Content = \left( 0.8 \cdot \Delta T_c + 0.2 \cdot \Delta \bar{T}_{sk} \right) \cdot C_b \quad \text{[J.g}^{-1}] \quad \text{[3.2]} \\

where:
\begin{align*}
\Delta T_c &= \text{change in core temperature (°C)} \\
\Delta \bar{T}_{sk} &= \text{change in mean skin temperature (°C)} \\
C_b &= \text{specific heat capacity of body tissue (3.49 J.g}^{-1}.°\text{C}^{-1})
\end{align*}

3.2.7 Statistics
All statistics were carried out using SPSS version 17. The distribution of data were analysed for normality using the Shapiro-Wilk test. Repeated measures ANOVA and paired samples t-tests were conducted on all data to identify any effect of the experimental conditions on all subjective data, and distance covered in the self-paced period. Where differences were identified, post hoc paired samples t-tests with Bonferroni correction for multiple comparisons were used. A one directional t-test was used to assess any difference between final distances covered. Final Statistical significance was set a priori to at p < 0.05, and the null hypothesis accepted or rejected accordingly. All data are presented as mean ± SD.
3.3 Results

Table 3.1: Mean distance covered during each 5-minute segment throughout the exercise trial. There were no significant differences between conditions.

<table>
<thead>
<tr>
<th>Time</th>
<th>Control (m)</th>
<th>Cooling (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Min</td>
<td>835.9 ± 64.7</td>
<td>834.5 ± 76.6</td>
</tr>
<tr>
<td>10 Min</td>
<td>846.8 ± 51.1</td>
<td>851.8 ± 74.6</td>
</tr>
<tr>
<td>15 Min</td>
<td>835.4 ± 36.8</td>
<td>869.1 ± 56.0</td>
</tr>
<tr>
<td>20 Min</td>
<td>850.0 ± 55.7</td>
<td>855.5 ± 63.1</td>
</tr>
<tr>
<td>25 Min</td>
<td>835.3 ± 39.4</td>
<td>852.6 ± 59.0</td>
</tr>
<tr>
<td>30 Min</td>
<td>855.4 ± 58.1</td>
<td>857.0 ± 59.5</td>
</tr>
<tr>
<td>35 Min</td>
<td>835.4 ± 32.5</td>
<td>852.9 ± 61.0</td>
</tr>
<tr>
<td>Total</td>
<td>5894.0 ± 288.2</td>
<td>5848.4 ± 256.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time</th>
<th>Simulated “half time”</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Min</td>
<td>866.13 ± 155.9</td>
</tr>
<tr>
<td>10 Min</td>
<td>847.0 ± 152.3</td>
</tr>
<tr>
<td>15 Min</td>
<td>823.4 ± 158.1</td>
</tr>
<tr>
<td>20 Min</td>
<td>851.9 ± 130.1</td>
</tr>
<tr>
<td>25 Min</td>
<td>791.6 ± 185.3</td>
</tr>
<tr>
<td>30 Min</td>
<td>887.9 ± 137.3</td>
</tr>
<tr>
<td>35 Min</td>
<td>848.9 ± 139.8</td>
</tr>
<tr>
<td>Total</td>
<td>5916.8 ± 879.2</td>
</tr>
</tbody>
</table>

3.3.1 Exercise Performance
Analysis demonstrated that there was normal distribution of data for both control (p=0.36) and cooling (p=0.24). There was a significant effect of time (p<0.05) but not condition on distance covered during the free paced second half run. Table 3.1 shows the mean distance covered during each 5-minute period throughout each trial. There was no significant difference in split distance covered between trials at any time point. However, six of the eight participants covered more distance following the cooling intervention and there was a 5.8% improvement in distance covered during the second period, which equates to an extra 331m covered, although this was non-significant (p = 0.2, figure 3.3).
Figure 3.3: Distance covered following a half-time cooling intervention lead to a trend of a 5.8% improvement in performance (*p*<0.1). *n*=8, data presented as mean ± S.D.

### 3.3.2 Thermal Sensation

Analysis revealed that the half-time cooling intervention had a significant effect on thermal sensation, causing a reduction from 5.8 ± 0.8 with no cooling to 4.3 ± 1.8 following cooling at the end of the 15 minute half time interval (*p* < 0.05, figure 3.4). This difference in thermal sensation lasted 15 minutes into the second half (*p* < 0.05).
Figure 3.4: Thermal sensation following forearm and hand immersion during a simulated half-time interval. * = p < 0.05. n=8, data presented as mean ± SD.

3.3.3 RPE

There was an overall effect of time on RPE (p<0.05) but not of condition (figure 3.5). There were no significant differences between conditions at any time point.
Figure 3.5: RPE following a cooling intervention after 35 minutes of exercise on subsequent ratings of RPE. n=8, data presented as mean ± SD

### 3.3.4 Blood Lactate

There was a significant effect of time on blood lactate concentration (p<0.01), but not of condition. There was a tendency for it to be elevated at the end of the self-paced exercise bout following forearm and hand cooling (3.8 ± 2.0, 5.0 ± 3.0 for control and cooling respectively p=0.1; figure 3.6).
Figure 3.6: Differences in blood lactate concentration. Blood lactate concentration throughout the trial did not differ at any time point between conditions. n=8, data presented as mean ± SD

3.3.5 Other Measures
There were no differences for CONT vs COOL respectively in heart rate (174 ± 4 vs 178 ± 6 bpm), $T_c$ (38.1 ± 0.2 vs 38.0 ± 0.3 °C), mean skin temperature (33.9 ± 0.4° vs 33.5 ± 0.4 °C) or body heat content (4.8 ± 0.1 vs 4.6 ± 1.0 J.g$^{-1}$) between conditions or at any time point within the second exercise bout.

3.4 Discussion
The main finding of this study was that 10 minutes of cold water immersion of the hands and forearms resulted in a reduced perception of thermal sensation of warmth, which lasted from the moment of immersion to 15 minutes into the second half. There was a trend of a 5.8% increase in distance covered during the second half of the simulated game. There were no significant differences in blood lactate concentration, core temperature, heart rate, mean skin temperature or body heat storage as a result of
hand and forearm immersion. Therefore, only half of the initial hypothesis can be accepted, regarding reductions in thermal sensation. The original working hypothesis is rejected regarding changes in performance, as there was no significant performance benefit following the cooling intervention.

3.4.1 Thermal Sensation and RPE
The present study supports previous findings that cooling of the forearms and hands results in an improved perception of thermal load (Green 2009), that is, participants reported feeling less hot following immersion. Duffield et al., reported that intermittent use of an ice cooling jacket during bouts of cycling resulted in a reduction in the perception of thermal load experienced (Duffield et al. 2003). Following an initial exercise period, whole body cold water immersion in 15°C resulted in a shift in thermal sensation towards cool, this reduction lasted for the duration of a second bout of exercise lasting 30 minutes (Vaile et al. 2008a). Taken together, these studies suggest an effective role for mid-event cooling in lowering perceptions of thermal load (Webster et al. 2005, Kume et al. 2009, Leon et al. 2004), which may in turn be of benefit to exercise performance (Schlader et al. 2011, Schlader et al. 2011).

In the present study, a strong effect of the half-time cooling intervention was evident as all participants, even those who performed less favourably in the cooling trial, reported improved feelings of thermal sensation following cooling. One possible explanation for the results described here is that there are regional differences in thermal sensation sensitivity (Nakamura et al. 2008) and the cooling power of a given zone (Koscheyev et al. 2002). It has been shown that the regional cooling power and thermal sensitivity of the arms and hands compared to other body zones was elevated when surface area was accounted for (Chapter 2). This shows that forearm and hand immersion implemented in the current study was of sufficient power to cause a significant change in thermal sensation, despite a relatively small proportion of body surface area exposed to the cooling when compared to previous studies. Therefore, it appears that cooling of the hands and forearms may be sufficient enough to result in improvements in individuals’ thermal sensation when exercising in warm environments.
The present data show no differences in RPE following pre-cooling, which is in contrast to much of the literature (Kwon et al. 2010, Mundel et al. 2007, Simmons et al. 2008). Elevations in RPE on exercise performance have been demonstrated to be associated with increased difficulty to maintain the required exercise intensity (Rasmussen et al. 2004) which suggests that elevations in the perception of effort lead to a faster decline in exercise performance. Indeed, Tucker et al., have shown that when RPE is maintained at a pre-determined level during exercise trials, the work rate selected to prevent a rise in RPE in warm conditions declines more rapidly than in cool conditions, but still results in a similar rate gain of body heat storage in both conditions (Tucker et al. 2006b). It is possible that the lack of a difference in RPE following our cooling application is due to a lack of overall cooling power and coverage of insufficient amount of body surface area (Kume et al. 2009). Despite this, when asked following completion of both trials, a number of the participants did report that the cooling intervention did feel beneficial.

Taken together, these results indicate that a moderate exposure to cold water can improve ratings of thermal sensation during exercise in the heat, but have no effect on RPE.

### 3.4.2 Exercise Performance

The observed trend of a 5.8% improvement in distance covered was associated with the implementation of the half time hand and forearm cooling intervention. However, the observed power of the performance data was only 0.2, indicating that the non-significant result on performance may actually represent insufficient statistical power, rather than their being no discernable difference between conditions. A posteriori calculation based on the obtained means and standard deviations indicates that it would be necessary for a sample size of 34 participants to be present in each condition. Nevertheless, the trend reported in the present data mirrors findings of other studies that have reported a tendency towards a performance benefit following cooling. Hornery et al., have demonstrated that 10 minutes of cooling via a cooling jacket between bouts of exercise resulted in a reduced perception of exertion and a tendency towards improved aerobic performance and reduced rectal temperature (Hornery et al. 2005). Furthermore, in an elite sporting environment even a 1% improvement in performance can have a significant effect on the final result.
Arngrimsson et al., have shown that the use of an ice vest prior to a 5000m run resulted in a 1.1% improvement in performance, which equated to a 57m lead at the finish (Arngrimsson et al. 2004). It has been suggested that the “noise” generated as a result of many performance tests will obscure any true performance benefits when analysed using normal statistical methodology (Hopkins et al. 1999), and that an improvement in elite sport of as little as 0.4 – 0.7% represents a worthwhile improvement in performance.

One explanation for a lack of a significant improvement in performance following half time cooling could be that changes in distance covered during intermittent exercise are due to changes in pace during sub-maximal exercise periods, rather than by an improvement in sprint performance (Duffield and Marino 2007). It is possible that the lack of an effect on the anaerobic component of intermittent exercise is because of the duration of rest between bouts of high intensity effort. It is likely that when there is a recovery of more than 60 seconds, as is the case in the present study, that the restoration of muscle ATP and phosphocreatine are close to full replenishment (Bogdanis et al. 1998), therefore allowing for near-maximal anaerobic effort during subsequent intervals. In the present experiment, it is possible that the self-selected pace during the submaximal phase is faster following cooling compared to control, resulting in a greater anaerobic contribution to performance, therefore allowing insufficient ATP resynthesis. However this cannot be substantiated from the current data. This may explain the tendency for elevated blood lactate at the end of the cooling condition. If the recovery phase was at a higher relative intensity, then the contribution of anaerobic metabolism would also be higher, resulting in a slower rate of lactate clearance (Baldari et al. 2005). However, two recent studies suggest that this is not the case, indeed, both conclude that a recovery closer to the lactate threshold results in a faster rate of lactate clearance (Menzies et al. 2010, Greenwood et al. 2008). It is possible that the elevation in end lactate concentration may simply be a result of a faster and/or a longer lasting “end spurt” following cooling, with the intervention resulting in an improvement in self-paced exercise, allowing for a faster sprint finish (Duffield et al. 2010).

Though not conclusively demonstrated in the present experiment, there are some data to suggest that cooling of the palm, or hand as a whole, may be an effective cooling
mechanism (Tipton et al. 1993) and result in improved exercise performance (Goosey-Tolfrey et al. 2008, Kwon et al. 2010, Grahn et al. 2005). Hand and forearm immersion in water at temperatures of between 10-30°C has been shown to effectively reduce core temperature within ten minutes in heat stressed individuals (House et al. 1997, Barwood et al. 2009). In addition, palm cooling has been shown to improve exercise duration by as much as 35% (Grahn et al. 2005), with palm cooling associated with a slower rate of oesophageal temperature increase and increased exercise duration. However the benefit of cooling did appear to be reduced with increasing workloads, suggesting that there may be an upper workload threshold, above which palm cooling becomes ineffective.

Conversely, in a recent study that considered the effect of cooling the hand on exercise performance using a palm-cooling device, it was demonstrated that cooling on the palm at 15°C has no effect on performance during intermittent exercise (Walker et al. 2009). Combined with the present data, this suggests that for there to be a performance benefit following cooling of the hands and/or forearms as is often reported when using whole body immersion or the use of ice vests, there may be a critical threshold for body surface area coverage (Kume et al. 2009). Indeed, this idea has previously been suggested (Cheuvront et al. 2003, Gao et al. 2010). Recently, Gao et al. have reported that the total area covered by a cooling garment will influence the cooling power. They report that when the cooling garment coverage was reduced by 50%, there was also a ~50% decline in total heat loss at the torso. Furthermore, Kume et al., demonstrated that there may be a threshold of 40% body surface area coverage for cooling to be effective. They reported that during exercise, increases in oesophageal and thigh temperature were significantly elevated if less than 40% of total body surface area had been exposed to cooling (Kume et al. 2009). Therefore, it is possible that the non-significant change in body heat storage is due to insufficient cooling power during hand and forearm immersion owing to the relatively small body surface area immersed in water.

The lack of any statistical differences in $T_c$ between the control and cooling conditions is in contrast to previous studies (Goosey-Tolfrey et al. 2008, Hsu et al. 2005, Giesbrecht et al. 2007). In order for $T_c$ to be reduced, it is necessary for heat transfer from the body core to the surrounding environment to occur. This happens
via a vasodilator response, which causes a re-distribution of blood flow away from the core and towards the skin. This phenomenon is clearly demonstrated using laser Doppler to measure skin blood flow, which is shown to be elevated in response to increased heat exposure (Song et al. 1990). Conversely, under conditions which may challenge maintenance of thermal homeostasis, such as cold water hand and forearm immersion, peripheral vasoconstriction restricts the rate of heat loss to the surrounding environment as skin blood flow is reduced (Bogerd et al. 2010, House and Tipton 2002). A possible explanation is that cooling throughout the body will not be uniform due to differences in perfusion between different tissues. For this reason, less well perfused tissues, such as the rectum will respond more slowly to cooling (Taylor et al. 2008), meaning that rectal temperature, as used in the present study, may be a poor indicator of the effectiveness of cooling regimes.

It has been postulated that the arteriovenous anastomoses (AVAs) play a key role in peripheral blood flow. The AVAs are blood vessels that directly link the venous and arterial circulatory systems, and may act as a short cut to blood flow reaching the skin surface. Counter intuitively, it has been proposed that during cold water immersion, the AVAs remain dilated and cooled blood from the hands and forearms flows directly to the body’s core via superficial veins to lower heat strain (Goosey-Tolfrey et al. 2008, House et al. 1997, Livingstone et al. 1989). In the current study, the absence of a significant change in $T_c$ may be due to an immediate vasoconstriction of both peripheral blood vessels and the AVAs occurring as the hands and forearms are submerged, resulting in blood flow increasing towards the core rather than the periphery. However, during intense exercise there is more competition between the core and periphery for skin blood flow due to increased cardiovascular and thermoregulatory demand (González-Alonso 2012). An increase in internal body temperature as a result of increased metabolic activity and thermal load will eventually trigger peripheral vasodilation, thus increasing skin blood flow, up to as much as 8 L.min$^{-1}$ (Kenney and Johnson 1992b) or ~60% of total cardiac output (Hashim and Tadepalli 1995). Following exercise cessation, $T_c$ will remain elevated and vasodilation will still be evident as a primary physiological cooling mechanism. However, when cooling is applied in such extreme cases, it has been shown that SkBF is not reduced via vasoconstriction as rapidly as in normothermic conditions (Wyss et al. 1975) and remains elevated in the face of peripheral cooling, as the body tries to
lose heat rapidly via convective heat exchange. As body temperature is reduced in response to cooling, vasoconstriction will eventually occur, in response to both falling blood pressure as a result of exercise cessation (Secher and Volianitis 2006) and a cold periphery, which will lead to an increase in central blood volume and reduce the rate of decline in $T_c$. Therefore, any cold water intervention with the aim of reducing $T_c$ should try to minimize the effect of peripheral vasoconstriction by using a less extreme cooling regime, which has been successfully used in reducing oesophageal temperature in hyperthermic individuals (Taylor et al. 2008).

3.4.3 Mechanisms by which performance may be improved

The final question to be addressed is how cooling of the extremities may improve performance. The results from the present experiment when combined with the findings of other similar studies that demonstrate an improvement in performance following cooling suggest that alterations in performance may be closely linked to alterations in the perception of thermal load and pacing strategy changes (Vaile et al. 2008a, Duffield et al. 2003, Goosey-Tolfrey et al. 2008, Duffield et al. 2010, Duffield et al. 2009, Tucker and Noakes 2009, Tucker 2009). One suggestion is that RPE may be a crucial component of the regulatory system that prevents exercising athletes from continuing to exercise and causing physiological damage at an RPE level which becomes intolerably high, resulting in volitional termination (Tucker 2009). Secondly, RPE may regulate adjustments in exercise intensity, which will allow for the completion of a task in the optimal performance time (Tucker 2009). Tucker suggests that RPE is influenced by a number of physiological factors, such as muscle glycogen content, skin temperature and core temperature, and knowledge regarding the expected exercise duration and previous experiences and competition, which leads to modifications in work rate to match the conscious and anticipated RPE.

It appears that changes in thermal sensation and RPE may alter the feedback loop to the central nervous system (CNS), which is likely to be involved in the fatigue process during exercise. The CNS will receive feedback detailing both central and peripheral body temperatures in response to exercise in the heat, which will influence neural stimulation of skeletal muscle (Marino 2004). The central effect on fatigue has received support from a number of authors (Noakes et al. 2004, Noakes et al. 2005,
Ansley et al. 2004, Bigland-Ritchie et al. 1978), but remains an issue of contention (Perrey et al. 2010, Marcora 2010, Amann and Secher 2010). Early work partially supporting a central command role in fatigue demonstrated that a decline in maximal voluntary force of the quadriceps could be overcome via electrically stimulated tetanic contraction (Bigland-Ritchie et al. 1978), showing that the decreased force output was not caused by local fatigue in the muscle. More recently, it has been shown that muscle recruitment and activation, as indicated by integrated electromyography (iEMG) activity, fluctuates through successive bouts of exercise. Ansley et al., report that the level of iEMG activity reflected changes in power output during repeated 4000m cycling time-trials (Ansley et al. 2004). Power output was characterised by a peak in power output at 60s, which then declined up to 240s, at which point there was an increase in power output until completion of the trial (an “end spurt”). If power output, and thus performance, were regulated by a peripherally driven mechanism, it would be expected that iEMG activity would demonstrate a continual increase throughout the course of the trial in an attempt to recruit a greater number of motor units to maintain power output in the face of fatigue. Furthermore, iEMG activity remained relatively constant between trials (~60% maximal activation), which would not be expected if peripheral fatigue caused a decline in the power output of individual motor units, requiring the recruitment of a greater number of motor units to compensate for the decline in power output of individual motor units (Ansley et al. 2004). Ansley et al., conclude that changes in pacing strategy are not solely regulated by peripheral mechanisms, rather that a central component alters the number of motor units recruited and de-recruited during exercise based on peripheral feedback and anticipatory feed-forward mechanisms. On the other hand, in a similar study iEMG activity was shown to increase towards the end of a 4000m time trial, leading the authors to suggest that a reduction in power output by individual motor units as a result of fatigue lead to an increase in CNS activity and motor neuron drive via afferent feedback from the muscles (Hettinga et al. 2006) which is more consistent with the response of a peripheral governor of fatigue. However, it must be acknowledged that in situations of excessive heat stress, the onset of hyperthermia can precede the development of any significant peripheral fatigue, thus determining exercise capacity independently of afferent feedback from fatigued locomotor muscles (Perrey et al. 2010).
It is apparent that a model of fatigue and pacing strategy alteration that integrates both central and peripheral arguments (Schlader et al. 2010a) along with other psychological and physiological factors needs development. The use of cooling strategies is likely to interfere with feedback loops governing exercise performance, particularly the temperature sensitive receptors, the activation of which has a clear negative role on exercise performance.

3.4.4 Limitations
The main issue with the protocol that was developed for this study is that the recovery period during the self-paced portion of the trial was not standardised as a percentage of a subject’s $\dot{V}O_2$max. This is an important issue, as it is likely to have an effect on any performance measures. This is because this portion of the trial was sub-maximal, and as already discussed is likely to be more influenced by a cooling strategy than an anaerobic component. In future studies, this should be standardised as a percentage of each subject’s $\dot{V}O_2$max, which will facilitate lactate removal (Menzies et al. 2010, Greenwood et al. 2008). Furthermore, the protocol neglects the influence of any inherent skill component (e.g. kicking, passing, tackling) involved in a game on performance. It is likely that the performance of skills inherent in any team game increases O2 consumption, due to the increase in muscle activity and metabolic demand which is likely to have an impact on sprint performance (Bangsbo 1994, Reilly 1994). Therefore, it would be beneficial if a protocol that incorporates some skill elements could be developed for laboratory based testing.

