Thermoregulatory responses of athletes with a spinal cord injury during rest and exercise

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by

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Abstract

Following on from Rio de Janeiro 2016, the Tokyo 2020 Paralympic Games will present a unique challenge for athletes, needing to prepare and adapt to the potential challenging environmental conditions of 20-27°C and ~73% relative humidity. It is well known that during exercise in hot and/or humid climates, able-bodied athletes experience an increase in thermal strain and a reduction in performance compared to cooler/drier conditions. Yet these conditions prove even more problematic for athletes, who as a consequence of their impairment have a dysfunctional thermoregulatory system, such as athletes with a spinal cord injury (SCI). To date, the thermoregulatory responses of athletes with an SCI have been an under-studied area of research. To gain a greater understanding of how heat balance is altered in individuals with an SCI and the thermoregulatory consequences as a result, studies need to first be conducted at rest, removing the additional metabolic heat production from exercise.

Although a large majority of athletes with an SCI compete indoors in wheelchair court sports (e.g. wheelchair basketball and rugby), exercising even in these climate-controlled environments has been shown to place these athletes under considerable thermal strain. In light of this, it is remarkable that existing research on the thermoregulatory responses of athletes with an SCI during exercise is scarce, especially studies encompassing "real-world" sporting environments. Athletes with high level lesions (tetraplegia, TP) are a particularly under-studied population group shown to have a greater thermoregulatory impairment than individuals with low level lesions (paraplegia, PA) during continuous exercise. Thus the aim of this thesis was to investigate the thermoregulatory responses of athletes with an SCI at rest and during "real-world" sporting scenarios, with specific focus on athletes with TP.

Study 1 aimed to determine how evaporative heat loss is altered, as a result of an SCI, compared to the able-bodied (AB), and the effect lesion level has on this response. The results provide evidence that in individuals with TP, even at rest, evaporative heat loss is not large enough to balance the heat load, when evaporation is the primary source of heat dissipation. Even though in individuals with PA T_{gi} increased by a smaller magnitude and they possessed a greater sweating capacity than individuals with TP, at ambient temperatures above T_{sk} latent heat loss is insufficient to attain heat balance, compared to the AB.

To investigate the thermoregulatory responses of athletes with an SCI during "real-world" sporting scenarios Study 2 examined athletes with TP compared to athletes with PA during

60 min of intermittent sprint wheelchair exercise on a wheelchair ergometer. The study was conducted in conditions representative of an indoor playing environment for wheelchair rugby and basketball (~21°C, 40% relative humidity). Results demonstrated that, despite similar external work, athletes with TP were under greater thermal strain than athletes with PA.

Study 3's novel approach investigated both physiological responses and activity profiles of wheelchair rugby players during competitive match play. Despite players with TP covering 17% less distance and pushing on average 10% slower, they were under a greater amount of thermal strain than players with non-spinal related physical impairments (NON-SCI). Furthermore, this study demonstrated that players with TP that had a larger body mass, larger lean mass, covered a greater relative distance and/or were a higher point player had a greater end T_{gi}. These data provide an insight for coaches and support staff regarding which players may need greater attention in regards to cooling strategies or breaks in play.

The effectiveness of cooling practices currently employed by athletes with TP has not been previously investigated. Study 4 determined the effectiveness of pre-cooling, using an ice vest alone and in combination with water sprays between quarters, at attenuating thermal strain in athletes with TP. Using the activity profile data from Study 3, an intermittent sprint protocol, conducted on a wheelchair ergometer, was used to represent a wheelchair rugby match. The combination of cooling methods lowered T_{gi} and T_{sk} to a greater extent than pre-cooling only, despite neither cooling condition having a positive or negative effect on performance. Unexpectedly, the pre-cooling only condition lowered T_{gi}, compared to no cooling, throughout the subsequent exercise protocol, even though the reduction in T_{sk} was not long lasting.

This thesis provides comprehensive evidence that athletes with TP experience heightened thermal strain during both rest and "real-world" sporting scenarios compared to the AB, athletes with PA, and within the sport of wheelchair rugby. Athletes with TP should employ practices, such as appropriate cooling methods or alter playing tactics to reduce thermal strain and the likelihood of attaining a heat related injury.

Key **words:** Thermoregulation, spinal cord injury, tetraplegia, paraplegia, wheelchair sport, exercise performance, cooling

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Abbreviations

AB	Able-bodied
ANOVA	Analysis of variance
C	Convection
CI	Confidence intervals
DXA	Dual-energy X-ray absorptiometry
E	Evaporation
ES	Effect size
GBWR	BT Great Britain Wheelchair Rugby squad
HR	Heart rate (b·min^{-1})
ISP	Intermittent sprint protocol
ITF	International Tennis Foundation
IWRF	International Wheelchair Rugby Federation
K	Conduction
M	Metabolic energy expenditure (W·m^{-2})
NON-SCI	Non-spinal related physical impairment
NC	No cooling condition
P	Pre-cooling condition
PW	Pre-cooling and water sprays condition
PA	Paraplegia
R	Radiation
Resp	Respiration
RH	Relative humidity
RER	Respiratory exchange ratio
RPE	Rating of perceived exertion
S	Heat storage
SCI	Spinal cord injury
SD	Standard deviation
T_{au}	Aural temperature (°C)
T_{core}	Core temperature (°C)
T_{es}	Oesophageal temperature (°C)
T_{gi}	Gastrointestinal temperature (°C)

T_{re}	Rectal temperature (°C)
T_{sk}	Mean skin temperature (°C)
TP	Tetraplegia
$\dot{V}O_2$	Oxygen uptake (L·min^{-1})
$\dot{V}O_{2peak}$	Peak oxygen uptake (L·min^{-1})
W	External work done (W)
WBGT	Wet bulb globe temperature
WERG	Wheelchair ergometer
WCR	Wheelchair rugby

Terms are written in full when first mentioned and subsequently abbreviated for the remainder of the thesis.

Chapter 1

Introduction

The London 2012 Paralympic Games were the largest and best attended Paralympic Games to date, earning the legacy of "the most accessible Games ever", with both promotion and reporting of the event being on an unprecedented scale (Girginov 2014). Great Britain finished third in the medal table, behind China and Russia, taking home a total of 120 medals (International Paralympic Committee, 2013). The medal success continued at the Rio de Janeiro 2016 Paralympic Games, improving on their medal haul at London, finishing second in the medal table with an incredible 147 medals (International Paralympic Committee, 2016). The sporting success of the Great Britain squad could be attributed to the enhanced training, professionalism and commitment of the athletes, in addition to the improved provision of sports science and medicine support. Following on from Rio de Janeiro 2016, the Tokyo 2020 Paralympic Games will again present a unique challenge for the athlete, with the need to prepare and adapt to the potential environmental conditions of 20-27°C and ~73% relative humidity (Japan Meteorological Agency, 2016). Preparing for these conditions is particularly challenging for athletes, who as a consequence of their impairment, have a dysfunctional thermoregulatory system, such as in athletes with a spinal cord injury (SCI). For these individuals their thermoregulatory impairment is proportional to their lesion level, due to a loss of sweating capacity and vasomotor control below the level of their lesion.

To date, the thermoregulatory responses of athletes with an SCI have been an under-studied area of research. To gain a greater understanding of how heat balance is altered in individuals with an SCI and the thermoregulatory consequences as a result, studies need to first be conducted at rest, removing the additional metabolic heat production from exercise. In particular, it is imperative to determine the extent of the changes in evaporative heat loss as a result of an SCI and effect lesion level has on this response.

Although a large majority of athletes with an SCI compete indoors in wheelchair court sports (e.g. basketball and rugby), exercising even in these climate controlled environments has been shown to place these athletes under considerable thermal strain (Goosey-Tolfrey et al.

2014). In light of this, it is surprising that existing research on the thermoregulatory responses of athletes with an SCI during exercise is limited, especially applied studies encompassing "real-world" sporting environments. A particularly under-studied population group is that of athletes with high level lesions (tetraplegia, TP), known to have a greater thermoregulatory impairment compared to individuals with lower level lesions (paraplegia, PA) and the able-bodied (AB) during continuous exercise (Price et al. 2003).

1.1 Aims and objectives of the thesis

The principal aim of this thesis was to examine the thermoregulatory responses of athletes with an SCI at rest and during "real-world" sporting scenarios. In order to achieve this, the following objectives were formulated:

1. To examine the differences in evaporative heat loss at rest between individuals with paraplegia and tetraplegia in comparison to able-bodied individuals.
2. To determine the thermoregulatory responses of athletes with tetraplegia compared to athletes with paraplegia during intermittent wheelchair exercise.
3. To determine the thermoregulatory responses of wheelchair rugby players with tetraplegia compared to players with non-spinal related physical impairments during competitive on-court match play.
4. To establish the effectiveness of current cooling practices employed by athletes with tetraplegia.

1.2 Organisation of the thesis and experimental aims

A comprehensive literature review (*Chapter 2*) was conducted focusing on thermoregulatory control in humans and how physiological responses are adapted in individuals with an SCI. The sporting environments in which athletes with an SCI compete are introduced and a critique of the previous research focusing on the implementation of cooling strategies in this population group is provided. Methods employed in more than one of the experimental chapters are described in the general methods section (*Chapter 3)*. Following the general methods, the thesis is structured into a total of four experimental chapters (*Chapters 4-7*), exploring the fundamentals of thermal physiology in individuals with an SCI and exercise studies encompassing "real-world" sporting environments, with the research questions of each addressed below.