3.4.5 Conclusions
The results from the present study show that half time cooling between two simulated halves of field hockey is an effective way of reducing perceptions of thermal load during competition in the heat, thus allowing partial acceptance of the original hypothesis. Furthermore, a trend is present suggesting that such a cooling intervention may lead to improvements in performance, i.e. greater distances covered by individual players. However, as this improvement did not reach statistical significance, the hypothesis concerning performance is rejected. Future studies should consider ways in which a similar cooling strategy influences performance during real
competitive situations, where the skill component of team games can be included, which is something often overlooked during laboratory based studies. The role of cooling strategies and the mechanisms that regulate fatigue remains unclear. The current method provides a possible practical method for applying half time cooling during team competition; however, the most effective combination of pre-and half-time cooling still needs to be established.
Chapter 4

The Effect of Pre-Cooling Using a Novel Cooling Garment on 5000m Running Performance

4 Chapter Summary
This chapter aimed to use the data obtained on regional cooling variations (Chapter 2) and consider the effect of forearm and hand cold-water immersion on exercise performance in the heat (Chapter 3) by applying a pre-cooling intervention prior to a self-paced 5000m running performance trial. Having previously obtained data identifying the most effective locations for applying cooling and facilitating heat loss (Chapter 2), a cooling vest incorporating specific areas of targeted cooling and individual cooling sleeves was designed. This was then implemented in a 30-minute pre-cooling intervention using different cooling intensities prior to and during the completion of a warm-up. Cooling intensity was manipulated via storage so that the garments were either kept in a water bath at 15°C (COOL) or refrigerated at 5°C (COLD) for a minimum of 12 hours prior to use. The vest and sleeves were removed following warm-up completion and participants completed a self-paced 5000m running time trial in moderate ambient conditions. Both pre-cooling interventions had a positive effect on lowering thermal sensation towards feeling more cool, and reduced mean skin temperature and mean body temperature. Despite reductions in thermal sensation, mean skin temperature and mean body temperature, there was no change in 5000m time trial completion between conditions. These data suggest that the intensity of cooling required to result in an improvement in exercise performance is greater than achieved in this study.

4.1 Introduction
In recent years, it has become much more common place for athletic events to be held in more thermally challenging environments, and in particular in hot environmental
conditions. Examples of such events include the recent Olympic Games in Beijing, Athens and Sydney. The influence of elevated environmental temperature on exercise performance has been well documented, with the majority of authors reporting a reduction in performance when environmental temperature is elevated (Galloway and Maughan 1997, Tatterson et al. 2000). There is a degree of uncertainty regarding the mechanism that may regulate this reduction of performance. The theory that has received the most support is that there is a critical core temperature ($T_c$) of ~40˚C (Gonzalez-Alonso et al. 1999) which needs to be avoided by adjustments in pacing strategy/exercise intensity to prevent premature exercise termination (Marino 2004). Methods employed to delay the attainment of critical $T_c$ include, alterations in pacing strategy (Lee et al. 2010), heat acclimatization (Lorenzo et al. 2010) or pre-cooling (Duffield and Marino 2007, Quod et al. 2008).

The underlying principle of pre-cooling is to reduce $T_c$ and body temperature prior to the onset of exercise. This will have the affect of increasing the range of $T_c$ by increasing heat storage capacity and delaying the time to reach the critical limiting $T_c$. The increased heat storage capacity will allow an athlete to complete a greater amount of work before the attainment of a critical limiting core temperature (Quod et al. 2006), thereby improving performance. Pre-exercise whole body cold water immersion has been shown to result in an increase in heat storage of ~90% during exercise and linked to an improvement in cycling performance in the heat (Kay et al. 1999).

There are a number of methods reported in the literature for applying cooling, including water immersion (Kay et al. 1999), the use of water perfused suits (Gonzalez-Alonso et al. 1999), ice/cold drink ingestion (Siegel et al. 2012) and the use of ice-vests (Bogerd et al. 2010). The use of pre-cooling has been shown to improve exercise performance (Arngrimsson et al. 2004, Booth et al. 1997, Duffield et al. 2010, Cotter et al. 2001). However, many of the methods used would be very difficult to apply to athletes in a number of competitive situations. In recent years, the focus has moved to methods that could be more easily applied in the competitive arena such as ice-vests (Duffield and Marino 2007, Luomala et al. 2012) and cold drink ingestion (Siegel et al. 2012, Dugas 2011) and a number of combination treatments (Ross et al. 2010, Duffield et al. 2009). It has been shown that pre-cooling
using an ice vest prior to and during a warm up before the start of a 5000m running race resulted in a 1% performance improvement in 32°C heat (Arngrimsson et al. 2004). Since then, a number of authors have reported ergogenic effects of a more pertinent form of pre-cooling methodology on exercise performance (Webster et al. 2005, Ross et al. 2010).

Elevations in skin temperature resulting from exercise in the heat have been demonstrated to increase the perception of effort (Maw et al. 1993) and thermal sensation and discomfort at a given intensity (Samuele 2007). In order to prevent an excessive rise in effort perception in the heat, it is necessary for a reduction in exercise intensity to occur (Schlader et al. 2010b), leading to impaired performance. Furthermore, it has been postulated that changes in effort perception may centrally regulate self-selected exercise intensity (Tucker 2009). This goes some way to suggesting that successful pre-cooling may not solely be related to changes in the initial core temperature, but lowering skin temperature, and by extension thermal sensation and perceived effort may also contribute to improved performance in the heat (Schlader et al. 2011, Mundel and Jones 2009, Gillis et al. 2010). A reduction in skin temperature is associated with most cooling procedures, and is likely to be as a result of peripheral vasoconstriction and the vest/cooling device acting as a heat sink.

In recent years, several authors have considered regional anatomical differences in body heat loss in response to cooling (Koscheyev et al. 2002, Leon et al. 2004, Grahn et al. 2005, Giesbrecht et al. 2007, Kuennen et al. 2010). Koscheyev et al. demonstrated that there is a great deal of regional difference in heat exchange with a water-perfused suit. They report that the thigh, torso, shoulders, calves and forearms transferred the most heat to the suit (Koscheyev et al. 2002). In Chapter 2 of this thesis, similar results are reported to those of Koscheyev and colleagues. Further to which we have also demonstrated that forearm cooling may have a beneficial effect on lowering thermal sensation during exercise in the heat, which may be beneficial to performance (Chapter 3).

Consequently, it seems that one possible way of reducing the weight, and therefore metabolic cost, of many cooling garments is to consider the regional anatomical placement of the cooling components rather than focusing on complete torso and back
coverage. This is particularly pertinent when allied with recent data detailing regional differences in sweat rates, with data showing the highest regional sweat rates being the mid back, chest and shoulders (Smith and Havenith 2011). These areas are largely covered by most conventional cooling vests meaning that there is likely to be a marked reduction in sweat evaporation, and reduced cooling efficiency of the body. Further, the weight of many commercially available pre-cooling systems may attenuate the benefit of cooling if a heavy garment is used during warm up as there will be an associated increase in the metabolic demand, and therefore heat production, of wearing the cooling devise throughout a warm up.

4.1.1 Aim
It was the aim of the experiment to consider how a cooling garment, comprised of a vest and separate sleeves designed to be worn prior to and during a warm-up, affects a number of physiological and performance measures. In addition a laboratory based free-paced running trial that would mimic the pacing characteristics of a 5000m running race in environmental conditions similar to those expected during the London 2012 Olympic Games was used.

4.1.2 Hypothesis
It was hypothesized that the cooling vest would be capable of lowering core temperature, skin temperature and improving thermal sensation prior to and during exercise. Secondly, the use of a pre-cooling manoeuvre would result in improved running performance and a faster 5000m running time compared to when no pre-cooling was used.

4.2 Method
4.2.1 Participants
Based on numbers from similar studies and a calculation for the required sample size required to detect a based on detecting a 5% improvement in running performance based on a mean finish time of 1200s, 12 competitive male runners and triathletes (20.7 ± 1.1 years; 181.1 ± 7.3cm; 73.3 ± 6.7kg) were recruited for this study. All
participants were required to be free from injury and have a 5000m personal best faster than 20 minutes in order to minimize variability between time trial performances. All procedures were approved by the University ethics committee. Participants gave their written informed consent.

4.2.2 Familiarisation
Prior to their first experimental visit to the laboratory, all subjects completed a familiarisation trial. This consisted of a 15 minute self-paced warm up followed by a self paced 5000m run on a motorized treadmill (PPS Med, Woodway, USA) at an incline of 1˚ to mimic aerodynamic drag and energetic cost of outdoor running (Jones and Doust 1996). Participants were instructed to complete the 5000m run as fast as possible. Participants were able to adjust the speed of the treadmill as they liked via a panel mounted in front of them. The warm up was designed to mimic a typical warm up that would be completed before a 5000m race. Participants were instructed to “jog” for the first 9 minutes and 15 seconds, at which point they were instructed to accelerate to “200m pace,” and the incline was increased to 1.5˚. The speed was adjusted by the experimenter at the request of the participant. This speed was held for 45s, after which the treadmill speed was reduced to “jog” speed. This process was repeated again at 14 minutes and 15 seconds. Running speed was continually recorded on a laptop throughout, and the warm up was programmed into the treadmill software (Woodway Treadmill Control, Woodway, USA) for each participant to allow exact replication for all subsequent trials. There was then a 5-minute interval, during which time participants were allowed to stretch and drink water ad libitum, after which they completed the self-paced 5000m run. During the familiarisation trial, participants were also requested to rate their rating of perceived exertion (RPE) (Borg 1982) thermal sensation (ASHRAE 1997) and thermal comfort (Appendix B(Gagge et al. 1969) at the same intervals as during the experimental trials.

4.2.3 Cooling Garments
The cooling garment consisted of a vest and two separate sleeves to be worn on the lower arm constructed of a breathable mesh fabric, and pockets of hydrophilic silica gel. The vest had gel “packs” located on the left and right hand side of the upper pectorals and above the oblique abdominal region (figure 4.1).
Figure 4.1: The cooling vest and sleeve ensemble. The vest and sleeves consisted of a breathable mesh body, with hydrophilic silica gel packs (blue regions) that became saturated following water immersion. Temperature was manipulated after saturation via cold-water immersion or storage in a refrigerator.

On the posterior side, there was a pack located over the upper trapezius region that extended across the width of the shoulders. There were also packs running vertically above the latissimus dorsi region of the back, lateral to the spine on either side. Each sleeve was made of a tube of fabric with a thumb loop to ensure optimal fit and stability. The main gel pack on each sleeve covered the majority of the anterior and posterior forearm and the palm of the hand. Additionally there was a small pack on the dorsal side of the hand. The gel packs acted as a reservoir for water, the temperature of which could then be manipulated following saturation. Water was also soaked up and spread by the mesh material, allowing for a greater whole body evaporative cooling effect, but concentrated on areas found to be more effective for applying cooling. The total mean cooling power of the suit after 60 minutes was calculated on a thermal manikin (NEWTON, Measurement Technology Northwest, USA). A surface temperature of 34°C was used to mimic skin surface temperature, and the surface was wetted to mimic the effect of sweat production on the evaporative cooling properties of the cooling garments. The power required to maintain the surface temperature at 34°C was recorded every 30 seconds for the duration of the test.
and the average power calculated over the entire 60 minute period. This procedure was repeated on two occasions for each condition. The vest and sleeve combination was left in place for a total of 60 minutes. The cooling power for the garments was calculated by subtracting the power required to maintain the manikin at 34˚C with no vest in place from the overall cooling power value for the garment and manikin combined. Prior to putting the garments on the manikin, they were prepared using tap water as described below.

4.2.4 Experimental Procedure
Prior to participant arrival, the cooling vests were prepared. Firstly, they were allowed to soak, fully submerged, in cold tap water (~15˚C) for 30 minutes, after which they were weighed to ensure minimal differences in vest weight between trials. Once saturated, the vest was then stored in an airtight zip lock bag (Tesco, UK) to prevent evaporation. The garment was then placed in either a fridge set at 5˚C or in a water bath at 15˚C and left overnight for a minimum of 12 hours to allow for temperature equilibration.

Participants reported to the laboratory in the morning (0600-0900) following an overnight fast and having abstained from caffeine and alcohol ingestion or any strenuous exercise in the preceding 24 hours. Each participant completed their trials at the same time of day to minimize the effects of circadian variation on exercise performance. Before each visit, participants were given a pre-calibrated ingestible temperature pill with a reported accuracy of ± 0.1˚C (VitalSense, Mini Mitter, Oregon) and instructed to take it 8-10 hours prior to arrival. On arrival the pill was located using a receiver to confirm that it was functioning correctly. Participants then had their nude weight recorded (Mettler ID1 Multi Range, Sartorius, Goettingen, DE). They were then instrumented at room temperature (~23˚C) with wireless temperature sensors (iButton, DS1922, Sunnyvale, CA) that were secured in place using Medipore tape (3M, Berkshire, UK). The locations of the iButtons were forehead, scapula, right bicep, left pectoral, left forearm, left hand, right thigh and left calf, to allow for the subsequent calculation on mean skin temperature (ISO 9886 1992). iButtons have been demonstrated to be a valid measurement of $T_{sk}$ when compared to thermistor measurement with a variability in measurement of ± 0.2˚C (Hubbard et al. 2005).
which is less than that reported by the manufacturer (± 0.5°C) with a correlation to a calibrated reference thermistor of $r>.999$ (Smith et al. 2010, van Marken Lichtenbelt et al. 2006). The iButtons recorded at 60s intervals throughout the duration of each trial. Heart rate was recorded throughout (RS800, Polar, Fi). In order to minimise differences in clothing insulation, all participants wore a standard athletic shirt (ClimaCool, adidas, Germany) and their own shorts socks and running shoes.

Following the completion of instrumentation, participants were moved to an environmental chamber maintained at 23.9 ± 0.1°C and 50.2 ± 1.5% relative humidity. A laser Doppler probe (Moor Instruments, UK) connected to a moorLAB server was attached to the participant’s right middle finger. Once recording, blood flow was allowed to stabilise and a biological zero was obtained. To obtain biological zero, blood flow to the finger was manually occluded over a period of 60s. The occluded flow was then subtracted from the un-occluded flow rate to leave a true biological zero measure, which was used as a baseline for all blood flow calculations. Samples were recorded every 1s throughout the baseline period (MoorSoft v2.01, Moor Instruments, UK). Participants were given 500mL of water to drink ad libitum throughout the baseline and warm up periods. They then remained seated for 30 minutes after which time baseline measures for $T_c$, thermal sensation, thermal comfort and heart rate were recorded. After the initial 30-minute baseline, participants’ baseline measures for $T_c$, thermal sensation, thermal comfort and heart rate were recorded, after which they underwent one of three conditions in a counterbalanced order: 1) Control (CONT)– participants remained in the t-shirt for the remainder of the 60 minute baseline period and during the warm up; 2) Cool (COOL) – participants donned a cooling vest and sleeves which had been maintained at 15.2 ± 0.4°C; 3) Cold (COLD)– participants donned the same vest and sleeves which had been maintained at 5.3 ± 0.5 °C in a refrigerator. In the COOL and COLD conditions, participants remained in the cooling garments until they had completed the warm up. Following the 30-minute intervention period, baseline measures for $T_c$, thermal sensation, thermal comfort and heart rate were repeated and the participants were moved to the treadmill, once the Doppler probe had been removed, to complete their individual standardised 15-minute warm up. During the warm up, participants were asked to rate thermal sensation, thermal comfort and RPE every 5 minutes, in addition, $T_c$ and HR were also recorded at the same intervals. On completion of the
warm up, participants removed the cooling garments and had a 5-minute period to drink and stretch. During this period, they were instructed to complete the 5000m as fast as possible, and that they could adjust the speed at any point. Participants were told that they would be asked to rate their thermal sensation, thermal comfort and RPE every 1000m throughout the 5000m run. In order to determine fluid loss, participants were re-weighed following completion of the trial, and the volume of fluid ingested recorded. To avoid any possible order effects, a balanced design was used. Schematic representation of the protocol is provided in figure 4.2.

Figure 4.2: Schematic representation of the protocol used. T-30 was the point at which cooling garments were donned, and they remained on until the completion of the warm up at WUP15

4.2.5 Calculations

4.2.5.1 Mean Body Temperature:

Mean body temperature ($T_b$) was calculated using the following formula based on $T_c$ and mean $T_{sk}$ (Hardy and Dubois 1938, Vallerand et al. 1992):

$$T_b = (0.8 \times T_c) + (0.2 \times T_{sk}) \quad \{^\circ C\}$$

[4.1]
4.2.5.2 Mean Skin Temperature:
Mean skin temperature (\(T_{sk}\)) was calculated using an area weighted 8-site calculation (ISO 9886 1992) using the following formula:

\[
T_{sk} = (0.7 \cdot T_{head}) + (0.175 \cdot T_{scap}) + (0.175 \cdot T_{cheek}) + (0.07 \cdot T_{accep}) + (0.07 \cdot T_{forearm}) + (0.05 \cdot T_{hand}) + (0.19 \cdot T_{nose}) + (0.2 \cdot T_{eye}) \quad \{^\circ C\} \quad [4.2]
\]

When cooling garments were donned, we ensured that there was no direct contact between the gel cooling pads and the iButtons, by altering the placement of the pad. It was only necessary to move the gel pads by a small distance to achieve no direct contact between the gel and the iButton.

4.2.5.3 Body Heat Content:
Change in body heat content (\(H_b\)) was calculated based upon total mean body temperature (\(T_b\), °C), the specific heat content of the body (\(C_p\), 3.49 J g\(^{-1}\) °C\(^{-1}\)) and each subject’s weight (\(b_m\), kg) using the following formula:

\[
\Delta H_b = \Delta T_b \cdot (C_p \cdot b_m) \quad \{kJ\} \quad [4.3]
\]

where:
\[\Delta T_b = \text{change in mean body temperature (°C)}\]
\[C_p = \text{specific heat capacity of body tissue (3.49 J g}^{-1}\) °C\(^{-1}\)}\]
\[b_m = \text{body mass (kg)}\]

4.2.5.4 Difference in Garment Cooling Power:
The difference in cooling power between cooling garments was calculated using the following equation:

\[
\text{Difference in Cooling Power} = (H_2O \text{ absorbed} \cdot C_p) \cdot \Delta T \quad \{W\} \quad [4.4]
\]

Where:
\(H_2O \text{ absorbed} = \text{mean change in vest weight following saturation (g)}\)
Cp is the specific heat of water (4.2 J.g\(^{-1}\).\(^\circ\)C\(^{-1}\))
\(\Delta T\) is the difference in temperature between the two cooling garments (\(^\circ\)C).

### 4.2.6 Statistics

Means and standard deviations were calculated and the normality of distribution of the data assessed using the Shapiro-Wilk test. A repeated measures analysis of variance (ANOVA) was used to determine differences between conditions over time. Where significant differences were identified, post-hoc two way paired samples t-tests with a Bonferroni correction were conducted. Final performance times were analysed with a one-way paired samples t-test. The accepted level of significance was set \textit{a priori} to \(p<0.05\) and the null hypothesis accepted or rejected accordingly. Where greater levels of significance were found, this has been reported accordingly.

### 4.3 Results

#### 4.3.1 Garment Cooling Power – manikin measurement

After 60 minutes of exposure to the thermal manikin, the total mean cooling power of the cooling garments was 190.4 ± 13.8 W.m\(^{-2}\) (COLD) and 169.6 ± 16.7 W.m\(^{-2}\) (COOL). The absolute peak cooling power occurred after 15 minutes in both conditions (COOL: 210.9 ± 15.8 W.m\(^{-2}\); COLD: 219.5 ±4.2 W.m\(^{-2}\)), after which there was a steady decline in mean cooling power. The forearms were the areas with the greatest cooling power (COLD: 253.7 ± 12.7 W.m\(^{-2}\); COOL 224.9 ± 27.5 W.m\(^{-2}\)).

#### 4.3.2 Garment Cooling power – weight x Cp

Assuming that the rate of evaporative cooling between pre-cooling conditions was the same, as both garments were saturated in water, the calculated difference in heat content between the two vests was 84.9kJ, which equated to a difference in cooling power of 31.5W.
4.3.3 5000m Performances

Throughout the course of the experiment, 3 subjects had to withdraw due to injury. Their data was not included in subsequent analysis. All data were confirmed to be normally distributed (CONT p = 0.14, COOL p = 0.75, COLD p = 0.23). There were no significant differences in the time it took to complete 5000m between CONT, COOL and COLD respectively (18.22.1 ± 1.14.1; 18.28.1 ± 1.41.0; 18.26.2 ± 1.25.7, figure 4.3). Of the 9 participants who completed the trials, 5 improved their 5000m time following one of the cooling interventions, and 4 showed no improvement in time to completion (figure 4.4). There were no differences in 1000m splits throughout the duration of the run time trial between conditions.

Figure 4.3: Mean ± S.D time to completion of 5000m run (n=9)

The coefficient of variation values for performance times were 6.7%, 9.1% and 7.7% for CONT, COOL and COLD respectively.
4.3.4 Core Temperature
When all time points were analysed, there was no significant effect of time or condition on $T_c$. However, when analysis was completed for 5000m run in isolation, there was a main effect of time ($p<0.01$) but not condition on $T_c$, with an overall tendency for $T_c$ to be lower following COOL and COLD, with a significant interaction between condition and time ($p<0.05$). Core temperature was lower at 1000m in COLD vs CONT (37.5 ± 0.2°C vs 37.7 ± 0.2°C, $p<0.05$) and at 3000m for both COOL (37.9 ± 0.4°C) and COLD (38.1 ± 0.1°C) vs CONT (38.4 ± 0.5°C; both $p<0.05$, figure 4.5).