The avenues of heat exchange, in particular evaporative heat loss will be altered as a result of an SCI, but the extent of this compared to the AB and its subsequent effect on heat balance is

currently unknown. Individuals with an SCI are thought to produce less heat than AB individuals, due to the muscular atrophy of the lower limbs and a reduction in the available sympathetic nervous system. Thus, heat dissipation may be impaired in individuals with an SCI but heat production may also be lower than the AB at rest. Study 1 (***Chapter 4***) determined how evaporative heat loss and heat balance are altered as a result of an SCI, compared to AB individuals, and the effect lesion level has on this response. Testing was conducted in hot conditions (37°C) to minimise heat loss via the dry heat exchange avenues, using stepwise increases in humidity to progressively reduce evaporative heat loss and at rest to remove the additional metabolic heat production from exercise.

The second experimental study (***Chapter 5***) investigated the thermoregulatory responses of athletes with PA and TP during intermittent sprint wheelchair exercise and post exercise recovery in an ambient environment representative of an indoor playing environment for wheelchair rugby (WCR) and basketball. Specifically, this chapter aimed to match the ambient conditions and intermittent nature of wheelchair court sports, to address whether thermoregulatory responses differ depending on lesion level.

To enhance ecological validity, Study 3 (***Chapter 6)***, extended these aforementioned experimental conditions to a sports specific field based match. The study addressed whether, within the sport of WCR (predominantly played by individuals with TP), players with TP were under greater thermal strain compared to players with a non-spinal related physical impairment. Combined with the use of a novel indoor tracking system, to establish activity profiles, whether the player's physical impairment, classification, and/or physical attributes were related to the thermal strain experienced during competitive WCR were established.

After determining the extent of the thermoregulatory impairment for athletes with TP in a laboratory and field environment, Study 4 (***Chapter 7***) investigated the effectiveness of current cooling strategies employed by these individuals during simulated WCR match play in a laboratory environment. The study involved a simulated match on a wheelchair ergometer (WERG) based on the indoor tracking system data from Study 3.

A general discussion of the main findings, practical applications and future directions for research are presented in ***Chapter 8.*** A summary of the experimental chapters is shown in Figure 1.1.

Study 1: Differences in evaporative heat loss between the able-bodied and individuals with a spinal cord injury of different lesion level

Research question: 1) How are evaporative heat loss and heat balance altered at rest as a result of a spinal cord injury compared to the able-bodied, and what effect does lesion level have on this response?

Exercise studies encompassing "real-world" sporting scenarios

Study 2: Thermoregulation during intermittent exercise in athletes with a spinal cord injury

Research question: 1) Do the thermoregulatory responses of athletes with paraplegia and athletes with tetraplegia differ during intermittent sprint wheelchair exercise and recovery?

Extending the findings from the laboratory to competitive sports specific on-court match play

Study 3: Thermoregulatory responses during competitive wheelchair rugby match play

Research question: 1) Do thermoregulatory responses and activity profiles differ between wheelchair rugby players with tetraplegia and players with a non-spinal related physical impairment during competitive on-court match play?

2) In players with tetraplegia does their classification, activity profile and/or physical attributes relate to the amount of thermal strain experienced during a match?

Application of current cooling practices employed by athletes with TP

Study 4: Effects of cooling before and during simulated match play on thermoregulatory responses of athletes with tetraplegia

Research question: 1) During simulated wheelchair rugby match play, in athletes with tetraplegia does the combination of pre-cooling using an ice vest and water sprays during breaks in play attenuate thermal strain and improve performance compared to no cooling or pre-cooling only?

Figure 1.1 Schematic representation of experimental chapters.

Chapter 2

Literature review

2.1 Heat Balance

Humans attempt to maintain a deep body core temperature (T_{core}) around 37°C, with severe consequences for more than a few degrees deviation. To maintain thermal balance, internal heat production needs to equate to the rate of heat dissipation to the environment. Core temperature rises if heat generated is greater than heat dissipation, whilst T_{core} falls if heat dissipation is greater. The conceptual heat balance equation, which incorporates the four main pathways of heat exchange (convection, radiation, conduction and evaporation), helps explain this dynamic equilibrium (Parsons 2003). A schematic diagram of heat production within active muscles, its transfer from the core to the skin and subsequent exchange with the environment using the four pathways is depicted in Figure 2.1.