4.3.5 Mean Skin Temperature
There was no difference in mean skin temperature ($\bar{T}_{sk}$) during the initial 30-minute equilibration period. However, there was an overall effect of condition on $\bar{T}_{sk}$ ($p<0.0005$). Immediately following the application of the cooling garments, $\bar{T}_{sk}$ declined significantly (COOL 31.4 ± 0.4°C, $p<0.0005$; COLD 31.0 ± 0.8, $p<0.0005$).
compared to CONT (32.7 ± 0.4°C). $T_{sk}$ remained significantly lower with COOL until 8 minutes into the 5000m run (p<0.05) and until 11 minutes with COLD (p<0.05). There were no significant differences in $T_{sk}$ between COOL and COLD at any time point (figure 4.6).

Figure 4.5: Core temperature responses following pre-cooling and during the 5000m performance trial. COLD < CONT, † = p<0.05, and at 3000m for COOL < CONT, * = p<0.05. n = 9. Data presented as mean ± S.D
4.3.6 Mean Body Temperature

There was an overall main effect for condition on $T_b$ (p<0.0005, figure 4.7). There was no difference between conditions at T-30 immediately before the cooling garments were donned. After 30 minutes of wearing a cooling garment (T-0) $T_b$ was significantly lower in both COOL (35.7 ± 0.3°C, p<0.001) and COLD (35.6 ±0.2°C, p<0.0005) versus CONT (36.05 ± 0.2). Throughout the warm up phase (WUP) and during the 5-minute post WUP recovery, $T_b$ was significantly lower in COLD at all time points (p<0.005). $T_b$ was significantly lower with COOL, although this lasted for only the first 10 minutes during the warm up (p<0.005) and approached significance at WUP 15 (p=0.057). From T0 through to WUP+5, there was no difference in $T_b$ between COOL and COLD. During the 5000m, there was a significant effect of COLD on $T_b$ compared to CONT at 1000m (36.2 ± 0.3°C vs. 36.7 ± 0.3°C, p<0.0005), 2000m (36.5 ± 0.4°C vs. 36.9 ± 0.3°C p<0.05) and 3000m (36.9 ± 0.3°C, vs. 37.3 ± 0.4°C, p<0.05). Additionally, at 5000m $T_b$ was lower in
COLD vs CONT (37.5 ± 0.4°C vs 37.8 ± 0.4, p<0.05). There was a significant reduction in COOL $T_b$ at 2000m (36.5 ± 0.4, p<0.05) and at 3000m (36.7 ± 0.4, p<0.005). There were no significant differences between COOL and COLD at any time point.

Figure 4.7: Changes in mean body temperature following pre-cooling. * = COOL < CONT, p<0.05; ** = COOL < CONT, p<0.005; *** = COOL < CONT, p<0.001; # = COOL < CONT p<0.0005; † = COLD < CONT, p<0.05; †† COLD < CONT, p<0.005; ††† = COLD < CONT, p<0.0005. n=9. Data presented as mean ± S.D

4.3.7 Change in Body Heat Content ($\Delta H_b$)
There was a significant overall effect of condition on the change in body heat content (p<0.005, figure 4.8). There was no difference in $\Delta H_b$ between conditions following the initial 30-minute stabilisation period. Following 30 minutes of wearing the cooling garment there was a reduction in $\Delta H_b$ for both COOL (p<0.005) and COLD (p<0.01) vs CONT. In addition, $\Delta H_b$ remained lower for COLD compared to CONT until the end of the warm up (both p<0.01) and for COOL until WUP15 (p<0.001). $\Delta H_b$ was smaller for the first 1000m of the run for COLD vs CONT (p<0.005) and
approached significance at 2000m (p = 0.07) with both remaining lower until 3000m (both, p<0.05).

Figure 4.8: Wearing the cooling garments prior to the exercise test resulted in a decline in the change in body heat content. CONT vs COOL: ***=p<0.0005; ** = p<0.01; * = p<0.05. CONT vs COLD: ††† = p<0.005; †† = p<0.01; † = p<0.05...
n=9. Data presented as mean ± S.D

4.3.8 Blood Flow
There were no differences in fingertip skin blood flow (SkBF) between conditions during the initial 30-minute stabilization period. Immediately following the application of the cooling garments (T-30), SkBF began to drop with a significant effect of condition (p<0.004, figure 4.9). At 31 minutes, this was significant in COLD only (p<0.005). At 32 minutes both COLD (p<0.01) and COOL (p<0.005) were significantly lower than in CONT. SkBF remained significantly lower in COOL and COLD (both p<0.05) for 8 minutes. After this time, the difference in SkBF compared to CONT began to diminish. At 39, 42, 52, 53, 55 and 56 minutes only COLD was significantly lower (all p<0.05). At 45 and 47 minutes, only COOL was significantly
lower (both p<0.05). At all other time points, both COLD and COOL SkBF was significantly lower than CONT (p<0.05, figure 10).

![Graph showing SkBF over time for Control, Cool, and Cold conditions](image)

*Figure 4.9: Mean SkBF was significantly lower in both COOL and COLD following the application of cooling garments (represented by vertical dotted line). * = COOL < CONT, p<0.05; **) = COOL < CONT, p<0.01; ***) = COOL < CONT, p<0.005; COLD < CONT, p<0.05; †† = COLD < CONT, p<0.01; ††† = COLD < CONT, p<0.005. N=9. Data presented as mean ± S.D

### 4.3.9 Other Physiological Measures

There were no significant differences between conditions for heart rate or blood lactate concentration at any time point. In addition, there were no differences in total sweat loss between any of the conditions.

### 4.3.10 Thermal Sensation

There was a significant effect of condition on thermal sensation (p<0.001, figure 4.10). Thermal sensation was significantly lower for COLD vs CONT at T0 (-2.4 ±1.2 vs 1.7 ±1.3, p<0.005), WUP5 (-0.6 ± 1.9 vs 1.7 ± 1.3, p<0.005), 2000m 4.7 ± 0.8 vs 5.4 ± 1.0, p<0.05). There was also a significant difference in thermal sensation for
COOL vs CONT at WUP5 (-0.7 ± 1.7 vs 1.7 ± 1.3, p<0.005) and WUP10 (1.6 ± 1.2 vs 3.4 ± 1.1, p<0.01).

**Figure 4.10: Differences in thermal sensation as a result of pre-cooling. **=COOL vs CONT = p<0.005; *=COOL vs CONT = p<0.05; ††= COLD vs CONT = p<0.005; †=COLD vs CONT = p<0.05. n=9. Data presented as mean ± SD

4.3.11 Thermal Comfort and RPE
There were no significant differences between conditions on thermal comfort or RPE at any point during the trials.

4.4 Discussion
The main aims of the present study were to determine the ways in which a cooling vest designed to be worn prior to and during exercise warm up were effective at improving 5000m running performance using a laboratory based 5000m running protocol in moderate environmental conditions, mimicking those expected during the London 2012 Olympic Games. Secondly, the effectiveness of the garment on reducing individual thermal load and perceived thermal sensation prior to the onset of
exercise was assessed. The data presented demonstrate that $\bar{T}_{sk}$, $\bar{T}_b$ and $\Delta H_b$ were all lower for both COOL and COLD following pre-cooling application. There were however no changes to $T_c$ or performance under any condition. Therefore, the original hypothesis can only be partially accepted, as we were able to demonstrate lowering of $\bar{T}_{sk}$, $\bar{T}_b$ and $\Delta H_b$ without evidence of a performance benefit.

It was demonstrated that following pre-cooling, there were declines in mean body temperature, $\Delta H_b$ and mean skin temperature, all of which may be capable of leading to improved exercise performance (Schlader et al. 2010b, Tucker et al. 2006b, Lee and Haymes 1995, Schmidt and Bruck 1981). Despite this, there was no difference in the time taken to complete a self-paced 5000m run following pre-cooling in either condition. Posteriori power analysis indicated that there was unlikely to be sufficient power to detect a statistically significant difference, and that in order to do so would require a sample size in excess of 2000 participants for each condition. This would therefore suggest that the findings reporting no difference in performance following the use of either cooling protocol do not represent any form of Type II statistical error. The reported finding of no ergogenic effect in response to pre-cooling is largely in disagreement with much of the precooling literature (Arngrimsson et al. 2004, Uckert and Joch 2007, Castle et al. 2006, Duffield et al. 2010), with most studies reporting a beneficial effect on endurance performance (Booth et al. 1997, Ross et al. 2010). However, this may represent a bias within the literature, with studies showing no effect of pre-cooling on performance remaining unpublished.

### 4.4.1 Differences in Garment Cooling Power

The difference in cooling power between COOL and COLD as calculated via equation 4.4 (31.5 W) may not be large enough to be able to lead to a difference in $T_c$ as reported here. It is possible that for a difference in $T_c$ and potentially performance to occur, that there needs to be an overall cooling power in excess of these values to overcome the effects of metabolic heat production on performance. This could be achieved by using more intensive cooling in the form of a frozen vest. This would add additional cooling power due to the increased latent heat of ice versus water and the phase change process from ice to water, creating the potential for a larger heat sink in a frozen cooling garment.
4.4.2 Perceptual Measures
Both cooling methods had a beneficial effect on improving thermal sensation. A reduction in thermal sensation has been linked to improved exercise performance by a number of authors (Duffield et al. 2010, Bogerd et al. 2005, Lee et al. 2008). Lowering thermal sensation may be of importance in the regulation of and control of pacing strategy selection. Several authors have reported that perceptual measures are linked to alterations in exercise performance (Crewe et al. 2008, Castle et al. 2006, Tucker 2009). Lee et al., have demonstrated that following the ingestion of a cold fluid bolus, thermal sensation was lower compared to controls and was associated with an improvement in cycling endurance (Lee et al. 2008). It is possible that perceptual measures including thermal sensation may act as a way of regulating pace or effort based on an individual’s expectations of a task and how it should “feel” when compared to similar tasks they have experience of. Several authors have suggested that these comparisons are used by the CNS to regulate work rate in order to complete an event as quickly as possible (Noakes et al. 2004, Noakes et al. 2005, Tucker 2009). However, the idea of central regulation as an anticipatory controller of exercise performance (Noakes et al. 2004, Tucker et al. 2006b, Noakes et al. 2005) is an area of much debate and controversy (Perrey et al. 2010, Marcora 2010).

4.4.3 Skin and body temperature
The reduction in $T_{sk}$, $T_b$ and $\Delta H_b$ despite no change in $T_c$ demonstrated here is of interest. It is possible that a reduction in $T_c$ prior to exercise is not as key as is commonly believed (Sawka et al. 2012). It is possible that lowering $T_b$ by lowering $T_{sk}$ only, and thereby improving the body’s heat storage capacity may have similar ergogenic effects. Following pre-cooling, as skin blood flow increases at the start of exercise, it draws warm blood away from the core region, which as it nears the surface is cooled before re-entering the deeper body tissues which stems the rise in $T_c$ and results in a lower $T_b$ and body heat content.

A number of authors have demonstrated that a decline in $T_{sk}$ is important in regulating pace/intensity selection (Tatterson et al. 2000, Schlader et al. 2010b, Tucker et al. 2004). Schlader et al., demonstrated that when $T_c$ is kept constant, but
$T_{sk}$ is manipulated from cold (~29.5°C) to hot (~32.5°C), mean power output throughout the course of the trial at ~70% VO$_2$ max was improved, compared to when going from hot to cold. Furthermore, Ely et al., have shown that a 15 minute time trial performance test in two different environmental conditions which caused similar changes in $T_c$ (~38.2°C) but cool-warm (30°C) or hot (36°C) skin temperatures resulted in a 17% decline in performance where hot skin was evident (Ely et al. 2010). This suggests that “hot skin” will result in impaired or altered performance well before core temperature and excess heat storage becomes a limiting factor (Sawka et al. 2012).

A lower $T_b$ following pre-cooling has been linked to improvements in exercise performance (Lee and Haymes 1995, Hessemper et al. 1984, Schmidt and Bruck 1981). Owing to the strong link between $T_c$ and changes in pacing strategy during self paced exercise (Tucker and Noakes 2009) it is reasonable to conclude that in the absence of lower $T_c$ at the onset of exercise in the heat, a reduction in overall $T_b$ may allow athletes to select a more effective pacing strategy based on their thermal perceptions and physiological feedback regarding thermal strain. It has been suggested that during exercise in hot conditions, the initial rate of heat storage is elevated due to increases in $T_{sk}$ and that this provides feedback which regulates pace selection in order to prevent excessive heat accumulation (Tucker et al. 2006b). Therefore, if this initial increase in $T_{sk}$ is prevented via pre-cooling, then a reduction in $H_b$ will ensue which may lessen the effect of hot ambient conditions on exercise performance. This is particularly true when a pre-cooling procedure results in a reduced $T_{sk}$, which has recently been shown to improve performance independently of a decline in $T_c$ (Schlader et al. 2011). Furthermore, the data reported in this chapter fails to show an overall drop in $T_c$, therefore, the drop in $T_{sk}$ in response to pre-cooling explains all of the changes in both $\Delta H_b$ and $T_b$. As a result, it appears that a reduction in $T_{sk}$ may be able to elicit an improvement in running performance. However, for a benefit to be gained, athlete habituation may be required so that they are more familiar with the effects of pre-cooling to prevent them setting off too fast for performance to be maximised (Ross et al. 2010).
The equation used here for mean body temperature calculation is based on a $T_c/T_{sk}$ weighting of 0.8/0.2 (Hardy and Dubois 1938, Vallerand et al. 1992). However, this formula was developed based on a resting population in a thermoneutral environment. As a consequence, the results reported here are likely to represent a conservative estimation of the drop in $\bar{T}_b$. This is particularly the case when you consider that during exercise (i.e. after cooling garments removed) total SkBF will gradually increase, therefore requiring an increase in the weighting of $T_{sk}$. It is possible that the body temperature reported here may in fact represent an overly conservative estimation, and may in fact be lower than the calculation suggests. This would point to a larger role for the importance of body temperature in regulating exercise. Consequently, as $\Delta H_b$ is derived from $\bar{T}_b$, it is also likely that there is a subsequent underestimation in body heat content.

Despite being widely used, it is acknowledged that a calculation based solely on skin and core temperature has its inherent limitations, due to the over simplification of the core and shell compartmentalization model which does not accurately reflect complex physiological and thermoregulatory processes that are in action during intense exercise. Jay et al., have shown that the two-compartment thermometry model of “core” and “shell” as used here, consistently underestimates $\bar{T}_b$ when compared to calorimetry, and a three-compartment model comprised of “core”, “muscle” and “shell” (Jay et al. 2007). These authors argue that as muscle makes up a larger proportion of total body weight than skin (~44% vs ~5%, (Wang et al. 1992)), and that muscle experiences a significant increase in blood flow during exercise, then to exclude a direct measure of $T_m$ and enclose the muscle compartment within the “core” is likely to lead to a lack of accuracy in $\bar{T}_b$ calculation. However, in many exercise situations this is not possible to include, but it is important to recognise the limitations of conclusions based on the two-compartment model.

4.4.4 Core temperature
Following both pre-cooling interventions, there was only very limited difference in core temperature prior to and during the performance trial. Interestingly, despite using a whole-body water immersion pre-cooling protocol, Kay et al., (Kay et al. 1999) report that there was no reduction in $T_c$ at the onset of exercise, but that a difference
did appear after 15 minutes of exercise, which is approximately at the same point as reported here. Although vasoconstriction was also evident in CONT towards the end of the cooling period, it can be assumed that this is due to the cool ambient temperatures and low resting metabolic rate of the participants causing vasoconstriction in an attempt to maintain body core temperature. Therefore, a possible reason for not seeing a significant decline in $T_c$ with either COOL or COLD at the onset of exercise is that the application of the cooling garments caused a large degree of peripheral vasoconstriction. Peripheral vasoconstriction results in a decrease in heat dissipation from the skin surface due to a decline in convective heat transfer by the blood from the core to the skin surface (Charkoudian 2003). This redistribution of blood and subsequent increase in central blood volume leads to heat conservation in the core, minimizing the temperature decline. Therefore, cooling is restricted to the cooled skin, which effectively acts as a heat sink. Once exercise commences and body heat begins to increase, this heat sink is activated and attenuates a rise in $T_c$. This is achieved by the increase in exercise induced SkBF resulting in a cooling of the circulating blood volume as it reaches the cool skin, prior to returning to the core and eliciting a cooling effect.

One possibility is that the duration of pre-cooling was not of sufficient length. Many of the pre-existing studies in the field of pre-cooling have used cooling periods in excess of 30 minutes prior to exercise onset (Kay et al. 1999, Bogerd et al. 2010, Sleivert et al. 2001), and it may be that a 30 minute pre-cool is not long enough to cause a significant decrease in $T_c$, particularly when using a moderate intensity of cooling as in this present study. It seems likely that the minor difference in cooling power between both cooling garments will have resulted in insufficient cooling intensity over a relatively short period of time to cause a decline in core temperature.

### 4.4.5 Pacing strategy

A possible explanation for the absence of a difference in performance between the conditions is the pacing strategy employed by the participants. In the present study, it was evident that participants tried to hold their initial speed for as long as possible before making any alterations in running speed. Although the majority of participants were able to increase their speed towards the end of the run, there were a number of
participants who were unable to finish with an increased “end spurt” or sprint, the presence of which is a feature that has been shown to be typical of self-paced time trial like events (Tatterson et al. 2000, Marino et al. 2004). Analysis of world record 5000m track races show a clear pacing strategy is employed, where by the first and last kilometres are always the fastest, with the middle 3000m run at a slightly slower pace (Tucker et al. 2006a). Participants in the present study may have adopted a different pacing strategy to that which would be expected during 5000m run in the field, possibly setting off at a higher initial speed, thus resulting in a faster onset of fatigue and slower overall time. This is reflected in the discrepancy between participants’ mean 5000m personal best and the mean trial finishing times, which were ~80s slower. Ross et al., demonstrated that following cold water immersion and the wearing of a cooling vest as a method of pre-cooling, athletes set off too fast, based on “feeling better” at the start of a cycling time trial (Ross et al. 2010). The pace selected could not be sustained over the entire time trial, and a decline in performance was evident. However, it may be possible that with greater training and experience of using a cooling garment, athletes would be able to learn how to improve pacing following pre-cooling.

A possible explanation for the lack of difference in performance between conditions in the present experiment, and particularly between COOL and COLD may be due to the difference in cooling power of the vests. It is possible that the 31.5W difference between COOL and COLD was not sufficient to lead to a large enough difference in core and skin temperature changes to lead to a change in pacing strategy, which would lead to very similar performance times as reported here. With greater differences in cooling power between vest, achieved by using more intense cooling (i.e freezing) it may be possible to elicit a performance benefit as reported widely within the pre-cooling literature (Quod et al. 2008).

4.4.6 Performance trial
The difference in finishing first and second in many sports events is often considerably less that 1%. Therefore it is important for performance trials to be able to detect such small changes in performance. This requires an improvement in the signal:noise ratio where the signal is the change in performance and the “noise” which
represents the coefficient of variation (CV) (Currell and Jeukendrup 2008). In this study a 5000m time trial test was used in an attempt to use a more valid measure of running performance than a time to fatigue test (Laursen et al. 2007), the data still showed a very high variation in finish times within each condition. This resulted in a within subject coefficient of variation (CV) of 6.8% for CONT, 9.2% for COOL and 7.8% for COLD. The CVs are higher than those reported for the majority of self-paced time trial protocols (<5%) but less than those reported for time to exhaustion tests (Currell and Jeukendrup 2008, Jeukendrup et al. 1996). Despite this, any actual change in performance resulting from pre-cooling is lost in the large variation in performance within participants.

The major limitation of the methodology employed in the present study was that participants were unable to unconsciously regulate their running speed as they would in a real 5000m race and is evident in the non-typical pacing strategy employed, where runners started fast and attempted to hold that pace for as long as possible. This lack of similarity in pacing between our treadmill based test and an actual 5000m race demonstrates the limited validity of the current time trial protocol. This could be overcome, if a system whereby treadmill speed was regulated by the position of the runner on the treadmill. For example if they moved to close to the back of the treadmill the speed slowed until the runner had returned to a fixed “reference” point in the middle of the belt, and vice versa for if they were running too fast. Systems that attempt this are currently available, but the response of the automated running speed is much too slow not to hinder performance. This is why in the present study we opted for the manual self-adjustment of running speed by the runner.

4.4.7 Conclusions
The study demonstrates that pre-cooling using a novel design of cooling vest is effective at reducing mean body and skin temperatures and lowering body heat content and thermal sensation. However, the lack of any difference in core temperature may be due to the intensity of cooling being too low. These data allow partial acceptance of the original hypothesis, as a decline in skin temperature and improvement in thermal sensation was evident, however, the hypothesis regarding a decline in $T_c$ in response to pre-cooling is rejected. For cooling garments to cause a
reduction in $T_c$ they appear to need to deliver an absolute cooling power in excess of 220W.m$^{-2}$ which was the maximum cooling power delivered by the cooling garments in the present experiment.
Chapter 5

The Effect of Pre-Cooling on Body Temperature and Cycling Performance In the Heat.