$$\textbf{M} - \textbf{W (W·m}^2\textbf{)} = \textbf{C} + \textbf{R} + \textbf{K} + \textbf{E} + \textbf{Resp} + \textbf{S}$$

Where:

M = metabolic rate
W = external work done
C = convection
R = radiation
K = conduction
E = evaporation
Resp = respiration
S = heat storage

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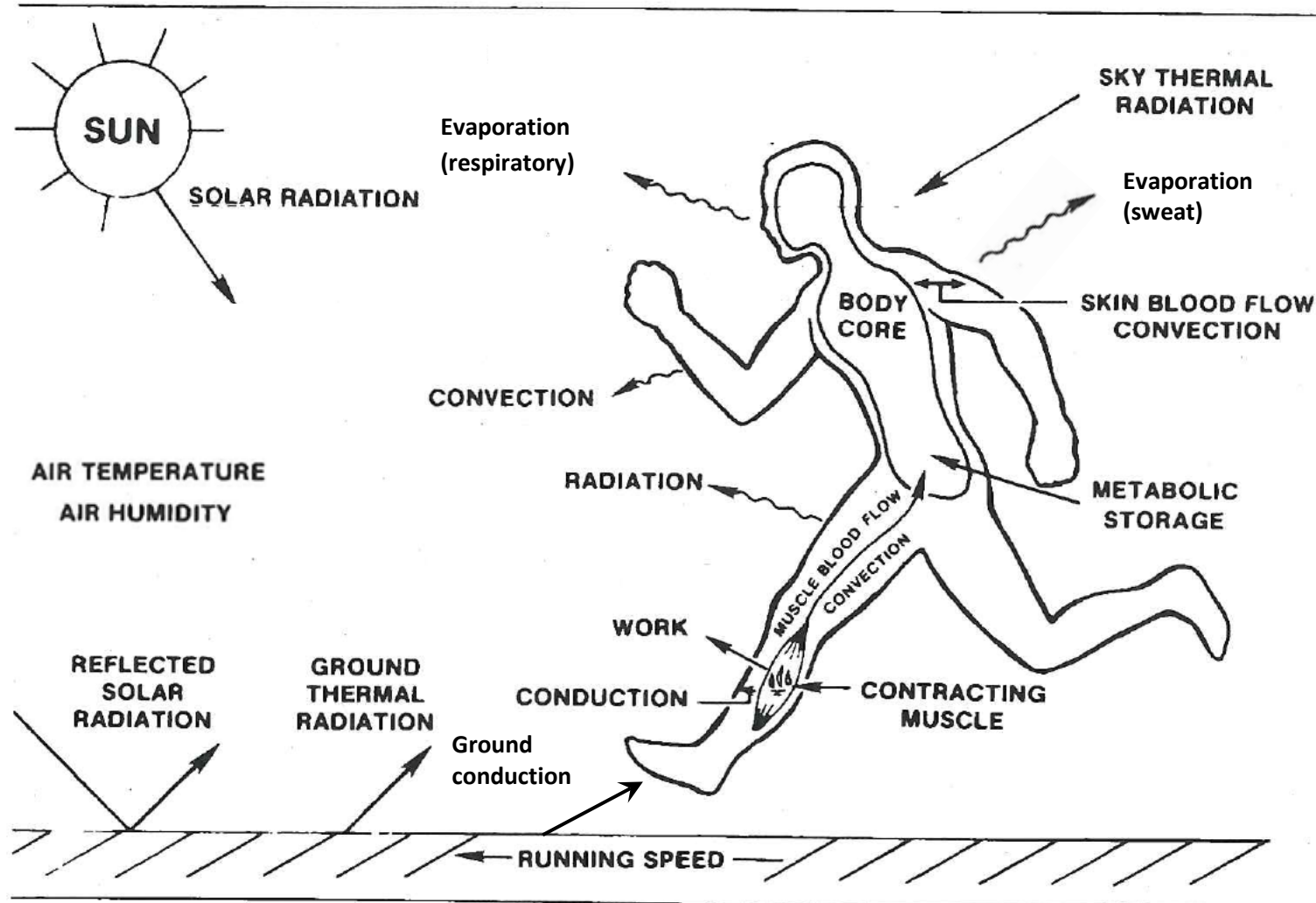
Figure 2.1 Schematic diagram showing heat production within active muscle, its transfer from the core to the skin and subsequent exchange with the environment. Adapted from Gisolfi et al. (1984).

The conversion of metabolic energy into mechanical and thermal energy produces heat in all body cells. This is an inefficient process and approximately 80-100% of energy liberated during muscle contractions is lost as heat and dispersed around the body (Edwards et al. 1975, Gonzalez-Alonso et al. 2000, Bangsbo et al. 2001, Krustrup et al. 2003, Krustrup et al. 2001). Thermal balance results from efficient heat exchange with the environment involving the pathways mentioned below.