5 Chapter Summary
In Chapter 4, it was demonstrated that it was possible to reduce mean skin and body temperatures and improve perception of thermal sensation during exercise in moderate ambient conditions following pre-cooling with a cooling vest and sleeve combination. Despite this, no performance benefit was found. It was postulated that this was due to a combination of factors including the intensity of cooling, the moderate ambient temperatures only causing mild thermal strain, and the performance test lacking the repeatability and sensitivity required to detect small (<1%) changes in performance. The present study implemented more powerful pre-cooling in more extreme environmental conditions than was previously used. Performance was tested using a cycling time trial performance against a set target workload. Pre-cooling resulted in a reduction in mean skin and body temperature. However, only the most powerful pre-cooling had a time trial performance benefit (4.8%). These data indicate that for there to be a benefit to performance following pre-cooling, the pre-cooling must be of sufficient power to significantly reduce mean skin temperature. In addition, when combined with data from chapter 4 it appears that there may be evidence to support a threshold temperature above which pre-cooling becomes more beneficial to endurance performance.

5.1 Introduction
Throughout recent decades, it has become more common for major sports events to take place in hot environments, for example the 2008 Beijing Olympic games and the future football World Cup due to be held in Qatar in 2022. Endurance exercise performance progressively deteriorates as the surrounding ambient temperature
increases (Galloway and Maughan 1997), which is further exacerbated when combined with increasing relative humidity (Watson et al. 2011). These responses to increased thermal strain are not exclusively limited to sports performance but are also evident in industrial settings. It appears that there is a strong link between increases in thermoregulatory strain due to elevations in both metabolic and ambient heat, and pacing strategy alteration and fatigue, particularly in prolonged exercise.

The attainment of a “critical” core body temperature has been proposed as the main factor limiting endurance performance in hot environments (Gonzalez-Alonso et al. 1999, Nielsen et al. 1993). Following cold water immersion to manipulate initial core temperature, it was demonstrated that fatigue was reached when a core temperature of ~40°C was reached (Gonzalez-Alonso et al. 1999). Furthermore, a faster rate of heat storage resulted in an accelerated attainment of a T_c of 40°C and fatigue (Gonzalez-Alonso et al. 1999). This led to the development of the notion that there is a critical core temperature of ~40°C, beyond which the body would be unable to function effectively. Therefore, it was suggested that this critical core temperature is used as a set point, around which the body bases pace judgment alteration and effort perception in an attempt to complete a given task as quickly as possible without achieving a dangerously high core temperature (Marino 2004).

More recently, it has been argued (Kenefick et al. 2010) that core temperature per se, may not be as important in determining exercise performance as was previously believed. In environments and exercise scenarios that are likely to lead to elevations in core temperature, it is not uncommon to see associated rises in skin temperature (T_sk). This comes about due to the body attempting to dissipate some internal heat via an increase in peripheral vasodilation and greater skin blood flow, but also as a consequence of more radiative heat gain from the surrounding environment in exposure to solar radiation or very high ambient temperatures. Skin temperature has now also been implicated as a main determining factor in regulating endurance performance in elevated ambient conditions (Sawka et al. 2012, Kenefick et al. 2010). In hot conditions, fatigue has been shown to be less reliant on high core temperature, but more dependent on elevated skin temperature (>35°C), as fatigue occurred at relatively low core temperatures of approximately 38.5°C (Montain et al. 1994, Latzka et al. 1998).
In light of the prevailing theory that core and/or skin temperature is a major limiting factor in endurance exercise, there has been a greater focus on ways in which the deleterious effect of becoming too hot can have on performance. One of the most widely adopted practices is that of “pre-cooling,” which has the aim of increasing the body’s ability to store the heat that builds up in response to greater metabolic activity during exercise. The topic of pre-cooling has previously been covered in detail in chapters 3 and 4 of this thesis.

Although several previous studies have demonstrated that pre-cooling prior to exercise has a beneficial effect on performance, very few studies have considered ways in which both vest design and cooling placement can influence body cooling a subsequent performance. In previous studies we have demonstrated that there is some regional variation in rates of heat exchange (chapter 2) and that a new cooling vest design is able to reduce skin and body temperature at the start of exercise, but also reduce the change in body heat content during exercise (chapter 3). However, in this study we were unable to demonstrate a performance benefit, although it is likely that this is due to insufficient cooling power, combined only moderate ambient conditions.

5.1.1 Aims
It was the aim of this study to use a more reliable and valid performance testing protocol, more extreme environmental conditions and a greater intensity of cooling to determine the effectiveness of our newly designed cooling vest on reducing body temperature and improving endurance cycling performance in the heat.

5.1.2 Hypothesis
It was hypothesized that core temperature, skin temperature and mean body heat content would be lower following pre-cooling. Furthermore, these reductions would lead to improved cycling performance, represented by a faster time trial completion time, and that the largest improvement would be seen with the coldest pre-cooling treatment.
5.2 Method

5.2.1 Participants
Based on participant numbers reported in the literature for similar types of performance focused research, ten endurance trained competitive male cyclists and triathletes (25.1 ± 6.1 yrs; height 178.9 ± 6.1 cm; weight 72.5 ± 5.1 kg; \( \dot{V}O_2 \text{ max} 61.3 ± 4.3 \text{ mL.kg.min}^{-1} \); body fat 7.2 ± 2.9% body fat) who were familiar with the type of testing involved were recruited for this study. All participants were required to be free from injury and have a \( \dot{V}O_2 \text{ max} \) in excess of 55 mL.kg.min\(^{-1}\). The Loughborough University ethical advisory committee approved all experimental procedures. Participants gave their full written informed consent.

5.2.2 Experimental Design
Participants visited the laboratory on a total of 5 occasions. Visit 1 consisted of body composition measurement and an incremental exercise test to exhaustion to determine \( \dot{V}O_2 \text{ max} \) and maximal power output (\( W_{\text{max}} \)). Visits 2, 3, 4 and 5 were simulated cycling time trials in which participants were instructed to complete a set amount of work in as short a time as possible. Visit 2 served as a familiarisation trial to ensure that participants were able to complete the required exercise and to minimise any potential learning effect on time trial performance. Visits 3, 4 and 5 constituted the experimental visits where participants underwent i) cold pre-cooling using a cooling garment frozen (-20˚C) over night (COLD), ii) moderate pre-cooling where the cooling garments were saturated in cool tap water (15˚C) for 30 minutes prior to wearing (COOL); or iii) control where no pre-cooling was implemented prior to the start of the time trial and the cooling garments not worn (CONT). Trials were conducted in a counterbalanced order, with each visit separated by a minimum of 7 days to minimize acclimation effects.

5.2.3 Visit 1
Participants first had their height (Seca, Birmingham, UK) and weight (ID1 Multi Range, Sartorius, Goettingen, DE) recorded. Body composition was calculated using skinfold callipers (Harpenden, HaB Intl Ltd, Warwickshire, UK) using the 7-site
skeinfold method and weighted for the athletic population (Jackson et al. 2004). The \( \dot{V}O_2 \) max test was conducted on an electronically braked cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands) to determine maximal oxygen uptake (\( \dot{V}O_2 \) max, mL.kg.min\(^{-1}\)) and consisted of 3 minutes at 95W, followed by 35W increments every 3 minutes until the participant reached volitional fatigue. Maximal power output (\( W_{\text{max}} \)) was determined using the formula:

\[
W_{\text{max}} = W_\text{out} + (35/180 \cdot t) \quad \{\text{W}\} \quad [5.1]
\]

Where:

\( W_\text{out} \) is the last completed stage (W)

\( t \) is the time completed of the final stage (s).

The difference in cooling power between COOL and COLD was calculated using the same equation based on water absorption following saturation and the specific heat of water (4.2 J.g\(^{-1}\).°C\(^{-1}\)) and ice (2.0 J.g\(^{-1}\).°C\(^{-1}\)) respectively, and the phase change properties of ice (333.6 J.g\(^{-1}\)) as previously outlined in equation 4.4 (Chapter 4). For the frozen vest, which incorporates a phase change, the difference in cooling power was calculated for -20°C to 0°C, the phase change from ice to water, and finally the difference in cooling power between 0-15°C. The sum of these values was then used as the value for the difference in cooling power between COOL and COLD.

5.2.4 Visits 3-5

Participants reported to the laboratory in the morning (0600-0900) following an overnight fast and having abstained from caffeine and alcohol ingestion or any strenuous exercise in the preceding 24 hours. Each participant completed their trials at the same time of day to minimize the effects of circadian variation on exercise performance.

Prior to each experimental visit, participants were given an ingestible temperature pill (VitalSense, Mini Mitter, Oregon) and instructed to take it 8-10 hours prior to reporting to the laboratory. On arrival the pill was located using a receiver to confirm
that it was functioning correctly. Participants then had their nude weight recorded (ID1 Sartorius, Goettingen, DE). They were then instrumented with wireless temperature sensors (iButton, DS1922, Sunnyvale, CA) that were secured in place using Medipore tape (3M, Berkshire, UK) to allow for calculation of mean skin temperature based on a 8-site weighting as described in chapter 4 (ISO 9886 1992). The iButtons recorded at 60 s intervals throughout the duration of each trial. Heart rate was monitored and recorded throughout the trials (RS800, Polar, Fi). In order to minimize differences in clothing insulation, all participants wore a standard athletic shirt during the stabilisation, cooling and warm up periods. This was removed on completion of the warm up.

Following instrumentation, participants remained passive in a room (21.2 ± 0.8°C) prior to the collection of baseline measures after 30 minutes. Participants were then moved to an environmental chamber maintained at 35.0 ± 0.4°C and 50.6 ± 1.3 % relative humidity, where they donned the cooling garments for the experimental conditions or remained seated in cycling clothing for a further 30 minutes. On completion of the precooling phase, participants then mounted the cycle ergometer to complete a standardised 9-minute warm up (WUP) which consisted of 3 minutes stages of 150W, 200W and 250W (figure 5.1). If worn, the cooling garments were removed on completion of the warm up and participants had 5 minutes to stretch and prepare for the start of the time trial. Participants only wore cycle shorts, socks and shoes for the duration of the time trial.

For the time trial, participants were given a set amount of work, equivalent to cycling for 1 hour at 75% $W_{\text{max}}$ (912.7 ± 131.3 kJ) to complete in as fast a time as possible. Target workload was calculated according to the formula:

$$\text{Total amount of work} = 0.75 \cdot W_{\text{max}} \cdot 3600 \text{s} \quad \{\text{J}\} \quad [5.2]$$

The ergometer set in linear mode so that 75% $W_{\text{max}}$ was obtained when participants cycled at their preferred cadence according to the formula:

$$W = L \cdot (\text{rpm})^2 \quad [5.3]$$
Rearranged to give:

\[
L = \frac{W}{rpm^{-2}} \tag{5.4}
\]

Where:

- \(L\) is a linear factor
- \(rpm^{-2}\) is the pedalling rate achieved during the \(VO_2\) max test.

This allowed bike power to fluctuate as a function of pedal cadence, so that a higher cadence resulted in a higher power output and reflected the change in air resistance at higher speeds. Participants exercised separately with no performance feedback other than the accumulated work done, target workload and a graphical representation of fluctuations in power output. They had minimal interaction with the investigators. This type of time trial procedure has been shown to be highly reproducible when performed in this way and with participants experienced in this type of exercise (Jeukendrup et al. 1996).
Figure 5.1: A participant completing the incremental warm up whilst wearing the cooling vest and sleeves ensemble
During the time trial, participants were allowed to drink water *ad libitum*, with the total volume consumed recorded to allow for sweat rate calculation. Water was kept at the same temperature as the surrounding environment. At 10% intervals of total work done, $T_c$ was recorded. At 20% intervals, RPE (Borg 1982), thermal sensation (ASHRAE 1997) and thermal comfort (Griffiths and Boyce 1971) were recorded. 20% intervals were chosen to minimize participant/investigator interaction.

### 5.2.5 Cooling Garments

The vest and sleeves were constructed of a “breathable mesh” fabric, and pockets of hydrophilic silica gel. The vest had gel “packs” located on the left and right hand side of the upper pectorals and above the oblique abdominal region. On the posterior side, there was a pack located over the upper trapezius region that extended across the width of the shoulders. There were also packs running vertically above the latissimus dorsi region of the back, lateral to the spine on either side. Each sleeve was made of a tube of fabric with a thumb loop to ensure optimal fit and stability. The main gel pack on each sleeve covered the majority of the anterior and posterior forearm and the palm of the hand. Additionally there was a small pack on the dorsal side of the hand (figure 4.1, chapter 4).

### 5.2.6 Calculations

#### 5.2.6.1 Mean Body Temperature:

Mean body temperature ($\bar{T}_{b}$) was calculated using the following formula based on weighted values for $T_c$ and $\bar{T}_{sk}$ (Hardy et al. 1938, Vallerand et al. 1992):

$$\bar{T}_{b} = (0.8 \cdot T_c) + (0.2 \cdot \bar{T}_{sk}) \quad \{^\circ C\} \quad [5.4]$$

#### 5.2.6.2 Mean Skin temperature:

Mean skin temperature ($\bar{T}_{sk}$) was calculated using an area weighted 8-site calculation (ISO 9886 1992) using the following formula:
\[ T_{\text{ref}} = (0.7 \cdot T_{\text{head}}) + (0.175 \cdot T_{\text{scap}}) + (0.175 \cdot T_{\text{cheat}}) + (0.07 \cdot T_{\text{bicep}}) + (0.07 \cdot T_{\text{forearm}}) + (0.05 \cdot T_{\text{hand}}) + (0.19 \cdot T_{\text{thigh}}) + (0.2 \cdot T_{\text{calf}}) \] °C \[ 5.5 \]

5.2.6.3 Mean Body Heat Content:
The change in mean body heat content (ΔH_b) was calculated using the following formula:

\[ \Delta H_b = \Delta T_b \cdot (C_p \cdot b_m) \] {kJ} \[ 5.6 \]

where:
\[ \Delta T_b = \text{mean body temperature (°C)} \]
\[ C_p = \text{specific heat content of the body (3.49 J.g}^{-1}.{\text{°C}^{-1}}) \]
\[ b_m = \text{the participant’s body mass (kg)} \]

5.2.7 Statistics
Preliminary analysis was conducted to ensure that there was no violation of the assumptions of the normality of distribution. Means and standard deviations were calculated. The coefficient of variation was calculated as the standard deviation divided by the mean, multiplied by 100. A repeated measures analysis of variance (ANOVA) was used to determine differences between conditions over time. Where significant differences were identified, post-hoc two way paired samples t-tests with a Bonferroni correction were conducted. Differences in finish time, mean power and total sweat loss were analysed using a paired samples t-test. The accepted level of significance was set \textit{a priori} to p<0.05 and the null hypothesis accepted or rejected accordingly. Where greater levels of significance occurred, they have been reported accordingly. Effect sizes were calculated for time trial completion times (Cohen’s d = (Mean_1 – Mean_2)/[(SD_1 + SD_2)/2], (Cohen 1988)). Effect size results we interpreted as described by Christensen and Christensen (Christensen and Christensen 1977), with effect sizes of <0.2 classified as small, 0.4-0.6 as medium and > 0.8 as large.
5.3 Results

5.3.1 Difference in Garment Cooling power
The difference in cooling power between COOL and COLD was calculated as being equivalent to 169W, with an overall difference in heat storage of 395.3 kJ.

5.3.2 Time Trial Performance
The time taken to complete the time trial reduced with increasing cooling intensity and was significantly faster following COLD (1:05:01 ± 0:04:21; p<0.05; figure 5.2) but not COOL (1:06:56 ± 0:05:29; p=0.09) when compared to CONT (1:08:16 ± 0:07:22). This equated to an improvement of 195 ± 170s or 4.8% for COLD and a medium strength effect size (Cohen’s $d = 0.6$). In addition COLD was faster than COOL (2.9%, p<0.05), with a medium effect size ($d = 0.4$). There were no significant differences at any of the individual time points between conditions. The coefficient of variations (CV) for each condition were 11.7%, 8.2% and 6.7% (mean 8.9%) for CONT, COOL and COLD respectively and 7.5% for the familiarisation trial, indicating that there were minimal learning or order effects on time trial performance.
5.3.3 Power output

Mean power output was higher for COLD (234.4 ± 33.8W) v CONT (227.1 ± 25.7 W; p<0.05), and showed a tendency for COOL vs CONT (224.4 ± 25.4; p=0.06; figure 5.3). This equates to a 10.0 ± 8.4W improvement in mean power output for COLD compared to CONT, or 4.5%. There were no effects of condition or time on the mean power output of each individual split.

5.3.4 Core Temperature

There was a significant effect of time (p<0.05) but not condition on core temperature. There were no significant differences in core temperature between conditions at any time points.
5.3.5 Mean Skin Temperature
There were significant effects of both pre-cooling application (p<0.05) and time (p<0.05) on mean skin temperature (figure 5.4). There was a significant interaction for condition and time on $T_{sk}$ (p<0.05). Mean skin temperature was significantly lower when compared to CONT at T0 for COOL (p<0.0005) and COLD (p<0.001); WUP COOL and COLD (both p<0.0005); REC, COOL (p<0.01) and COLD (p<0.0005) and 10% target workload COLD (p<0.01). $T_{sk}$ was also lower for COLD vs. COOL at T0 (p<0.005), WUP (p<0.005), REC (p<0.005), 10% target workload (p<0.005) and at 20% target workload (p<0.05).

![Figure 5.4: Differences in mean skin temperature as a result of pre-cooling.](image)

Figure 5.4: Differences in mean skin temperature as a result of pre-cooling. #: COOL < CONT p<0.01; ## = COOL < CONT p<0.0005; **= COLD < CONT p<0.001; *= COLD < CONT p<0.01; †† = COLD < COOL p<0.005. Data presented as mean ± S.D.

5.3.6 Mean Body Temperature
There were significant effects of both condition (p<0.05) and time (p<0.0005) on mean body temperature following pre-cooling. The reduction in mean body temperature lasted until the start of the time trial for COOL (p<0.05) and 20% for COLD (37.2 ± 0.4°C, p<0.05, figure 5.5). At the onset of the time trial, mean body
temperature was lower for COLD vs CONT (36.1 ±0.3 vs 37.0 ±0.3˚C p<0.0005) and for COOL vs CONT (36.5 ± 0.6 vs 37.0 ± 0.3˚C, p<0.05).

**Figure 5.5:** Mean body temperature responses to pre-cooling. #$ = COOL < CONT p<0.01; ##$ = COOL < CONT p<0.0005; **$ = COLD < CONT p<0.001; $ = COLD < CONT p<0.01; †† = COLD < COOL p<0.005. n=9. Data presented as mean ± SD

### 5.3.7 ΔBody Heat Content
The change in body heat content following pre-cooling, warm up completion and the end of the recovery phase was lower for COLD vs. CONT (p<0.01). For COOL vs CONT ΔH_b was lower until the end of the warm up (p<0.05). ΔH_b was significantly lower for COLD vs COOL between T0 (p<0.005) and warm up completion (p<0.05, figure 5.6).
Figure 5.6: The δ body heat content using a core to skin temperature weighting of 0.8/0.2. *=COOL < CONT p<0.05; **=COOL<CONT p<0.01; † = COLD < CONT p<0.01, †† = COLD < CONT p<0.005; ††† = COLD < CONT p<0.001; # = COLD < COOL p<0.005; ## = COLD<COOL p<0.05. n=9. Data presented as mean ± SD

5.3.8 Blood Lactate
There was a significant effect of time on blood lactate concentration (p<0.005), but no significant effect of condition, or between conditions at any time-point (figure 5.7). In all conditions, following the warm up, blood lactate was >4mmol.L⁻¹, exceeding the anaerobic threshold.
Figure 5.7: Blood lactate concentrations were not different between trials. a = CONT vs. La T-30; b = CONT vs. La T0; c = CONT vs. La T-30; d = COOL vs. La T-30; e = COOL vs. T0; f = COLD vs. La T-30; g = COLD vs. La T0. n=9. Data presented as mean ± SD.

5.3.9 Heart Rate
There was no effect of either time or condition on heart rate, nor were there any significant interaction effects. There was however a trend for heart rate to be elevated throughout the time trial in COOL (172 ± 4) vs. CONT (167 ± 5; p=0.06).

5.3.10 Perceptual Measures
There was a significant effect of both time (p<0.005) and condition x time (p<0.05) on thermal sensation (figure 5.8). An increase in thermal sensation towards feeling “hot” was evident in all conditions throughout the course of the trial. There was a trend for thermal sensation to be lower for both COOL and COLD compared to CONT, and COLD < COOL. This trend reached significance at T0 (COOL < CONT, p<0.05; COLD < CONT p<0.01), WUP (COOL < CONT, p<0.05), REC (COLD<CONT, p<0.05). Pre-cooling application had no effect on either RPE or thermal comfort.
5.4 Discussion

The main aim of the present study was to determine whether a pre-cooling garment, incorporating additional sleeves to facilitate forearm and palm cooling, was able to improve performance in the heat using a protocol which has been more widely used and validated than the self-paced 5000m running trial used in chapter 4. A secondary aim was to determine if performance improvements were concurrent to reductions in $T_c$, $T_{sk}$, $T_b$ and $\Delta H_b$.