M-W represents the heat generation of the body, whilst convection, radiation, conduction and evaporation, denote the exchange of heat between the body's skin surface and the environment. Combining the rates of heat production and loss the equation above provides a rate of heat storage; a rate of zero (e.g. a constant amount of heat stored in the body) signifying the body is in heat balance. For a net gain in heat, heat storage will be positive and body temperature will rise, whilst for a net loss in heat, heat storage will be negative with a fall in body temperature. Heat exchange is also influenced by environmental variables such as, air temperature, radiant temperature, air movement and humidity in addition to metabolic rate and clothing (Parsons 2003).

2.1.1   Dry heat exchange

Conduction, convection and radiation are referred to as dry heat exchange avenues and are dependent on the temperature gradient between the body and the environment. Conduction is the transfer of heat with solids in direct contact with the body or in solid-fluid interfaces, primarily driven by a thermal gradient between the two. During exercise, the majority of heat is generated by exercising muscle, some of which will be lost to the environment through the tissue by conductive heat loss (Doubt 1991). Heat conductance through tissues is a slow process and depends on the temperature gradient between the skin and muscle, and the thermal conductivity and specific heat capacity of the muscle (Gonzalez-Alonso 2012). Heat can also be gained from external sources at the skin and transferred to the body core via conduction.

Convective heat loss refers to fluid or air movement across a surface resulting in heat exchange. The speed of movement of the fluid against the body surface, the temperature gradient and the surface area all affect convective heat exchange. There are two forms of convection, natural (free) and forced. A boundary layer of warm air forms around a body when heat from the body is transferred to air or other molecules in contact with the skin. The

movement of the molecules increases, pushing them further apart, so they become less dense and more buoyant. The molecules rise away from the heat source as cooler air fills the vacant space. This is referred to as natural convection. When the body moves or the fluid medium in which the body is placed actively moves, the boundary layer is destroyed, increasing convection through forced convection. Heat transferred convectively to the body core from contracting muscles is influenced by tissue blood flow and/or arteriovenous blood temperature difference. Therefore, conditions, such as exercise and/or environmental stress, which alter either blood flow and/or arteriovenous blood temperature difference will likely determine changes in convective heat exchange (Gonzalez-Alonso 2012). Local convective air currents created by body movements, such as the arm and leg action during running, may also result in increased convective cooling.

Radiation is the transfer of heat in the form of electro-magnetic waves between the environment and the body. It is dependent on clothing, posture, surface area exposed and environmental conditions, such as cloud cover and time of day (Cheung 2010). Thermal radiation is emitted by all bodies above a temperature of absolute zero (Parsons 2003) and the radiation component in the heat balance equation is the net result of gains and losses by the body.

2.1.2 Wet heat exchange

Wet heat loss occurs from the evaporation of water and refers to the conversion of a liquid to a vapour, primarily dependent on the water vapour pressure gradient between the environment and the body surface. When secreted sweat is vaporised at the skin, maximal evaporative heat dissipation from the body occurs, whereas no evaporative cooling is provided by sweat dripping off the body or towelling off. For instance, to evaporate 1g of sweat 2,427 J of energy is required (Wenger 1972). Due to its effect on water vapour pressure, the relative humidity of the environment largely determines the capacity for evaporative heat exchange. For instance, in the tropics the high ambient temperature and humidity, i.e. high water vapour pressure, greatly reduces both dry and wet heat dissipation, increasing the risk of hyperthermia (Cheung 2010). When ambient air temperature approaches the mean skin temperature (T_{sk}), the skin-to-air temperature gradient is reduced, minimising heat loss by dry heat exchange. Evaporation thus becomes the principle pathway for heat dissipation. Whilst a high relative humidity reduces the water vapour pressure between the skin surface and the environment, leading to a reduction in evaporative heat loss.

Therefore, sweating is crucial for maintaining a stable T_{core} during bouts of increased metabolic heat production, providing protection against excessive heat strain. In addition to ambient conditions, exercise intensity and clothing also influence the production and evaporation of sweat. For instance, athletes performing high intensity exercise in the heat often sweat 1.0-2.0 $L \cdot hr^{-1}$ (Sawka et al. 2000).

If parts of the thermoregulatory system are absent or dysfunctional, such as the limited or absent sweating response of the SCI population, thermal balance is potentially difficult to attain. Resultant increases in T_{core} and skin temperature, particularly during thermal stress, could therefore affect the health and, in sports, athletic performance of the individual.