The results demonstrate that the frozen cooling garment (COLD) resulted in a faster time trial performance (4.8%) in the heat (35°C) compared to when no pre-cooling was undertaken, and that there appears to be an intensity dependent increase in performance subject to the strength of cooling applied. The use of cooling resulted in reduced CV between trials, indicating less of an effect of the environmental heat on pacing strategy disruption. It appears that the additional cooling power achieved with
the use of a vest frozen at -20°C (COLD) compared to a water saturated vest at a temperature of 15°C (COOL) was sufficient to lead to an improvement in performance compared to when lower cooling intensities are used as reported in chapter 4. Furthermore, the data show that pre-cooling under both conditions was effective in reducing $T_{sk}$, $T_b$ and reducing the $\Delta H_b$. These data allow for the original working hypothesis to be accepted, although as there was no change in $T_c$, the null hypothesis has to be retained for this particular variable.

From the current data, it is not possible to determine the combined effect of more intense pre-cooling occurring in hotter environmental conditions. Although beyond the scope of this experiment, this raises the question of whether there is an effective threshold ambient temperature above which pre-cooling should be used. The data demonstrate that pre-cooling in both conditions led to a reduction in $T_{sk}$, $T_b$ and $\Delta H_b$, coupled with improvements in thermal sensation at the onset of the time trial. As there was no significant difference between trials on core temperature, it is proposed that improvements in performance may be due to changes in the peripheral feedback and central regulation of pacing strategies owing to reductions in both mean skin temperature and concomitant changes in body heat content.

5.4.1 Performance Measures

Performance related data were all confirmed to be normally distributed (mean power, $p > 0.26$, finish times $p > 0.89$). Thirty minutes of pre-cooling prior to the start of a warm up and cycling time trial resulted in a 4.8% improvement in time trial performance in COLD ($195 \pm 170$s) compared to when no pre-cooling was used. Therefore, the hypothesis that pre-cooling would lead to performance can be accepted. This was associated with an overall improvement of in power output (4.5%) during the course of the time trial. Although not significant, there was a tendency for an improvement in performance in COOL ($140 \pm 160$s) compared to CONT. This improvement in performance following pre-cooling with our novel design of ice vest and cooling sleeves is consistent with that reported throughout the literature (Quod et al. 2008, Duffield et al. 2010, Ross et al. 2010). Despite not showing a beneficial effect of pre-cooling on reducing $T_c$ at the onset of exercise, there was still a performance benefit. The improvement in performance may be due to the reduction in
mean $T_{sk}$. A reduction in skin temperature at the onset of exercise has previously been demonstrated to lead to increased power output during a 60-minute cycling performance test compared to when $T_{sk}$ was elevated at exercise onset (Schlader et al. 2011). However, a placebo effect cannot be totally excluded, as owing to the nature of pre-cooling research, it is not possible to blind the participants to the experimental condition. To the investigators’ knowledge, participants were however unaware to the underlying principles and hypothesis of the study.

The case of one individual’s response to pre-cooling is of interest. In both cases where cooling was not applied, namely the familiarisation and control trials, this individual’s core temperature rose rapidly and reached 40˚C (our cut-off criterion) between 70-75% of the target workload on each occasion, despite reportedly feeling no ill effects of such a high $T_c$. However, when either pre-cooling intervention was used, this subject had no difficulty in completing the trial, despite there being no difference in $T_c$ at the start of the time trial. It does appear that the $\Delta T_c$ for this individual participant was slower in both pre-cooling conditions, with $T_c \sim 1˚C$ lower in COLD at 50% of the completed workload compared to CONT. It appears likely in this instance, that this particular individual may regulate from a higher thermoregulatory ceiling, and as he was an elite endurance athlete, it is not uncommon for them to experience core temperatures in excess of 40˚C at the end of prolonged competition with no adverse physiological side-effects (Ely et al. 2009, Lee et al. 2010).

5.4.2 Physiological Measures
This study demonstrates that pre-cooling with an ice vest incorporating forearm and palm cooling is capable of reducing $\bar{T}_{sk}$ and $\Delta H_b$, with the values reported here replicating those detailed in chapter 4. As these reductions are associated with a concurrent improvement in time trial performance, it appears likely that both $\bar{T}_{sk}$ and $\Delta H_b$ have potential roles in regulating exercise performance in the heat, and that core temperature may have less of a dominant regulatory role than has previously been suggested (Gonzalez-Alonso et al. 1999, Nielsen et al. 1993). More recently, evidence has begun to emerge that skin temperatures in excess of 35˚C and resultant high skin blood flow requirements can impair prolonged aerobic exercise (Schlader et al. 2011, Sawka et al. 2012, Arngrimsson et al. 2003). In environmental conditions
similar to those employed in the present study, exhaustion has been shown to occur at relatively low core temperatures (<38.5°C) but with skin temperatures in excess of 35°C (Montain et al. 1994, Latzka et al. 1998). Furthermore, it appears that there may be a threshold ambient temperature above which pre-cooling begins to be of more benefit, as one of the major differences between this and study 3 (chapter 4) is the ambient conditions used (~24°C vs. ~35°C).

Despite the obvious difficulties in separating the effect of elevations in both T_c and T_sk, Schlader et al have demonstrated that when T_sk is manipulated from cold to hot via changes in water temperature in a water perfused suit, total work done during 60 minutes of self-paced cycling was higher than when T_sk was manipulated from hot to cold, despite similar pre-exercise T_c and heart rate (Schlader et al. 2011). They attribute this to an increase in the initial self-selected power output in the cold to hot condition, suggesting that T_sk and the accompanying thermal perceptions are important inputs in the selection of exercise intensity. Similarly, using a 30-minute cycling time trial protocols in hot (32°C) vs moderate (23°C) ambient conditions, Tatterson et al., reported that mean power was reduced by 6.5% in a warm environment and was associated with a T_sk of ~33°C versus 27°C in cooler ambient conditions, despite similar peak core temperature values in both conditions (Tatterson et al. 2000). In runners it has been shown that T_sk in excess of 34°C results in a reduction of VO_2 max in proportion to the increase in T_sk (Arngrimsson et al. 2003). Therefore, in situations where T_sk is elevated, such as during prolonged endurance exercise and/or in moderate to warm ambient conditions, an individual will work at a greater percentage of VO_2 max for the same relative workload, compared to when T_sk is lower or when ambient conditions more temperate (Kacin et al. 2008).

As a result of elevations in T_sk, there is an increase in skin blood flow in an attempt to dissipate some of the accumulated heat. The increase in skin blood flow causes redistribution away from the active musculature (Ely et al. 2010, Cheuvront et al. 2005) and can result in hypovolemia, which in itself can lead to a decline in performance in the range of 20% if accompanied by even moderate dehydration (Cheuvront et al. 2005). From the present data, it was not possible to demonstrate a change in skin blood flow, however, it is well established that vasoconstriction occurs.
as a consequence of peripheral cooling, as was demonstrated in Chapter 4 and by a
number of other authors (Wilson et al. 2007, Johnson 2007). Therefore, it is possible
that there is greater maintenance of central blood volume following pre-cooling,
which allows for greater skeletal muscle blood flow and oxygen delivery during
exercise, and assists in improving performance.

Taken together, these studies suggest that high skin temperatures alone are capable of
impairing aerobic performance. In the present study, pre-cooling had the effect of
reducing skin temperature, furthermore, the point at which a $T_{sk}$ of 35°C was reached
was delayed for between 14 (COOL) and ~23 minutes (COLD). Therefore, if $T_{sk}$ at
the onset of exercise provides an important input into initial self-selected power
output and thus overall performance, the improvement in both mean power output and
time trial performance reported here may be due to a reduction in skin temperature in
response to the intensity the pre-cooling interventions used. This adds to the
suggestion that high $T_{sk}$ may have an important regulatory function in the fatigue
process via a combination of central and peripheral mechanisms in hot ambient
conditions.

Elevations in mean body temperature and body heat storage have also been associated
with impaired aerobic performance during exercise in the heat (Tucker et al. 2006b,
Lee and Haymes 1995, Hessemey et al. 1984, Schmidt and Bruck 1981), albeit with
considerable debate surrounding this suggestion (Jay and Kenny 2009, Marino 2009).
Our data suggest that an improvement in performance following COLD pre-cooling
application may be attributable to the increased intensity of cooling in this condition,
thus resulting in a reduction in body heat content at the onset of exercise. This finding
replicates those reported by Bogerd et al., who suggest that the reduction in $T_{sk}$, $\bar{T}_b$
and $\Delta H_b$ content as a result of cooling creates a heat sink that continues during
exercise and allow for improved performance (Bogerd et al. 2010). The lack of a
difference in the reported core temperatures at the onset of exercise in the present
study may be attributable to a lower intensity and duration of pre-cooling compared to
previous studies where such a reduction in $T_c$ has been reported. Furthermore, the
lack of statistical difference in $T_c$ between conditions means that it is $T_{sk}$ that is
causing all of the changes in both $\bar{T}_b$ and $\Delta H_b$. Therefore, adding to the recent
evidence that indicates $T_{sk}$ has a greater influence on regulating exercise performance than previously thought (Schlader et al. 2011, Sawka et al. 2012).

Despite its wide usage, it is acknowledged that a calculation for mean body heat content, and therefore $\Delta H_b$, based solely on skin and core temperature has its inherent limitations, due to the over simplification of the core and shell compartmentalization model which does not accurately reflect complex physiological and thermoregulatory processes that are in action during intense exercise. The issues surrounding the use of a two-compartment model to calculate body heat content have been discussed elsewhere in this thesis (Discussion, Chapter 4), but it remains important to acknowledge this potential limitation that also exists with the present data.

5.4.3 Perceptual Measures
Thermal sensation was reduced following both COOL and COLD, although the reduction only lasted until the start of the time trial in COLD. Throughout the time trial there was a tendency for thermal sensation to be lower in both pre-cooled conditions versus CONT. Furthermore, when asked, all participants reported that they felt “better” following cooling with both COLD and CONT compared to when no cooling was used and that this was beneficial to their performance. Maintaining thermal sensation towards feeling of “cool” via the use of a cooling garment may be of importance in the regulation of pacing strategy selection. Several authors have reported that perceptual measures are linked to alterations in exercise performance (Crewe et al. 2008, Castle et al. 2006, Duffield et al. 2010, Tucker 2009, Bogerd et al. 2005). Siegel et al., (Siegel et al. 2010) and others (Dugas 2011, Lee et al. 2008) have demonstrated that thermal sensation was lower following the ingestion of a cold bolus and associated with improved running performance in the heat. It is possible that perceptual measures may act as a way of regulating pace or effort based on an individual’s expectations of a task and how it should “feel” when compared to similar tasks they have experience of. Several authors have suggested that these comparisons are used by the CNS to regulate work rate in order to complete an event as quickly as possible (Noakes et al. 2004, Noakes et al. 2005, Tucker 2009). However, the idea of central regulation as an anticipatory controller of exercise performance (Noakes et al. 2004, Tucker et al. 2006b, Noakes et al. 2005) is a current area of much debate and
controversy (Perrey et al. 2010, Marcora 2010) and warrants more in-depth investigation.

5.4.4 Conclusions
The current study demonstrates that the use of a novel design of a pre-cooling garment, incorporating forearm and palm cooling is effective at improving cycling time trial performance in the heat by 4.8% when the cooling garment has been prepared in a frozen state (COLD) Furthermore, the use of more intense cooling is required to provide any sort of performance benefit, with only the frozen vest improving time trial performance. This is in line with the conclusions reached in chapter 4, where it was suggested that cooling power and intensity will limit pre-cooling’s effectiveness on performance. The data suggest that the role of a critical limiting $T_c$ as a regulator of exercise may be of questionable importance, rather, peripheral changes in skin temperature, with a concomitant reduction in body heat content contribute to improved endurance exercise performance in hot ambient conditions. Therefore, the original hypothesis that core temperature, skin temperature and mean body heat content would be lower following pre-cooling and time trial performance improved following the most powerful pre-cooling can be accepted.
6 Chapter Summary
This chapter aimed to determine the effect attenuating muscle temperature decline by passive insulation or external heating during recovery following a sprint specific warm up on thigh muscle temperature and subsequent maximal sprint performance. In many competitive sports settings such as track and field athletics or velodrome-based track cycling competitions, there are often extended periods of time in between warm up completion and performance execution. During this time, it is possible that the beneficial effect of completing a warm up on many physiological parameters, in particular muscle temperature elevations may begin to decline. As muscle temperature is a key component in determining muscle power output, any decline is likely to lead to impaired performance in power based sprint events. In order to determine the potential effects of a delay between warm up completion and sprint cycling performance, a protocol was developed which was designed to mimic the type of warm up procedure used by track cyclists and incorporated a delay between its completion and the performance of a maximal sprint test. Participants completed a standardized 15 min intermittent warm up on a cycle ergometer, followed by a 30 min passive recovery period before completing a 30 sec maximal sprint test. During this recovery period, participants donned one of three pairs of trousers i) a standard pair of tracksuit bottoms (CONT); ii) an insulated pair of trousers (INS); or iii) an insulated pair of trousers combined with electrical heating elements (HEAT). Muscle temperature was measured in the vastus lateralis at 1, 2 and 3 cm depth prior to and following the warm up and immediately before the sprint test. Absolute and relative peak power output was determined. During passive recovery muscle temperature in HEAT was higher than both the control and insulation only condition, which resulted in a ~9% improvement in peak power output.
6.1 Introduction

It is well established that muscle temperature ($T_m$) has a significant effect on muscle function. (Asmussen and Boje 1945, Bergh and Ekblom 1979, Sargeant 1987, Racinais et al. 2005, De Ruiter and De Haan 2000, Edwards et al. 1972). Much of the available literature suggests that events that are of short duration (<5 minutes) and are more heavily reliant on high levels of power production tend to benefit from increases in muscle temperature (Asmussen and Boje 1945, Hajoglou et al. 2005). For example, it has been demonstrated that there is a ~4% per °C improvement in instantaneous power output during a vertical jump as $T_m$ increased (Bergh and Ekblom 1979). In addition, during short term (<30 sec) maximal sprint cycling peak power output increases between 2 and 10% per °C as $T_m$ was elevated (Sargeant 1987). In contrast to short term “sprint” based activities, performance during endurance events may be impaired if the warm up results in depleted glycogen stores (Genovely and Stamford 1982, Bergstrom et al. 1967) and an increase in thermoregulatory strain (Marino 2004, Drust et al. 2005). Therefore, it appears that the use of extensive warm ups, may be of most benefit for short duration activities that require high levels of short term power output.

Muscle temperature in humans may be elevated in one of two ways. Firstly it can be achieved via an active warm up, involving exercise that induces increases in metabolic activity and heat production within the body. Active warm ups are commonly completed using a method which mimics the activity for which the warm up is done, such as running, swimming or cycling (Bishop 2003b). Following 15 minutes of active warm up, $T_m$ has been shown to increase by approximately 3-4°C at depth of 2-4cm (Bishop 2003b). Secondly, passive heating, which involves the use of an external heat source to add heat to the desired muscles, can be used to elicit a rise in $T_m$. This is commonly done using water immersion (Sargeant 1987, Gray et al. 2006), warm air exposure (Simmons et al. 2008) or heating pads (Gray et al. 2006). Grey et al. have demonstrated that with a combination of 30 minutes warm water immersion followed by passive heating using electric blankets, $T_m$ can be elevated by approximately 3°C at a depth of 3cm (Gray et al. 2006).
Although most athletes perform some sort of warm up technique in preparation for their specific athletic event it is common for athletes to experience delays between completion of the warm up and the start of competition or where there are delays between repeated efforts/rounds of competition. These periods of time may be sufficient for T\textsubscript{m} to drop below an optimal level, as very little, no activity is possible in these periods, which may have a detrimental effect on performance, possibly due to the temperature related effect on power output. Currently, there is very little information about the exact effect a standardized sprint based warm up has on muscle temperature, and what the rate of decline in T\textsubscript{m} is following warm up cessation.

It is also logical to suggest that if T\textsubscript{m} can be artificially maintained following a warm up by the use of insulative clothing or clothing incorporating a form of external heating it may yield a performance benefit in subsequent activities that require high levels of power output.

**6.1.1 Aim**

The aim of this study was to examine how different ways of externally insulating the thigh muscles with either an insulated pant or a combined heated and insulated pant would influence T\textsubscript{m} during a recovery period following a standardized warm up procedure, and subsequently whether power output during a 30 sec maximal sprint test would be affected.

**6.1.2 Hypothesis**

It was hypothesized that added insulation, and moreover the combination of heating and insulation would result in better maintenance of T\textsubscript{m} following a warm up and contribute to elevated power output in the subsequent trial.
6.2 Method

6.2.1 Participants
Eleven healthy males (age 24.7 ± 4.2 years, height 1.82 ± 0.72m, body mass 77.9 ± 9.8 kg; mean ± S.D.) volunteered to participate in this study. All participants performed at least 3 cycle based training sessions per week. Participants completed a general health-screening questionnaire and were non-smokers and free from injury. They were informed of the requirements of the study before giving written informed consent. All procedures were approved by the Loughborough University Ethical Advisory Committee.

6.2.2 Study Overview
Prior to the main experimental trials, participants were familiarised with the nature of the exercise testing and general measurement procedures. For this, participants completed at least four 30s maximal sprint tests separated by approximately 10 minutes of passive recovery. Trials were continued until the time to peak power output and peak power output showed minimal deviation. Participants visited the laboratory on three further occasions at the same time of day to minimize circadian variation. On each occasion they completed a 15-minute standardized cycle sprint based warm up followed by 30 minutes passive recovery. During the 30-minute recovery period, participants underwent one of three experimental interventions (details below) before completing a 30 second maximal sprint performance test on a cycle ergometer. All trials were completed in a balanced order, separated by a minimum of 72 hours. In the 24 hours prior to each trial, participants were asked to refrain from caffeine and alcohol ingestion and any strenuous exercise. They were also asked to keep a record of their food intake and replicate this prior to the subsequent visits. Experiments were performed in an environmental chamber maintained at 15.9 ± 0.3°C and 54.0 ± 4.0% relative humidity, reflecting UK conditions.

6.2.3 Experimental Protocol
Participants attended the laboratory following a minimum of a four-hour fast, during which time they were allowed to consume water only. On arrival, participants voided
and had their height (Seca, Birmingham, UK) and body mass (ID1 Multi Range, Sartorius, Goettingen, DE) recorded. Participants then inserted a rectal probe (Grant Instruments Ltd., UK) 10cm beyond the anal sphincter to allow for monitoring of core temperature ($T_c$).

Participants entered the environmental chamber and remained seated for 30 minutes wearing a standard tracksuit to allow for stabilisation of muscle and core temperature. After the stabilisation period, baseline measures for thermal sensation, thermal comfort, core temperature ($T_c$), heart rate, blood lactate concentration and muscle temperature ($T_m$) were taken. Participants then mounted an electronically braked cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands) and performed the standardized warm-up exercise which consisted of 5 minutes cycling at an external power output of 100W, followed by five 10 sec maximal sprints, with each sprint separated by 1 min 50 sec of cycling at 75W. Participants were instructed to maintain a cadence of 85 rpm, until the start of each sprint. The maximal sprints were performed at a frictional load equivalent to 10% body mass. Immediately on completion of the warm up exercise, participants dismounted from the ergometer and $T_m$ was measured. In addition, measurements for $T_c$, heart rate, blood lactate concentration, thermal sensation of the legs and whole body and thermal comfort (legs and whole body) were made. Participants then donned a standard tracksuit top (adidas Clima365, adidas AG, Germany), and one of the three types of pant that made up the intervention: 1) control (CONT) where participants wore commercially available tracksuit trousers (adidas Clima365, adidas AG, Germany) 2) insulation only (INS), where participants wore a pair of insulated athletic trousers; 3) insulation plus heating (HEAT), where participants wore the same insulated pant with the addition of a heating element located around the thigh. The element was designed to cover the *vastus medialis, rectus femoris, vastus lateralis, biceps femoris, semitendinosus* and *semimembranosus* of both legs. There was no coverage directly over the adductor muscles to allow for some variation in leg size between subjects, but the heating element remained in close contact with both thighs in all participants. The heating element was capable of reaching temperatures of 40-42°C and was powered by a 14.8V battery that generated 7.5W to each heating pad. Once donned the participant remained in the environmental chamber in a seated position for 30 minutes. During this period measurements of thermal comfort, thermal sensation,
heart rate and $T_c$ were made every 5 minutes. At the end of the 30-minute recovery the tracksuit top and trousers were removed and a further $T_m$ measurement was made, along with measures of thermal sensation, thermal comfort, core temperature, heart rate and capillary blood lactate concentration. The participant then remounted the cycle ergometer and performed a 30s maximal sprint test with a frictional load equivalent to 10% body mass. The sprint test was preceded by a 15 sec period of cycling against 75W at a pedal cadence of 85 rpm. A further blood sample was taken within 20s of completion of the sprint.

6.2.4 Measurements

6.2.4.1 Power output and pedal cadence
Power output and pedal frequency were recorded continuously (at a sampling rate of 10Hz) throughout the warm up and sprint tests (Wingate Test Plus Module, Lode, Groningen, The Netherlands). Peak, minimum and mean power output, time to peak power, peak pedal cadence and time to peak pedal cadence were determined. Fatigue index representing the rate of anaerobic fatigue, and thus the contribution of anaerobic metabolism to performance was calculated as the change in power output divided by peak power multiplied by 100.

6.2.4.2 Muscle temperature
Muscle temperature of the vastus lateralis of the left leg was measured at depths of 3 cm, 2 cm and 1 cm using a calibrated needle thermistor probe (MKA08050A275T, Copenhagen, Denmark). The probes were calibrated using water immersion in a thermostatic circulator water bath (GD120 R1, Grant Instruments, UK) at 5 x 5 minute stable plateau temperatures (32°C, 34°C, 36°C, 38°C and 40°C). The measurement of the thermistors was referenced against a calibrated certified referenced thermometer. The needle probe was inserted to an initial depth of 3 cm beyond the muscle fascia where the temperature was allowed to stabilise before the probe was withdrawn to 2cm and then 1cm depths, with the temperature recorded at each depth.
6.2.4.3 **Heart rate, and blood lactate concentration**
Heart rate (HR) was recorded using a wireless heart rate monitor (RS800, Polar, Kempele, Finland). Thermal sensation (TS) (ASHRAE 1997) and thermal comfort (TC) (Gagge et al. 1969) were recorded. Capillary blood samples (~5 μl) were taken from the finger-tip and analysed immediately using an automated blood lactate analyser (Lactate Pro, Arkray, Shiga, Japan).

6.2.5 **Calculations**
The temperature dependence (temperature coefficient, $Q_{10}$) of both absolute and relative power output is presented as temperature coefficients ($Q_{10}$), calculated as follows (Bennett 1984):

$$Q_{10} = \left(\frac{R_2}{R_1}\right)^{10/(T_2-T_1)} \quad [6.1]$$

Where $R_2$ and $R_1$ represent the change in power output between two conditions; $T_2$ and $T_1$, represent the muscle temperature for each condition immediately prior to completion of the maximal sprint test. A $Q_{10}$ value of $> 1.0$ indicates a positive thermal dependence; a $Q_{10} = 1$ indicates a thermal independence and $Q_{10} < 1.0$ indicates a negative thermal dependence.

6.2.6 **Clothing insulation**
Insulation values for the heated trousers for the legs and hips and whole body were determined using a thermal manikin (Newton, MTNW, Seattle, US) with a uniform skin temperature of 34°C and environmental temperature of 21°C. For dry heat insulation the following equation was used (Havenith 2009):

$$I_T = \frac{T_{sk} - T_a}{\sum (\alpha_i \cdot H_i)} \quad \{\text{m}^2\cdot\text{K}\cdot\text{W}^{-1}\} \quad [6.2]$$

where:
\[ I_T = \text{total insulation of complete ensemble including enclosed and surface air layers (m}^2\text{.K.W}^{-1}) \]

\[ \bar{T}_s = \text{mean skin temperature (°C)} \]

\[ T_a = \text{ambient temperature (°C)} \]

\[ a_i = \frac{\text{(surface area of segment } i)}{\text{(total surface area of manikin)}} \]

\[ H_I = \text{heat loss of segment } I (\text{W}). \]

### 6.2.7 Statistics

Preliminary analysis was conducted to ensure that there was no violation of the assumptions of the normality of distribution. Performance data were analysed using repeated measures ANOVA. \( T_m \), thermal sensation, thermal comfort, \( T_c \), HR data were analysed using two way repeated measures ANOVA (condition x time). Where significant effects were identified, *post-hoc* two-way paired samples t-tests with a Bonferroni correction were conducted. The accepted level of significance was set *a priori* to \( p < 0.05 \). Data are presented as mean ± SD

### 6.3 Results

#### 6.3.1 Clothing Insulation

When the heating element was inactive the insulation value of the insulated trousers alone was 0.438 m\(^2\).K.W\(^{-1}\) (2.8 clo), with whole body insulation, comprising of the tracksuit top and insulated trousers being 0.241 m\(^2\).K.W\(^{-1}\) (1.6 clo). When the heating element was activated, insulation of the legs and hips increased by 0.378 m\(^2\).K.W\(^{-1}\) (2.4 clo) to give a total insulation for the trousers of 0.815 m\(^2\).K.W\(^{-1}\) (5.3 clo), with whole body insulation increasing to 0.263 m\(^2\).K.W\(^{-1}\) (1.7 clo). Effective insulation values for the heated trousers will be even higher than those reported here (17). As the heating input from the trousers reduces the manikin heat loss to zero, and even warms up the manikin, the measured values underestimate the full impact of the heating. Nevertheless, the observed values provide an indication of the lowest estimate of the effect size of the added heating.
6.3.2 Muscle temperature
There were no differences in $T_m$ at any depths prior to the warm up in any condition. Immediately following the completion of the warm up $T_m$ increased at all depths and was the same between conditions (Figure 6.1). Following the recovery period, $T_m$ declined in all conditions, however, remained higher during HEAT at all depths compared to CONT and INS ($p<0.0005$).
Figure 6.1: Muscle temperature at 3, 2, and 1cm depth measured before the warm up (0WUP), immediately following the warm up (15WUP) and after 30 min seated recovery (30REC) in the control (CONT), insulation only (INS) and insulation + heating (HEAT). * = HEAT > CONT p<0.0005, † = HEAT > INS p<0.0005. n=11. Data presented as mean ± SD.
The difference in $T_m$ at the three depths between conditions following the recovery period is further highlighted in figure 5.2, which shows the $T_m$ gradient for all three conditions at 30REC.

![Figure 5.2: Muscle temperature measured at 3, 2 and 1 cm depth after 30 min seated recovery (30REC) in the control (CONT), insulation only (INS) and insulation + heating (HEAT). ** $p < 0.005$, $HEAT > CONT$; †† $p < 0.01$, $HEAT > INS$; * $p < 0.0005$, $HEAT > CONT$; † $p < 0.01$ $HEAT > INS$. $n=11$ Data presented as mean ± SD](image)

### 6.3.3 Power related data

There was a general tendency for the means of the power related data to suggest higher power and faster power development with both interventions. Absolute and relative peak power output were higher in HEAT compared to CONT ($p<0.05$) by 9.6% and 9.1% respectively (Table 6.1). There were positive correlations between peak power output and muscle temperature measured at depths of 1cm ($r = 0.38$, $n = 33$, $p<0.05$), 2cm ($r = 0.48$, $n = 33$, $p<0.01$) and at 3cm ($r = 0.4$, $n = 33$, $p<0.05$, figure 6.3). This is supported by the finding that absolute peak power output had a strong positive thermal dependence ($Q_{10}$=2.4 at 1cm, 2.5 at 2 and 3cm) as did relative peak
power output ($Q_{10} = 2.2$ at all depths). There were no significant differences in absolute or relative peak power output between HEAT and INS or between INS and CONT (Table 6.1). There was no effect of condition on mean power output, minimum power output, time to peak power output, peak cadence or time to peak cadence (Table 6.1). There was an overall effect of condition on fatigue index ($p<0.05$), but no significant differences between individual conditions.

Table 6.1: Peak power output (PPO), relative peak power output (rPPO), mean power output (Mean PO), minimum power output (min PO), peak cadence (Peak RPM), time to peak cadence and fatigue index for control (CONT), insulation only (INS) and insulation + heating (HEAT). All data presented as mean ± SD

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<th>CONT</th>
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<td>PPO (W)</td>
<td>1468 ± 260</td>
<td>1545 ± 338</td>
<td>1609 ± 270*</td>
</tr>
<tr>
<td>rPPO (W.kg$^{-1}$)</td>
<td>19.2 ± 1.7</td>
<td>20.3 ± 2.3</td>
<td>20.9 ± 1.6*</td>
</tr>
<tr>
<td>Mean PO (W)</td>
<td>711 ± 153</td>
<td>707 ± 127</td>
<td>769 ± 77</td>
</tr>
<tr>
<td>Min PO (W)</td>
<td>443 ± 81</td>
<td>435 ± 136</td>
<td>409 ± 61</td>
</tr>
<tr>
<td>Time to peak PO (s)</td>
<td>1.9 ± 0.3</td>
<td>1.8 ± 0.2</td>
<td>1.6 ± 0.2</td>
</tr>
<tr>
<td>Peak cadence (RPM)</td>
<td>123.8 ± 5.3</td>
<td>124.3 ± 6.2</td>
<td>127.0 ± 6.3</td>
</tr>
<tr>
<td>Time to peak cadence (s)</td>
<td>3.4 ± 0.8</td>
<td>3.1 ± 0.7</td>
<td>2.7 ± 0.7</td>
</tr>
<tr>
<td>Fatigue Index (%)</td>
<td>68.8 ± 8.2</td>
<td>69.8 ± 9.5</td>
<td>74.2 ± 4.3</td>
</tr>
</tbody>
</table>

* Significant difference between HEAT and CONT ($p<0.05$)
Figure 6.3: The correlations between peak power output and muscle temperature taken immediately prior to the completion of the 30s sprint test. At all depths, there was a significant correlation between muscle temperature and power output. $n = 33$; $p < 0.05$
6.3.4 Blood lactate concentration

Following the warm up, blood lactate concentration increased (p<0.05) and was the same in all conditions. After the recovery period blood lactate concentration declined in all conditions but remained higher (p<0.01) in INS compared to HEAT (Figure 6.4). Following the maximal sprint test, blood lactate concentration increased (p<0.05) in all conditions and was higher in HEAT compared to CONT (p<0.05). Moreover, the change in blood lactate concentration during the sprint test was greater (p<0.05) in HEAT (Δ = 6.3 ± 1.8 mmol.L⁻¹) compared to CONT (Δ = 4.1 ± 1.9 mmol.L⁻¹).

Figure 6.4: Blood lactate concentrations at baseline (0 WUP), following warm up (15 WUP), after passive recovery (30 REC) and immediately following the maximal sprint test (POST WIN) for control (CONT), insulation only (INS) and insulation + heating (HEAT). * = INS > HEAT p<0.01; ** = HEAT > CONT p <0.05. n=11. Data presented as mean ± SD
6.3.5 Heart rate and rectal temperature
There was no effect of condition on either heart rate or core temperature during the trials (Table 6.2).

Table 6.2: Core temperature ($T_c$), heart rate (HR) following warm up (WUP 15), after 30 minutes passive recovery (30 REC) and immediately following the maximal sprint test (POST WIN) for control (CONT), insulation only (INS) and insulation + heating (HEAT) conditions. All data presented as mean ± SD

<table>
<thead>
<tr>
<th></th>
<th>15 WUP</th>
<th>30 REC</th>
<th>POST WIN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CONT</td>
<td>INS</td>
<td>HEAT</td>
</tr>
<tr>
<td>$T_c$ (°C)</td>
<td>37.4 ± 0.3</td>
<td>37.4 ± 0.4</td>
<td>37.5 ± 0.2</td>
</tr>
<tr>
<td>HR (b.p.m)</td>
<td>137 ± 17</td>
<td>138 ± 13</td>
<td>138 ± 10</td>
</tr>
</tbody>
</table>

6.3.6 Thermal sensation and comfort
Thermal sensation of the legs was higher towards “warm” in the legs for HEAT compared to CONT at the following time points: 10REC (p<0.05), 15REC (p<0.005), 20 REC (p<0.001), 25REC (p<0.05) and 30REC (p<0.0005). There were also elevations in thermal sensation for INS vs CONT at the following: 20REC (p<0.001) and INS vs HEAT at 25REC (p<0.05). Thermal comfort for the whole body or legs between conditions was the same at all time points (figure 6.5).
Figure 6.5: Subjective measures of A) thermal sensation of the legs and B) whole body thermal comfort for control (CONT), insulation only (INS) and insulation + heating (HEAT). * = HEAT > CONT p < 0.005; ** = INS > CONT p < 0.05; † = HEAT > INS p < 0.05. n=11. Data presented as mean ± SD
6.4 Discussion

This study has demonstrated that the use of an insulated garment combined with internal heating elements around the thigh (HEAT) attenuated the decline in muscle temperature that occurs following a sprint specific cycling warm-up, while an insulated garment alone (INS) had no performance benefit. Therefore, the original working hypothesis that additional insulation in combination with passive external heating would improve power output is accepted. The heated garment resulted in a muscle temperature that was approximately 1°C higher at a depth 1cm and 0.4°C higher at 3cm 30 minutes after the warm-up compared to when no additional insulation or insulation only was provided. This was associated with a greater peak power output (~9%) during a 30 s maximal sprint when muscle temperature was maintained with HEAT compared to CONT. The use of frictional load equivalent to 10% body mass during the 30s sprint test has been shown to be optimal for well trained athletes (Dotan and Bar-Or 1983, Bar-Or 1987), thus leading to increased sensitivity of the test to detect changes in overall performance. Furthermore, the completion of a number of familiarisation sprint tests will have reduced any practice effects gained from repetition of the tests. Taken together, this allows us to be confident that the results presented here are a true reflection of performance changes that would be mirrored in actual sprint competition. In support of this, it has been shown that 30s of maximal sprinting on a cycle ergometer is moderately correlated to field based measures of sprint performance (Baker and Davies 2002), suggesting that the performance benefit reported in the present study will translate to improved field based sprint performance. It is suggested that the external heating procedure used here could be applied in situations where athletes experience delays between warm up and competition, or where there are repeated efforts/rounds separated by periods of low to moderate activity which are not sufficient to maintain T_m via metabolic heat production alone. Such scenarios are evident in many track and field athletics and track cycling competitions.

The present data demonstrates that a 9% improvement in peak power output per °C elevation in T_m, when T_m is measured at depths of between 1-3cm. With a correlation between muscle temperature and peak power output clearly evident at all depths, with increased muscle temperature associated with increased peak power output. This
supports the notion that at a depth of between 1 and 3cm with every 1°C rise in muscle temperature there is an approximate 4-10% improvement in peak power output (Bergh and Ekblo 1979, Sargeant 1987), although this is dependent on pedal cadence (Sargeant 1987). Despite this, it is likely that there is an optimal ceiling for muscle temperature, above which continued improvements in peak power are no longer evident. It is possible that there is a bell-shaped relationship between muscle temperature and power output, however this requires future investigation. The relationship between muscle temperature and skeletal muscle function has been well documented (Bergh and Ekblo 1979, Sargeant 1987, de Ruiter et al. 1999, Rall and Woledge 1990, Ranatunga 2010), with increasing muscle temperature impacting upon the force/velocity relationship in both fast and slow twitch muscle fibres (de Ruiter et al. 1999, Ranatunga 2010). This interaction causes a shift in the force/velocity curve, resulting in increased peak power output with a temperature coefficient \(Q_{10}\) of 2 – 2.5 (Ranatunga 1998). This is similar to the \(Q_{10}\) reported here (\(Q_{10} 2.4\)), indicating that the in vivo thermal dependence of peak power output mirrors that documented in single fibre and animal models.

The increase in power output following HEAT is probably due to an elevated rate of ATP turnover as a consequence of the higher muscle temperature (Gray et al. 2006). This is reflected by the higher concentration of blood lactate following the maximal sprint in the HEAT condition. However, blood lactate concentration is dependent on many other factors including its rate of appearance and disappearance. Nevertheless, direct measurements of ATP turnover have shown ATP turnover to be elevated with increased muscle temperature. Gray et al., have shown that when muscle temperature is artificially elevated using water immersion of the legs, there is an increase in anaerobic ATP turnover during 6s maximal sprint cycling, as derived from direct measurement of ATP turnover via muscle biopsy analysis (Gray et al. 2006). Furthermore, in partial agreement with the present results they report an increase in both mean and maximal power output and peak pedal cadence following passive heating. During short-term maximal exercise, anaerobic metabolic pathways account for approximately 70-80% of ATP turnover (Smith and Hill 1991, Withers et al. 1991). Therefore, it would be expected that there was a higher concentration of blood lactate following the maximal sprint test when power output is elevated, as demonstrated here. However, it is possible that the differences in blood lactate
concentration reported in the present study represent an increased peripheral vasodilatation in the HEAT condition resulting in faster blood lactate appearance, and may not necessarily directly indicate a greater anaerobic component of the 30s sprint test, which can only reliably be gained from direct measures of muscle metabolites.

It can be seen as positive that the only significant difference in perceptual measures reported was a change in thermal sensation of the legs. These differences are likely due to the increased insulation and $T_{sk}$ in the HEAT condition. Had there been associated negative changes in thermal comfort as a result of the heating protocol, it is possible that performance would have been adversely affected. Despite the inherent difficulties in isolating thermal comfort from other physiological and thermal perceptions and their effects on exercise performance, Schlader et al., have demonstrated that elevations in pre-exercise thermal discomfort were associated with impaired cycling performance (Schlader et al. 2011). Importantly, in the present study there were no differences in ratings of overall thermal comfort or thermal sensation, which indicates that the degree of heating was not perceived as more uncomfortable than when no heat was applied, and is therefore less likely to have a negative effect on performance.

6.4.1 Conclusion

This study has demonstrated that external heating of the quadriceps and hamstrings during periods of inactivity between exercise bouts can attenuate the reduction in $T_m$. Importantly, it is only the use of the additional external heating that is present in the HEAT condition which leads to a significant and relevant improvement in peak power output compared to CONT and INS after 30 minutes of inactivity. The INS only condition has no additional benefit on any physiological measures compared to when CONT is used. This may have important practical implications for power athletes who may experience delays in their competition performance following the completion of a warm up or experience muscle cooling due to the intermittent nature of their sport or competition.
Chapter 7

The Effect of Passive Heating During and After Warm Up on Sprint Cycling Power Output and Muscle Temperature Decline

7 Chapter Summary

In chapter 6 it was shown that the use of external heating between warm up completion and sprint cycling performance has a positive effect on a maximal sprint effort. The current chapter aimed to determine whether warm up completion combined with passive heating had any further benefit on muscle temperature and subsequent sprint performance. On three occasions, 10 male cyclists completed a 15-minute intermittent sprint based warm up on a cycle ergometer, followed by a 30 min passive recovery period before completing a 30 sec maximal sprint test. The warm up was completed either with or without additional external passive heating. When additional passive heating was not used, participants completed the warm up in their usual cycling apparel. During recovery, external passive heating was used in shorts warm up (SH) and heated warm up (HH) conditions, in control, a standard tracksuit was worn (CONT). Muscle temperature was recorded throughout the recovery period at 2-minute intervals at a depth of 2cm in the vastus lateralis. Mean power and absolute and relative peak power output was determined from the 30s maximal sprint test. Peak (11%), relative (10.8%) and mean (4%) power were all improved with both SH (p<0.005) and HH (p<0.05) compared to CONT. There was no additional benefit of HH on \( T_m \) or power output compared to SH. \( T_m \) declined exponentially during CONT, but SH and HH reduced \( \Delta T_m \) during recovery. The data show that using electrically heated trousers during warm up and recovery has no additional performance benefit than when used for recovery alone.
7.1 Introduction

It is well established that muscle temperature ($T_m$) has a significant effect on muscle function and force production (Asmussen and Boje 1945, Bergh and Ekbom 1979, Sargeant 1987, Racinais et al. 2005, De Ruiter and De Haan 2000, Edwards et al. 1972). Much of the available literature suggests that events which are of short duration and are more heavily reliant on high levels of power production tend to benefit from increases in muscle temperature (Asmussen and Boje 1945, Hajoglou et al. 2005). This is primarily due to optimization of the force velocity relationship of $T_m$ at higher temperatures and increase in subsequent dynamic strength (Bergh and Ekbom 1979). Following 15 minutes of active warm up, $T_m$ has been shown to increase by approximately 3-4°C at depth of between 1-4cm (Bishop 2003b) (Chapter 6). It has been reported that there is a ~4%/°C improvement in vertical jump performance as $T_m$ increased (Bergh and Ekbom 1979). In addition, it has been shown that changes in $T_m$ following water immersion of the legs prior to cycling directly influences peak force production during isokinetic cycling (Sargeant 1987). Therefore, it has become commonplace for vigorous, intermittent warm ups to be completed prior to the execution of sprint and power based activities to maximize exercise performance.

The completion of a warm up prior to exercise affects performance via a number of different physiological mechanisms. These include temperature dependent changes such as, decreased viscous resistance of the joints (Wright and Johns 1961, Wright 1973), increased rate of metabolic reactions (Fink et al. 1975) and faster nerve conduction (Ross and Leveritt 2001), along with non-temperature related changes including increased blood flow and oxygen consumption (McCutcheon et al. 1999) and increased psychological preparedness (Bishop 2003a, Bishop 2003b). All of these changes acting in synchrony are highly likely to lead to improvements in overall physical performance.

As it is common for athletes to experience delays in performance onset following the completion of a warm up, or between bouts or rounds of activity, there may be time for $T_m$ to drop below an optimal level (Chapter 6). This may have a detrimental effect on performance, particularly during power-based activities such as weight lifting and...
sprinting. However a detailed time course of post exercise $T_m$ decline has only been reported on a number of occasions (Kenny et al. 2003, Kenny et al. 2002, Saltin et al. 1972, Saltin et al. 1970, Aikas et al. 1962, Allsop et al. 1991), with none directly assessing any subsequent performance changes. In general, it appears that $T_m$ begins to decline immediately post exercise (Kenny et al. 2003, Saltin et al. 1970, Allsop et al. 1991), although the rate at which $T_m$ declines does appear to be partially dependent on environmental conditions (Saltin et al. 1972, Saltin et al. 1970).