2.2 Thermoregulatory control

To achieve thermal balance, mechanisms which interact and respond to the ever-changing environment to ensure comfort and survival broadly fit into two categories; behavioural and physiological. Both of which will be explained briefly below.

2.2.1 Behavioural thermoregulation

A powerful form of thermoregulation is behavioural driven by the conscious perception of temperature and comfort. Individuals will actively change their behaviour to feel more thermally comfortable initiated by their perceptions of the surrounding environment (Parsons 2003). Examples include donning and doffing clothing, moving and changing posture etc. By simply putting on more clothes or moving nearer to a heat source significant effects on thermoregulation can be attained.

2.2.2 Physiological thermoregulation

Internal temperature and cell temperatures across the body are maintained at ~37°C to avoid permanent damage. Regulating processes operate within the cells and the process the body uses to regulate all cell temperatures produces the human thermoregulation system. The human thermoregulatory system combines central and peripheral sensors, efferent and afferent pathways and central integrating and controlling centres. Yet, there is disagreement over the regulated variable in thermoregulation. Models of human thermoregulation dispute whether body temperature (Bligh 1978) or body heat content is the controlled variable (Houdas et al. 1972) or the rate of heat outflow is altered to balance metabolic heat production (Webb et al. 1978). However, all models state that the body loses heat by

vasodilation and sweating and preserves heat by vasoconstriction and shivering. It is also agreed that the hypothalamus is the control centre for thermoregulation processes.

Centrally the anterior hypothalamus controls heat loss, whilst the posterior hypothalamus controls vasoconstriction and shivering (Parsons 2003). Cutaneous and central (such as the spinal cord, blood vessels, medulla oblongata, abdominal cavity) (Hensel 1981) thermoreceptors provide information on the body's thermal status. Thermoreceptors at the skin provide thermal feedback signals and are extremely sensitive to temperature, either responding to cold or warm stimuli. The unequal number and distribution of these receptors (believed to be four times more cold than warm sensors) helps explain the variation in autonomic response at different body locations (Hensel 1981). For instance, cooling the face is two to five times more powerful at suppressing sweating and thermal discomfort than an equivalent skin surface area (Cotter et al. 2005). Thermal information from both cutaneous and central thermoreceptors is transmitted by afferent nerves to the anterior hypothalamus to initiate appropriate effector responses, such as vasomotor and sudomotor activity to regulate T_{core} (Hensel 1981).

During the first few minutes of exercise in a thermoneutral environment, heat production is greater than heat loss, leading to a storing of heat and an increase in T_{core}. As T_{core} rises beyond the threshold for vasodilation and sweating, heat transfer to the skin surface and elimination of this heat to the environment increases to match metabolic heat production. The increase in T_{core} then markedly attenuates and approaches a plateau, indicating a state of heat balance. The attainment of such a thermal steady state, for a given exercise intensity is only possible within a certain range of environmental conditions, known as the 'prescriptive zone' (WHO 1969). The greatest increases in T_{core} arises early during exercise whereas larger increases in the effector responses, such as skin blood flow and sweating, occur later accompanied by small changes in T_{core} (Johnson et al. 1975). The magnitude and pattern of skin blood flow during exercise is modified by factors such as age, training and heat acclimation.

During dynamic exercise a principal drive for redistribution of blood flow away from metabolically active tissues to active muscle occurs. Yet, contracting muscle also produces heat and since skin blood flow provides the thermoregulatory dissipation of heat, there is competition between these two blood flow pathways. The competitive control is dependent upon the mode, duration and intensity of the exercise (Kenney et al. 1992).

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In warm conditions and when the skin is warmer than the ambient environment, vasodilation of the skin blood vessels occurs, redirecting blood flow from the core to the periphery for heat loss to occur via convection, conduction and radiation. Vasoconstrictor tone of the blood vessels close to the skin surface is withdrawn, leading to an increase in skin blood flow and a loss of heat through the skin. This cools the blood returning to the core and attempts to lower T_{core}. An increase in T_{core} and T_{sk} also stimulates sweat glands to increase/initiate sweat production, elevating evaporative heat loss and providing the final pathway for the elimination of the metabolic heat produced. In the extremities, arterio-venous anastomoses deep to the skin capillaries control large variations in blood flow, opening and closing to control heat loss. When the arterio-venous anastomoses are open for maximum flow, the preferential pathway for the blood to return to the core is through superficial veins, raising skin temperature and increasing heat loss (Livingstone et al. 1989).