Most interventions to raise or maintain muscle temperature (e.g. warm water immersion) are not feasible to be used just prior to competition in athletic events. Therefore, if $T_m$ can be artificially maintained following a warm up by the use of clothing incorporating a form of external heating, it may yield a performance benefit in subsequent power based activities. We have previously shown (Chapter 6) that it is possible to attenuate the decline in muscle temperature that is evident during post exercise rest/recovery in cool ambient conditions. Following a 30-minute recovery period where electrically heated trousers were worn, $T_m$ remained 1°C, 0.5°C and 0.4°C, higher at depths of 1, 2 and 3cm respectively compared to when participants wore a standard tracksuit ensemble. Furthermore, both absolute and relative peak power outputs were ~9% higher following the heated recovery, as was mean power over the course of a 30s maximal sprint test. The temperature coefficient ($Q_{10}$) for peak power was shown to be 2.4 at 1cm, 2.5 at 2cm and 2.0 at 3cm, indicating a positive thermal dependence. However, as only a solid needle probe was used to measure muscle temperature, it was not possible to determine the rate of decline in $T_m$ over the course of the recovery period. Furthermore, as external passive heating was only used during the recovery portion of the protocol, the question of whether an active warm up with simultaneous external passive heating has an additional affect on $T_m$ and maximal sprint performance remains to be elucidated.

7.1.1 Aims

The aims of the present study were threefold; firstly, how does the use of passive heating in combination with an active warm up influence the time course in the change in $T_m$. Secondly, is there a subsequent effect on $T_m$ decline during the recovery period with the use of heated trousers during recovery and/or warm up?
Finally, we aimed to assess any difference in sprint performance resulting from use of passive heating during recovery and/or warm up.

7.1.2 Hypothesis

It was hypothesized that the use of passive heating during a warm up will lead to additional gains in $T_m$ over and above that of a warm up completed without additional passive heating. Secondly, it is expected that the post exercise decline in $T_m$ will be reduced with the addition of passive heating. Furthermore, we hypothesized that $T_m$ maintenance will convey an additional performance benefit during a maximal sprint test.

7.2 Methods

7.2.1 Participants

Ten healthy male cyclists volunteered to participate in this study (23.5 ± 3.4 yrs; 180.9 ± 4.1cm; 73.7 ± 0.65 kg; 16.2 ± 6.4 hrs training/week). All participants performed at least 3 cycle based training sessions per week. Participants completed a general health-screening questionnaire, were non-smokers and free from injury. They were informed of the requirements of the study before giving their full written informed consent. All procedures were approved by the Loughborough University Ethical Advisory Committee.

7.2.2 Study Overview

Prior to the experimental trials, participants were familiarised to the nature of the exercise testing and general measurement procedures. 7-10 days prior to their first experimental visit, participants completed at least four 30s maximal sprint tests (Wingate test) separated by approximately 10 minutes of passive recovery. Trials were continued until the time to reach peak power output showed minimal deviation. Participants visited the laboratory on three further occasions at the same time of day to minimize any effects of circadian variation on performance. On each occasion they completed a standardised sprint based warm up followed by a 30 minute seated passive recovery period. Participants then completed a 30 second maximal sprint performance test (figure 1). During the 30-minute recovery period, participants underwent one of three experimental interventions: 1) control (CONT) where
participants wore their own cycle shorts in the warm up and commercially available tracksuit pants during recovery, 2) short/heat (SH), where participants warmed up in normal cycling shorts and then wore a pair of heated pants during the recovery phase; 3) heat/heat (HH), participants wore the same heated trousers during both the warm up and the recovery phase. In all conditions participants wore a commercially available tracksuit top (adidas AG, Germany) during the recovery phase. All trials were completed in a balanced order, with a minimum of 7 days between trials. During the 24 hours before each trial, participants were asked to refrain from caffeine and alcohol ingestion and any strenuous exercise. They were also required to keep a record of their food intake and match this prior to the subsequent visits. Experiments were performed in an environmental chamber maintained at 16.1 ± 0.2°C and 53.4 ± 2.0% relative humidity.

7.2.3 Experimental Protocol
Participants attended the laboratory following a minimum of a four-hour fast, during which time they were allowed to consume water only. On arrival, participants voided and had their height and weight (ID1 Multi Range, Sartorius, Goettingen, DE) recorded. Participants then inserted a rectal probe (Grant Instruments Ltd., UK) 10cm beyond the anal sphincter to allow for monitoring of core temperature ($T_c$).

Participants entered the environmental chamber and remained seated for 30 minutes wearing a standard tracksuit (comprised of top and trousers), cycle clothing and shoes to allow for stabilisation of muscle and core temperatures. After the stabilisation period, baseline measures for thermal sensation (legs and whole body), thermal comfort (legs and whole body), core temperature ($T_c$), heart rate, blood lactate concentration and muscle temperature ($T_m$) at depths of 1, 2 and 3cm, were recorded (figure 7.1). For the warm up, participants then mounted an electronically braked cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands) and performed a standardised warm up protocol. This consisted of 5 minutes cycling at an external power output of 100W, followed by five 10 sec maximal sprints against a load equivalent to 10% of body mass, with each sprint separated by 1 min 50 sec of active recovery at 75W. Participants were instructed to maintain a cadence of 85 rpm during the recovery periods, until the start of each sprint. During the final active recovery
period, measurements for $T_c$, heart rate, blood lactate concentration, thermal sensation (legs and whole body) and thermal comfort (legs and whole body) were recorded.

Immediately after completion of the warm up exercise, participants dismounted from the bike and a flexible indwelling muscle probe was inserted to a depth of ~2cm into the *vastus lateralis*. Participants then donned a standard tracksuit top, and one of the three types of trouser that made up the interventions. The trousers used in this experiment were modified from those in chapter 6. The heating elements we positioned to allow for greater coverage of the active musculature and primary agonists involved in cycling, whereas those trousers used in chapter 6 only covered the thigh region. There was also a rippable seam down the length of both legs to facilitate faster removal of the trousers to reduce the potential to $T_m$ decline before the completion of the maximal sprint test. This also allowed for the indwelling muscle probe to be inserted with the trousers already on, again minimizing the possible decline in $T_m$ between warm up completion, probe insertion and the first $T_m$ measure been recorded. The heating element in the trousers was designed to cover the *gluteus maximus*, *vastus medialis*, *rectus femoris*, *vastus lateralis*, *biceps femoris*, *semitendinosus* and *semimembranosus* of both legs. There was no coverage directly over the adductor muscles to allow for some variation in leg size between subjects, but the heating elements remained in close contact with both thighs in all participants. The heating element was capable of reaching temperatures of 40-42°C and was powered by a 14.8V battery that generated 7.5W to each heating pad, covering a total surface area of 2,821.6cm$^2$ for both pads. Once donned, the participant remained in the environmental chamber in a supine position for a duration of 30 minutes. During this period measurements of thermal comfort, thermal sensation, heart rate and $T_c$ were made every 5 minutes. $T_m$ was recorded every 2 minutes. At the end of the 30-minute recovery another finger prick lactate sample was obtained and then the tracksuit top and trousers were removed, as was the indwelling muscle probe. The participant then remounted the cycle ergometer and performed a 30s maximal sprint test against a load of 10% body mass. The sprint test was preceded by a 15s period of cycling against 75W at a pedal cadence of 85 rpm. Participants received a 5s countdown in the lead in to the maximal sprint test, during which time cadence was maintained at 85 rpm. Verbal encouragement was provided for the duration of the 30s sprint test, although no indication of elapsed time was provided. A fingertip capillary
blood sample for the determination of blood lactate concentration was taken within 20s of completion of the sprint. Measurements for peak power, time to peak power, total mean power during the 30s sprint, maximum heart rate, and end point $T_c$, thermal sensation (whole body and legs) and thermal comfort (whole body and legs) were recorded.

![Diagram of experimental procedure](image)

*Figure 7.1: Outline of the experimental procedure, showing points at which physiological, psychological and performance measures were taken. $T_m$, muscle temperature; $La^+$, lactate measurement; $T_{comfort}$, Thermal Comfort; $T_{sens}$, Thermal Sensation; $T_c$, Core Temperature; HR, heart rate; 15 WUP, 15 minute warm up; W Test, Wingate Test*

### 7.2.4 Measurements

#### 7.2.4.1 Power output and pedal cadence

Power output and pedal frequency were recorded continuously (at a sampling rate of 10Hz) throughout the warm up and sprint tests (Wingate Test Plus Module, Lode, Groningen, The Netherlands). Peak, minimum and mean power output, time to peak power, peak pedal cadence and time to peak pedal cadence were determined. Fatigue index was calculated as the change in power output divided by peak power output multiplied by 100.
7.2.4.2 Muscle temperature
Prior to the start of the warm up procedure, muscle temperature of the lateral quadriceps of the left leg was measured at depths of 3 cm, 2 cm and 1 cm using a calibrated needle thermistor probe (MKA08050A275TS Ellab, Copenhagen, Denmark). The needle probe was first inserted to an initial depth of 3 cm beyond the muscle fascia of the vastus lateralis, the temperature was allowed to stabilise before the probe was withdrawn to 2 cm and then 1 cm depths, with the temperature recorded at each depth after stabilisation. During the recovery phase, continual $T_m$ measures were obtained using a calibrated (Chapter 6.2.4.2) flexible indwelling muscle probe (MCA 08170A275TS Ellab, Copenhagen, Denmark). An 18-gauge cannula (Venflon, BD, UK) was first inserted to a depth of 2 cm into the vastus lateralis and secured in place using two Tegaderm film dressings (3M, UK). The probe was then fed through the cannula until it was residing in the muscle tissue. The probe was then further secured in place using Transpore tape (3M, UK) to prevent any unwanted movement in the probe’s location within the muscle. Probe insertion took approximately 90s following cessation of cycling.

7.2.4.3 Heart rate, thermal sensation and blood lactate concentration
Heart rate was recorded using a wireless heart rate monitor (RS800, Polar, Kempele, Finland). Thermal sensation was measured using a 20-point scale (10 extremely hot, 0 Neutral -10 extremely cold (ASHRAE 1997). Thermal comfort was measured on a 4-point scale (1- comfortable, 4- uncomfortable) (Gagge et al. 1969). Both thermal sensation and thermal comfort were recorded at 5-minute intervals throughout the trial. Capillary blood samples (5ul) were taken from the fingertip and analysed immediately using an automated blood lactate analyser (Lactate Pro, Arkray, Shiga, Japan).

7.2.4.4 Clothing insulation
Insulation values for the heated trousers for the legs and hips and body as a whole were determined using a thermal manikin (Newton, MTNW, Seattle, US) with a
uniform skin temperature of 34°C and environmental temperature of 21°C. For dry heat insulation the following equation was used (Havenith 2009):

\[
I_T = \frac{T_{sk} - T_a}{\sum (a_i \cdot H_i)} \quad \text{[m}^2\text{.K.W}^{-1}] \quad [7.1]
\]

where:

- \(I_T\) = total insulation of complete ensemble including enclosed and surface air layers (m\(^2\).K.W\(^{-1}\))
- \(T_{sk}\) = mean skin temperature (°C)
- \(T_a\) = ambient temperature (°C)
- \(a_i\) = (surface area of segment i)/(total surface area of manikin)
- \(H_i\) = heat loss of segment I (W).

The rate of decline in muscle temperature was analysed using an exponential model using the equation:

\[
T_m(t) = T_{end} + e^{\left(\frac{t}{\tau}\right)} \cdot (T_{start} - T_{end}) \quad [7.2]
\]

where:

- \(T_m\) = muscle temperature (°C)
- \(T_{end}\) = muscle temperature at the end of the time period (°C)
- \(T_{start}\) = muscle temperature at the start (°C)
- \(e\) = a base logarithm (2.17)
- \(t\) = time (s)
- \(\tau\) = time constant (18.65)

### 7.2.5 Statistics

Preliminary analysis was conducted to ensure that there was no violation of the assumptions of the normality of distribution using the Shapiro-Wilk test. Performance and \(T_m\) data were analysed using repeated measures ANOVA followed by a post hoc
paired sample t-test. TS, TC, \( T_c \), HR data were analysed using two way repeated measures ANOVA (condition \( \times \) time). Where significant effects were identified, post-hoc two way paired samples t-tests with a Bonferroni correction were conducted. The relationship between variables was assessed using Pearson product-moment correlation coefficient. The accepted level of significance was set \textit{a priori} to \( p < 0.05 \). Data are presented as mean ± S.D.

7.3 Results

7.3.1 Clothing Insulation
When the heating element was inactive, the insulation value was 0.559 m\(^2\).K.W\(^{-1}\) (3.6 clo) for the legs and hips in isolation which were covered by the garment. The whole body insulation comprising of the tracksuit top and inactive heated trousers was 0.266 m\(^2\).K.W\(^{-1}\) (1.7 clo). When the heating element was activated, insulation of the legs and hips increased by 0.284 m\(^2\).K.W\(^{-1}\) (1.8 clo) to give a total insulation value for this area of 0.842 m\(^2\).K.W\(^{-1}\) (5.4 clo). Whole body insulation was increased to 0.293 m\(^2\).K.W\(^{-1}\) (1.9 clo). Effective insulation values for the heated trousers will be even higher than those reported here (Havenith 2009). As the heating input reduces the manikin heat loss to zero around the upper leg and even warms up the manikin, the measured values underestimate the full impact of the heating. Nevertheless, the observed values provide an indication of the lowest estimate of the effect size of the added heating, which is a heat loss reduction over the legs of at least one third.
7.3.2 Muscle Temperature

There were no differences in resting $T_m$ at any depths taken following the stabilisation period (CONT 36.1 ± 0.4°C; SH 36.2 ± 0.4°C; HH 36.1 ± 0.4°C, mean across all depths 36.1 ± 0.4°C). Following the completion of the warm up, there was an increase in $T_m$ of 2-2.4°C at all depths, with no differences between conditions (CONT 38.1 ± 0.5°C; SH 38.1 ± 0.3°C; HH 38.5 ± 0.5°C, mean across all depths 38.2 ± 0.5°C). During recovery, $T_m$ declined exponentially during CONT, with a time constant of 18.7 minutes, indicating a return to within 5% of the baseline $T_m$ value in 56 minutes. For both SH and HH, when analysed as exponential decays, time constants were 24 and 30 minutes respectively, however, the data do not fit the exponential model very well, as $T_m$ appears to level off for both SH and HH at a value above the baseline $T_m$. There were differences in $\Delta T_m$ between HH and CONT from 20 minutes onwards (p<0.05, figure 7.2). In SH $\Delta T_m$ was higher after 28 minutes (p<0.05, figure 7.2). There were no differences between SH and HH at any time point.

Figure 7.2: Time course of the decline in muscle temperature during recovery measured at a depth of 2cm. † HH > CONT p<0.05; †† HH > CONT p<0.01; *SH > CONT p<0.05; ** SH > CONT p<0.01. n=10. Data presented as mean ± SD
Table 7.1: Peak power output (PPO), relative peak power output (rPPO), mean power output (Mean PO), peak cadence (Peak RPM), time to peak cadence and fatigue index for control (CONT) warm up in shorts and heat recovery (SH) and combined heated warm up and recovery (HH) conditions. All data presented as mean ± SD

<table>
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<th>CONT</th>
<th>SH</th>
<th>HH</th>
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<tr>
<td><strong>PPO (W)</strong></td>
<td>1397.2 ± 238.6</td>
<td>1561.2 ± 257.5**</td>
<td>1541.6 ± 222.5†</td>
</tr>
<tr>
<td>rPPO (W.kg⁻¹)</td>
<td>18.9 ± 3.0</td>
<td>21.0 ± 2.2**</td>
<td>20.9 ± 1.8†</td>
</tr>
<tr>
<td><strong>Mean PO (W)</strong></td>
<td>702.9 ± 108.9</td>
<td>733.5 ± 125.7**</td>
<td>728.5 ± 124.9††</td>
</tr>
<tr>
<td><strong>Time to PPO (s)</strong></td>
<td>1.9 ± 0.5</td>
<td>1.7 ± 0.3</td>
<td>1.7 ± 0.2</td>
</tr>
<tr>
<td><strong>Peak cadence (RPM)</strong></td>
<td>120.6 ± 8.6</td>
<td>127.4 ± 8.8</td>
<td>126.7 ± 8.6</td>
</tr>
<tr>
<td><strong>Time to peak cadence (s)</strong></td>
<td>2.7 ± 1.3</td>
<td>2.2 ± 0.8</td>
<td>2.7 ± 0.6</td>
</tr>
<tr>
<td><strong>Fatigue Index (%)</strong></td>
<td>71.1 ± 6.1</td>
<td>73.6 ± 4.7</td>
<td>71.6 ± 6.8</td>
</tr>
</tbody>
</table>

Significant difference between: † HH vs. CONT (p<0.05), †† HH vs. CONT (p<0.005) ** SH vs. CONT p<0.005.

### 7.3.3 Power Output

All power related data were normally distributed (all p > 0.55). There was a significant effect of condition on both peak and relative peak power output (p<0.05, figure 7.4, table 7.1), although 3 of the participants failed to show an improvement in HH compared to CONT. For peak power, SH (p<0.005) and HH (p<0.05) were higher than CONT (figure 7.4a). This equated to an improvement in relative peak power output of 9.9 ± 9.9% and 9.0 ± 14.5% for SH and HH respectively vs. CONT. There was no difference in peak power output between SH and HH. In addition, there was also an effect of condition on mean power output during the 30s maximal sprint test (p<0.05, table 7.1). Mean power output was higher for both SH (4.4%, p<0.005) and HH (3.6%, p<0.001) compared to CONT. There was only a trend for an effect of condition on time to peak power output (p=0.09).
There was a moderate positive correlation between $\Delta T_m$ and peak power output ($r = 0.36$, $N=30$, $p<0.05$, figure 7.3). There was no such significant relationship between mean power output and $\Delta T_m$ ($r=0.26$, $n=30$, $p = 0.2$).

Figure 7.3: There was a positive correlation between $\Delta T_m$ and peak power output, with a lower $\Delta T_m$ associated with increased peak power output. $n=30$, $r=0.36$, $p<0.05$

### 7.3.4 Blood lactate concentration and Core Temperature

Following warm up completion, blood lactate increased ($p<0.005$) and was the same in all conditions. During recovery, blood lactate declined in all conditions ($p<0.005$) with no difference between conditions. There was no difference in blood lactate concentration following the 30s maximal sprint test between conditions (table 7.2). There was no overall effect of time ($p>0.1$) or condition ($p>0.4$) on core temperature.
Table 7.2: Core temperature \( (T_c) \), heart rate (HR) for control (CONT) warm up in shorts and heat recovery (SH) and heated warm up and recovery (HH) conditions, following warm up (WUP 15), after 30 minutes passive recovery (30 REC) and immediately following the maximal sprint test (POST WIN). \( n=10 \). All data presented as mean ± SD

<table>
<thead>
<tr>
<th></th>
<th>15 WUP</th>
<th>30 REC</th>
<th>POST WIN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CONT</td>
<td>SH</td>
<td>HH</td>
</tr>
<tr>
<td>( T_c (^\circ C) )</td>
<td>37.1 ± 0.4</td>
<td>37.0 ± 0.2</td>
<td>37.4 ± 0.2</td>
</tr>
<tr>
<td>( HR (b.p.m) )</td>
<td>121 ± 17</td>
<td>120 ± 20</td>
<td>129 ± 18</td>
</tr>
<tr>
<td>( BLa (\text{mmol.L}^{-1}) )</td>
<td>8.6 ± 2.3</td>
<td>9.0 ± 3.2</td>
<td>8.2 ± 3.3</td>
</tr>
</tbody>
</table>
Figure 7.4: Differences in A) relative power output and B) mean power output for control (CONT) warm up in shorts and heat recovery (SH) and combined heated warm up and recovery (HH) conditions. * SH vs. CONT p<0.005; † HH vs. CONT p<0.05. n=10. Data presented as mean ± SD

7.3.5 Thermal Sensation

There was a significant effect of condition on whole body thermal sensation (p<0.001, figure 7.5a). There was an increase in whole body thermal sensation towards feeling
“warm” for HH vs. CONT from WUP 10 onwards. There were also differences for SH vs. CONT from REC 10 onwards. In addition, there was a significant increase in thermal sensation of the legs as a result of condition (p<0.0005, figure 7.5b). Thermal sensation increased towards “warm” and “very warm” for HH vs. CONT from WUP 5 onwards. Furthermore, there was an increase in thermal sensation of the legs for SH vs. CONT from REC 5 (figure 7.4b).

Figure 7.5: Differences in A) Whole body thermal sensation and, B) Thermal sensation of the legs during control (CONT) shorts warm up and heat recovery (SH) and combined heated warm up and recovery (HH) conditions. † HH vs. CONT p<0.05, *SH vs. CONT p<0.05; # SH vs. HH p<0.05. n=10. All data presented as mean ± SD

7.3.6 Thermal Comfort
There was a significant effect of condition on whole body thermal comfort (p<0.01, figure 7.6a). Changes in whole body thermal comfort towards feeling less comfortable were evident for HH vs. CONT from WUP 15 to REC 25 (p<0.05). Additionally, there was a significant effect of condition on thermal comfort of the legs (p<0.0005, figure 7.6b). Changes in thermal comfort of the legs towards feeling less comfortable between HH and CONT existed at WUP 10 to REC 30 (p<0.05). There was a similar
response in SH at REC 5 to REC 30 (p<0.05). There were no differences in whole body thermal comfort between SH and HH at any time point. However, thermal comfort of the legs was more uncomfortable for HH vs. SH at WUP 10 (p<0.05) and WUP 15 (p<0.05).

Figure 7.6: Differences in A) Whole body thermal comfort and, B) Thermal comfort of the legs during control (CONT) shorts warm up and heat recovery (SH) and combined heated warm up and recovery (HH) conditions. *SH vs. CONT p<0.05; # SH vs. HH p<0.05.. n=10. All data presented as mean ± SD

7.4 Discussion

The main findings of the present study demonstrate that muscle temperature following completion of an intermittent, sprint based warm up activity, exponentially decline on exercise cessation when no form of passive external heating is implemented. Secondly, the data reconfirm our previous findings (Faulkner et al (in press), Chapter 6) that passive external heating used during the recovery period is capable of attenuating this loss in $T_m$. Use of the heated garment for both warm up and recovery resulted in a $T_m$ that is approximately 1.4°C higher following 30 minutes of recovery.
compared to CONT, although it does not provide a significant improvement in $T_m$ compared to SH following warm up completion. With this elevated $T_m$, as we have previously shown, relative, peak and mean power output are all improved. Furthermore, a reduction in the $\Delta T_m$ was correlated to improvements in peak power output. The resultant performance effect equated to a ~10% improvement in relative power output for SH and HH compared to CONT, and approximately 4% in mean power and total work done. No additional benefit of completing a warm up with additional passive heating over heating in the rest period alone for sprint performance was observed. Based on these data, the hypothesis that the use of passive heating during a warm up will lead to additional gains in $T_m$ over and above that of a warm up completed without additional passive heating is rejected as no additional gain in muscle temperature was evident for HH compared to SH. The hypothesis that the post exercise decline in $T_m$ will be reduced with the addition of passive heating is accepted. Finally, it was hypothesized that $T_m$ maintenance will convey an additional performance benefit during a maximal sprint test was shown to be the case, and this final part of the original hypothesis was accepted accordingly.

### 7.4.1 Muscle Temperature
The insertion of the flexible temperature probe was aimed to be at a depth of 2cm. Muscle temperature at that depth was virtually the same as that measured using a solid needle probe at a depth of 2cm following an identical warm up procedure (38.2°C, Chapter 6). This suggests that the desired depth of 2cm for the indwelling probe following warm up was achieved.

It is well established that one of the primary functions of a warm up prior to power or sprint based activities is to increase muscle temperature (Asmussen and Boje 1945, Sargeant 1987, Bishop 2003b), with a 2-3°C increase in $T_m$ being required to facilitate improvements in performance, with a 2-2.4°C rise achieved in the present study. The present data demonstrate that during post warm up recovery, a difference in $T_m$ drop of just 0.5°C is capable of impairing sprint performance and that it is possible to reduce this drop by using an electrically heated trouser during warm up and recovery. In addition, the data show that if the $\Delta T_m$ is reduced, as is the case in both SH and more so the HH condition, that this is associated with an increase in peak power...
output. This result confirms the finding of previous research (Faulkner et al in press, Sargeant 1987, Asmussen and Boje 1945) changes in muscle temperature can have a large impact on the muscle’s ability to achieve optimal contractile conditions and generate the maximum amount of power. However, despite the effectiveness of the HH intervention in particular resulting in an improvement in sprint performance, there was still a large drop in muscle temperature. This is likely to be due to the effect of circulatory blood cooling as it reaches the lower leg, and in particular the foot, thus cooling the muscles of the thigh as it returns towards the heart. Despite this drop, $T_m$ in HH is still ~0.5°C higher than when no passive heating was used, and this difference leads to better performance. It is possible that the performance increase is due to a placebo effect, as it was not possible to blind participants to the experimental condition. This combined with the improvement in $T_m$ drop exaggerates the sprint performance benefit of passive heating during both warm up and recovery.

There is only limited evidence detailing the post exercise muscle temperature response in humans. That which does exist tends to show a transient decline in $T_m$ following exercise termination (Kenny et al. 2003, Kenny et al. 2002, Saltin et al. 1972, Saltin et al. 1970, Aikas et al. 1962, Allsop et al. 1991). In rats, $T_m$ has previously been shown to follow an exponential decline immediately following moderate exercise cessation, with resting temperatures reached within 60 minutes (Brooks et al. 1971). In the limited number of similar experiments on humans, $T_m$ has been shown to decline immediately post exercise, with a ~1-2°C drop occurring within 30-40 minutes post exercise (Kenny et al. 2003, Allsop et al. 1991), which is similar to the decline reported here. There are however some discrepancies in the exact nature of this decline. Some authors report that upon exercise termination, there is still a gradual increase in $T_m$ which can continue for up to 10 minutes before $T_m$ begins to drop (Kenny et al. 2002, Aikas et al. 1962), whereas others report an immediate decline in $T_m$ (Kenny et al. 2003, Saltin et al. 1970, Allsop et al. 1991). It is possible that the differences reported in post exercise $T_m$ decline are due to differences in the exercise protocols used between the various studies (leg extensions (Kenny et al. 2003, Kenny et al. 2002) versus continual cycling (Saltin et al. 1970, Aikas et al. 1962, Allsop et al. 1991)) or variation in environmental conditions. Saltin et al., suggest that cooler conditions will have a greater effect on reducing muscle tissue temperature post exercise as muscle and skin blood perfusion is reduced (Saltin
et al. 1968). They report that in higher ambient temperatures, the rate of $T_m$ decline following exercise appears to be slower than is evident in cooler conditions (Saltin et al. 1970). It is likely that the increase in the thermal gradient between the muscle and surrounding ambient air results in faster temperature loss evident in cooler conditions. This is consistent with the effect of the heated trousers on $T_m$ in both SH and HH conditions presented here. As the heating elements are capable of reaching $\sim 40^\circ C$, they counter any effect of the cool surrounding air and effectively reverse the thermal gradient in favour of air to body heat transit, resulting in elevated $T_m$ following 30 minutes of recovery. As metabolic heat production alone was able to raise $T_m$ to $38^\circ C$, for there to be an additional increase in HH, the heating capacity of the elements used would have to be much higher than the $40^\circ C$ they could achieve, which may explain why no additional benefit found for HH compared to SH or CONT on post warm up $T_m$. However, if passive external heating in excess of $40^\circ C$ was used, then we would be in danger of exceeding both the pain (Hardy et al. 1951, Hardy et al. 1952) and skin burn ($45 \pm 1.7^\circ C$) (Hardy 1956) thresholds.

7.4.2 Power Output
The elevation in $T_m$ when passive heating is used as part of an active warm up and recovery or in recovery alone following 30 minutes of rest, resulted in an overall mean improvement of 11.1%, 10.5% and 3.9% in peak, relative and mean power output respectively, confirming our previous findings on use of recovery heating alone (Chapter 6). From the existing body of literature and our previous findings, it is clear that there is a temperature dependence of skeletal muscle on its ability to produce power. The reported temperature coefficient ($Q_{10}$) values being in the region of 2-2.5, which is consistent with the existing literature (Gray et al. 2006, Ranatunga 1998, Lionikas et al. 2006) (Chapter 6), indicating a positive thermal dependence.

Although we cannot determine the exact depth of the temperature probe during recovery, based on previous data, it was estimated to be at a depth of approximately 2cm beyond the muscle fascia. We report that for a $T_m$ elevation of $\sim 0.5^\circ C$ following recovery with external passive heating compared to when no heating is used, that there is an improvement in relative peak power output of 10.8%. This is a greater improvement in power output than has previously been reported per $^\circ C$ rise in $T_m$. 

168
(Bergh and Ekblom 1979, Sargeant 1987). Nevertheless, we cannot conclude that this is all down to the alteration in $T_m$ at the onset of the maximal sprint test, as for obvious reasons, we were unable to completely blind participants to the experimental condition, although they were blind to our hypothesis. Therefore, there may be an additional benefit due to psychological changes brought about by improved perception of “readiness” and this may be why we see a larger per °C rise in power than has been reported previously.

Physiologically, the increase in power output following HH and SH is possibly due to an elevated rate of ATP turnover as a consequence of the higher muscle temperature (Gray et al. 2006, Gray et al. 2008). Direct measurement of ATP turnover using muscle biopsies have shown ATP turnover to be elevated with increased muscle temperature. Gray et al., have shown that when muscle temperature is artificially elevated using water immersion of the legs, there is an increase in anaerobic ATP turnover and lactate during 6s maximal sprint cycling (Gray et al. 2006). Furthermore, in agreement with the present results they report an increase in both mean and maximal power output during the sprint test. It is therefore likely that maintenance of $T_m$ during periods of rest or recovery increases the rate of anaerobic turnover during maximal sprint effort. However, for this to be the case, we would expect to see a concurrent increase in blood lactate concentration as shown previously (Chapter 6). Although we were unable to replicate this in the present study, there was a tendency for lactate concentration to be higher following the maximal sprint in both HH and SH.

7.4.3 Perceptual Measures
It is possible that the elevations in sensations of warmth and that of the legs in isolation we have reported during recovery elicit a perception of improved preparedness to execute the maximal sprint test. Anecdotal evidence from the present study supports this, as a number of participants in the present study reported feeling “better” before the start of the sprint test following recovery using passive heat. However, this speculation requires experimental corroboration before any firm conclusions can be drawn. Although there are differences in whole body thermal sensation and that of the legs following passive heating application, participants
reported only being mildly uncomfortable. There is evidence to suggest that impaired thermal comfort is associated with a reduction in performance (Schlader et al. 2011). However, in the present study this does not occur, and it is likely that the elevations in muscle temperature and thermal sensation have a beneficial effect on the physiological and psychological preparedness of the participant prior to the maximal sprint effort.

7.4.4 Practical Application
The present data demonstrate that using passive heating as part of a pre-race or mid event strategy to maintain muscle temperature is capable of improving sprint/power related performance measures. It may be of particular importance to realize that $T_m$ appears to decline immediately upon exercise cessation. Therefore even where delays between exercise bouts, or between warm up completion and competition are relatively short, using passive external heating to maintain $T_m$ may be of benefit to the subsequent performance. Adding this heating during the warm up did not provide any additional benefit.

7.4.5 Conclusion
This experiment has been successful in replicating the results reported in chapter 6 regarding the attenuation in muscle temperature decline and sprint cycling performance. The present data show that heating additional agonist muscles used in cycling provides a further improvement in performance compared to when heating is limited to the thighs alone. In addition, the data show that when no heating is applied post warm up, muscle temperature declines exponentially, with the rate of decline attenuated in both SH and HH, showing that passive heating during warm up and periods of enforced rest is capable of improving sprint cycling performance. This adds further weight to the argument that power and sprint athletes should use some form of passive heating in between competitive performance exercise bouts when $T_m$ will decline due to limited activity.
Chapter 8
General Discussion and Application of Research

8 Chapter Summary

This chapter will review the main findings of the work presented in this thesis. The applications of these findings will be highlighted along with potential areas for future research.

8.1 General Discussion

It was the aim of this thesis to determine the way in which body temperature manipulation, is capable of improving exercise performance in both power and endurance based events, using novel competition applicable methodologies. The anatomical regions that are more susceptible to heat loss via exogenous cooling were successfully identified (Chapter 2) and that the forearms and hands are regions which, when cooled, may alleviate some of the perceived thermal strain and potentially improve exercise performance in the heat (Chapter 3). These data allowed for the design of a new athletic “cooling garment” which targeted the specific areas identified as having high potential for heat exchange. The subsequent two studies reported in chapters 4 and 5 suggest that the use of the new garment can improve thermal perceptions during exercise and that it may lead to improvements in endurance performance. However, these two studies demonstrate that there may be threshold ambient temperature above which pre-cooling may have more of an ergogenic effect, as in the second study (Chapter 5), the ambient conditions posed far greater levels of heat stress. Finally, the question concerning whether local cooling of the skin is a driving factor behind pacing strategy and performance changes following pre-cooling requires future clarification. Currently, the debate surrounding skin versus core temperature as a main driver of pacing strategy alteration remains unresolved. As a result, it is not possible to establish from this thesis or elsewhere whether local changes in $T_{sk}$ – i.e. where cooling is applied, such as the hands, has a greater effect
on performance, than the gross change in $\bar{T}_{sk}$ reported here and throughout the current body of literature. Furthermore, it was not possible to establish the exact mechanism of pacing strategy control, whether it be a central or peripheral mechanism or a combination of both. It was not the aim of this thesis to establish this, but the debate surrounding a central controller verses a peripheral mechanism is one which is currently under wider investigation within the scientific community.

In the final two experimental chapters of this thesis (Chapters 6 and 7), the effect of temperature manipulation on power based performance was considered, such as is evident in sprinting. It was successfully demonstrated that muscle temperature rapidly declines in an exponential manner following the cessation of exercise. More importantly, we have shown for the first time that the use of combined passive heating and clothing insulation surrounding the legs in a 30 minute rest in between a warm up and the actual performance is highly effective in reducing the decline in muscle temperature, but also leads to ~10% improvement in some sprint cycling performance parameters.

The following main findings and conclusions were drawn from body temperature manipulation and its effect on exercise performance:

- Different anatomical regions demonstrate different levels of heat loss in response to exogenous cooling, with the regions with the highest rates being the forearms, hands, feet and upper back.
- The highest rates of heat loss are associated with regions that are low in adipose tissue and skeletal muscle and are highly vascularised.
- Cooling of the forearms between bouts of exercise in the heat provides a practical way of applying mid-event or half time cooling, and may be an effective way of improving exercise performance.
- The use of a cooling garment combining cooling of the torso, back, forearms and hands reduces mean skin and mean body temperatures.
- A cooling garment appears to need to deliver a cooling in excess of 220 W.m$^{-2}$ if it is to provide cooling which may benefit performance.
• There may be a critical ambient temperature above which pre-cooling becomes more important in improving exercise tolerance.

• A reduction in skin temperature with no change in core temperature prior to exercise in the heat appears to improve exercise performance.

• It appears that a reduction in skin temperature may play a more pivotal role in performance regulation during exercise in the heat than has been previously reported.

• A prolonged delay between warm up completion and performance has a negative effect on subsequent sprint performance.

• This is largely due to a decline in muscle temperature as a result of limited levels of activity.

• During enforced rest, muscle temperature declines exponentially when no passive heating is used, with passive heating attenuating the exponential decline.

• The drop in muscle temperature can be attenuated with the use of external passive heating surrounding the working musculature, which leads to an improvement in sprint performance compared to when no passive heating is used.

• Elevations in muscle temperature are closely correlated with improvements in both peak and mean power output.

These findings show that the majority of hypotheses predicting reductions in body temperature in response to pre-cooling reported in chapters 2, 3, and 4 can be accepted. However, only in chapter 4 was it possible to accept the hypothesis that pre-cooling would result in improved performance. The hypotheses that reducing the decline in muscle temperature following a 30-minute delay between warm up completion and sprint performance would result in improved power output, is also accepted.

8.2 Application of Research
The data from the research presented here have been directly applied to the design of novel sports clothing. Knowledge of both differences in regional heat flux and changes in muscle temperature are important in designing garments which are effective at improving both endurance and power based exercise performance, particularly at the elite end of the performance spectrum.

Data concerning the effective maintenance of muscle temperature between warm up and sprint performance has been used to design and develop the adipower “hot pants” which were successfully implemented by members of Team GB in a number of track cycling events in the London 2012 Olympic Games, where a number of gold medals and World Records were achieved.
Chapter 9

Recommendations for Future Work

The research conducted in this thesis was of a highly applied and exploratory nature. A number of tests were employed to test novel garment designs based on sound physiological principles, and their subsequent effect on performance in highly trained male endurance and power athletes. The results from the present body of data, give rise to a number of further questions, the most pertinent of which are detailed below.

- The role of pre-cooling prior to endurance competition has been demonstrated to be an effective way at improving performance in hot ambient conditions. However, what currently remains unclear is a clearly defined threshold above which pre-cooling with differing methodologies becomes effective in improving endurance performance. From the present research, it would appear that a threshold between 16°C and 35°C is in existence as it is demonstrated here that only in the higher ambient temperature was pre-cooling effective.

- Further research regarding the effects of local cooling versus whole body changes in mean skin temperature and its effect on performance. Current work fails to identify what is the driving force behind performance changes in relation to $T_{sk}$, whether it is a gross change in mean skin temperature, or more acute, local skin temperature changes at the site of cooling. More recent developments using infrared imaging would help to establish a greater understanding of the effect and importance of local and whole body changes in skin temperature.

- A more mechanistic study considering the effects of muscle temperature maintenance on improving performance would be of interest. The elevation in muscle temperature is accepted as central to improving contractile force production and power output, however, it would be of interest to study the
effects of elevated muscle temperature on ATP breakdown and resynthesis as this will be one of the major causes of fatigue during short duration high intensity exercise. The data suggest that the rate of ATP turnover would be elevated with higher muscle temperature, resulting in increased power output.
Chapter 10

References


HOUSE, J., et al. Reducing heat strain using phase-change cooling vests with different melting temperatures


ROWSELL, G.J., COUTTS, A.J., REABURN, P. and HILL-HAAS, S., 2009. Effects of Cold-Water Immersion on Physical Performance between Successive Matches in...


STAPLETON, J.M., C.Q. LAN, S.G. HARDCASTLE and G.P. KENNY. The effect of wearing a cooling vest to alleviate thermal strain during moderate intensity work


Appendices

Appendix A  Health Screen Questionnaire
             Informed Consent

Appendix B  Rating of Perceived Exertion (RPE) Scale
             Thermal Sensation Scale
             Thermal Comfort Scale
Athlete pre-cooling and its ability to improve athletic performance in warm conditions.

INFORMED CONSENT FORM
(to be completed after Participant Information Sheet has been read)

The purpose and details of this study have been explained to me. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethical Advisory Committee.

I have read and understood the information sheet and this consent form.

I have had an opportunity to ask questions about my participation.

I understand that I am under no obligation to take part in the study.

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.

I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.

I agree to participate in this study.

Your name

Your signature

Your contact number

Signature of investigator

Date
Health Screen Questionnaire for Study Volunteers

As a volunteer participating in a research study, it is important that you are currently in good health and have had no significant medical problems in the past. This is (i) to ensure your own continuing well-being and (ii) to avoid the possibility of individual health issues confounding study outcomes.

If you have a blood-borne virus, or think that you may have one, please do not take part in this research.

**DO NOT UNDERGO NUCLEAR MAGNETIC RESONANCE (NMR, MRI) SCANNING WITHIN 72 HOURS OF TAKING THE TEMPERATURE PILL.**

Please complete this brief questionnaire to confirm your fitness to participate:

1. **At present**, do you have any health problem for which you are:
   - (a) on medication, prescribed or otherwise .............. Yes ☐ No ☐
   - (b) attending your general practitioner.................. Yes ☐ No ☐
   - (c) on a hospital waiting list .......................... Yes ☐ No ☐
   - (d) Obstructive disease of GI tract ...................... Yes ☐ No ☐
   - (e) Any inflammatory bowel disease .................. Yes ☐ No ☐
   - (f) Impaired gag reflex .................................. Yes ☐ No ☐
   - (g) Likely to have MRI/NMR scanning ................ Yes ☐ No ☐
   - (h) Hypomobility of GI tract .............................. Yes ☐ No ☐

2. **In the past two years**, have you had any illness which required you to:
   - (a) consult your GP ....................................... Yes ☐ No ☐
   - (b) attend a hospital outpatient department............ Yes ☐ No ☐
   - (c) be admitted to hospital .............................. Yes ☐ No ☐

3. **Have you ever** had any of the following:
   - (a) Convulsions/epilepsy ................................. Yes ☐ No ☐
   - (b) Asthma ................................................. Yes ☐ No ☐
   - (c) Eczema ............................................... Yes ☐ No ☐
   - (d) Diabetes ............................................... Yes ☐ No ☐
   - (e) A blood disorder ................................. Yes ☐ No ☐
4. Has any, otherwise healthy, member of your family under the age of 35 died suddenly during or soon after exercise? ...

If YES to any question, please describe briefly if you wish (eg to confirm problem was/is short-lived, insignificant or well controlled.)

.................................................................................................................................
.................................................................................................................................

5. Allergy Information

(a) are you allergic to any food products? Yes No

(b) are you allergic to any medicines? Yes No

(c) are you allergic to plasters? Yes No

If YES to any of the above, please provide additional information on the allergy

.................................................................................................................................
.................................................................................................................................

6. Please provide contact details of a suitable person for us to contact in the event of any incident or emergency.

Name:

.................................................................................................................................

Telephone Number:

.................................................................................................................................

Work □ Home □ Mobile □
7. Are you currently involved in any other research studies at the University or elsewhere?

Yes ☐  No ☐

If yes, please provide details of the study

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Rating of Perceived Exertion (RPE) Scale

<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>7</td>
<td>Extremely Light</td>
</tr>
<tr>
<td>8</td>
<td>Very Light</td>
</tr>
<tr>
<td>9</td>
<td>Light</td>
</tr>
<tr>
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<td>Somewhat Hard</td>
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<tr>
<td>12</td>
<td>Hard (Heavy)</td>
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<tr>
<td>15</td>
<td>Very Hard</td>
</tr>
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<td>19</td>
<td>Extremely Hard</td>
</tr>
<tr>
<td>20</td>
<td>Maximal Exertion</td>
</tr>
</tbody>
</table>
Thermal Sensation Scale

10  Extremely Hot
  9  Hot
  8  Very Warm
  7  Warm
  6  Slightly Warm
  5  Neutral
  4  Slightly Cool
  3  Cool
  2  Very Cool
  1  Cold
  0  Extremely Cold
Thermal Comfort Scale

1 Comfortable

2 Slightly Uncomfortable

3 Uncomfortable

4 Very Uncomfortable