2.3 Prescriptive Zone

To maintain body T_{core} in equilibrium, the amount of heat gained by the body needs to equate to the amount of heat lost from it. In AB, body T_{core} is able to equilibrate at levels proportional to metabolic rate and independent of ambient conditions over a wide range of environments, known as the "prescriptive zone" (Lind 1963). At the upper limit of this zone, heat gain is exactly matched to heat loss and the skin is fully wet. Above this zone, an environment will be reached that signifies a critical upper limit to the ability to perform continuous work at a given intensity, resulting in a continuous rise in T_{core} (Figure 2.2, Lind 1963). Below this critical environment prolonged work can be accomplished.

Previous literature has aimed to determine the critical conditions that define the upper limit of the prescriptive zone for given metabolic heat productions (Lind 1963, Lind 1973), particular clothing ensembles (Kenney et al. 1993, Bernard et al. 2008, Bernard et al. 2005, O'Connor et al. 1999) and subject variables, such as gender (Kamon et al. 1978, Kamon et al. 1976) and acclimation status (Kenney et al. 2002). These critical limits have predominantly been used to determine occupational work times and are often expressed as wet bulb globe temperatures (WBGT), which is used to model and quantify the perceived heat stress imposed through all four heat exchange pathways. Similarly in sport, WBGT's have been defined for athletic competition to determine the risks of exercising in particular environments and when the environment is above a certain WBGT, either modifying the activity or cancelling the event

to reduce the risk of heat injury (American College of Sports Medicine et al. 2007, American College of Sports Medicine 1987).

Often studies have investigated prescriptive zones to predict work times in different environmental conditions and scenarios in the AB. Yet understanding how certain population groups respond to various environmental conditions at rest, compared to the general population, is imperative to be able to offer guidance to potential at-risk individuals. A population group which could particularly benefit from understanding in which environmental conditions they can attain heat balance is the SCI population. The physiological adaptations that occur as a result of an SCI will alter heat loss by dry and, in particular, wet heat exchange. Yet the extent this effect has on the thermoregulatory responses of individuals with an SCI at rest, and the effect lesion level has on this response, is currently unknown.
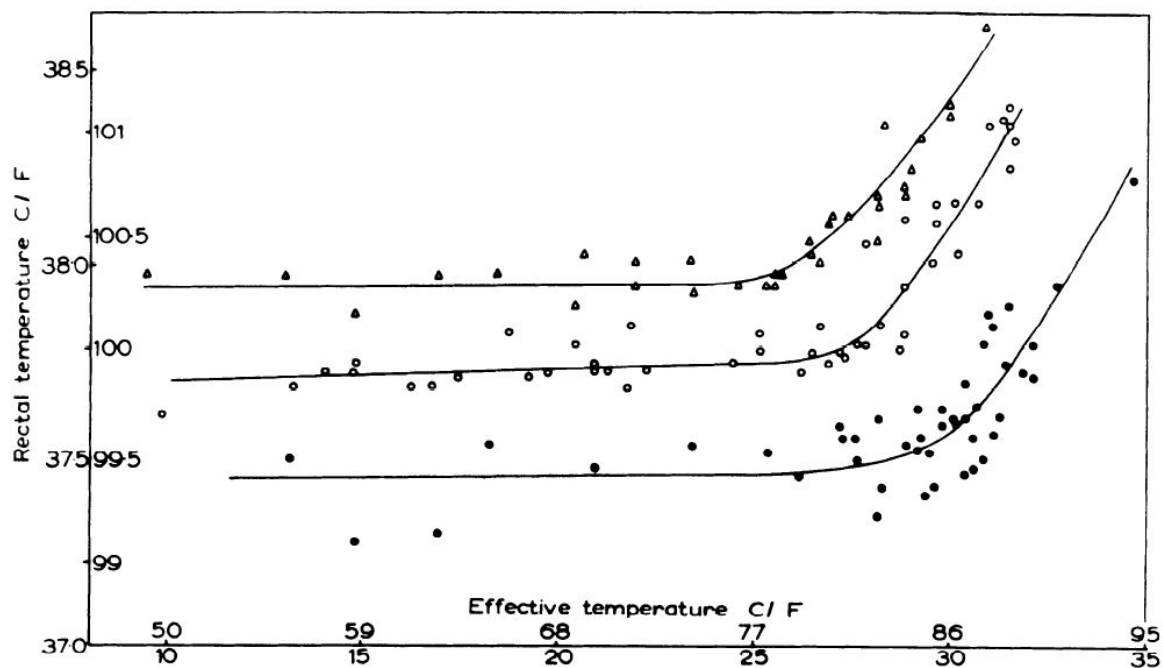
Figure 2.2 Equilibrium levels of rectal temperature at three work rates over a wide range of environmental conditions, depicting the prescriptive zone (From Lind, 1964).

2.4 Body Temperature

Conceptually the body can be considered in two parts, a 'core' and a 'shell.' The thermoregulatory system attempts to maintain T_{core} around 37°C, whilst shell temperature varies widely over the surface of the skin. Mean skin temperature is often calculated to

represent 'shell' temperature by using a weighted average of a number of individual skin temperature sites.

2.4.1 Core Temperature

The term T_{core} does not describe one particular anatomical region. Yet the temperature of the blood in the pulmonary artery is considered to be the best representation of the average internal temperature of the body (Byrne et al. 2007). This site is not accessible, thus a number of measurement sites are used to estimate T_{core}, for example the rectum, auditory canal, tympanic membrane, oesophageal and gastrointestinal tract. Measurements will differ in temperature with each method possessing its own advantages and disadvantages of use, such as practicality and suitability for the studied population. An ideal site for T_{core} measurement is unaffected by environmental conditions, convenient, responds rapidly and reflects small changes in central blood temperature (Sawka, et al. 2011). It is beyond the scope of this thesis to discuss the use of each method, but Table 2.1 briefly describes the advantages and disadvantages of the methods mentioned above.

Table 2.1 Advantages and disadvantages of the experimental methods used to measure core temperature.

Method	Advantages	Disadvantages
Rectum	• Most common site used in scientific research and diagnostic tests • Practical and accurate	• Delayed response time during rapid changes in T_{core}
Tympanic membrane	• Reflect temperature of the blood in the internal carotid artery • Easily accessible	• Can be painful • Influence of external environmental conditions
Auditory canal	• Similar principle to tympanic temperature • Easily accessible	• Influence of external environmental conditions, need for insulation • Participant discomfort when used over long period of time
Oesophageal	• Deep body location, provides the closest agreement with central blood • Rapid response during rapid changes in T_{core}	• Subject discomfort • Difficulty in inserting the thermistor • Irritation to nasal passages • Temperature not the same for length of oesophagus • Consumption of drink and food will influence readings
Gastrointestinal tract	• Practical in field-based studies • Once swallowed, participants are unaware of measurements being made	• Possibility of temperature gradient along gastrointestinal tract • Consumption of drink and food will influence readings, depending on position of sensor in gastrointestinal tract • Uncertainty of sensor transit time

Based on a review of experimental methods presented in Parsons 2003, Byrne et al. 2007 and Moran et al. 2002.

A commonly held view is a 'critical' threshold for T_{core} exists, (38-40°C), beyond which fatigue will occur (Gonzalez-Alonso et al. 1999, Nielsen et al. 1993). Studies have found that despite altering initial T_{core}, rate of heat storage or final skin temperature, a consistent final T_{core} is apparent (Gonzalez-Alonso et al. 1999, Nielsen et al. 1993). These studies seem to suggest that humans elicit a voluntary cessation of exercise prior to a catastrophic system failure as a result of hyperthermia. For instance, Gonzalez-Alonso et al. (1999) reported an end T_{core} of ~40°C during prolonged exercise in an uncompensable hot environment, despite differences in initial T_{core} (Gonzalez-Alonso et al. 1999). Furthermore, T_{core} at the onset of exercise was inversely related to time to exhaustion and directly related to the rate of heat storage (Gonzalez-Alonso et al. 1999), thus suggesting T_{core} at the onset of exercise may also influence exercise performance (Gonzalez-Alonso et al. 1999, Booth et al. 1997, Olschewski et al. 1988). Therefore, lowering initial T_{core} is thought to result in an increase in heat storage capacity and a greater time to exhaustion. This notion has led to extensive studies in pre-cooling in the AB population (Wegmann et al. 2012, Tyler et al. 2015, Ross et al. 2013).

However, not all studies have supported the notion of a critical limiting T_{core} of 40°C, especially as rectal temperatures of ≥40°C have been reported to be well tolerated for extended periods of time in distance runners (Maron et al. 1977, Christensen et al. 1980). Ely et al. (2009) reported that in addition to T_{core} in excess of 40°C at the end of a 8 km running race in well-trained endurance runners, no difference in average running velocity and running velocity during the final 600 m between runners with T_{core} above, and runners with T_{core} below 40°C, were apparent (Ely et al. 2009). Therefore, a critical limiting T_{core} may not be the sole dependent of heat stress fatigue but may be better referred to as a dependent complex interplay from multiple physiological systems (Cheung et al. 2004, Gonzalez-Alonso et al. 2008, Nybo 2008).

2.4.2 Shell Temperature

The external environment and the thermoregulatory state of the body vary mean and local skin ('shell') temperature, with more variable temperatures than the deep body tissues. The variability in skin temperature is location dependent, both between (Webb 1992, Marins et al. 2014) and within skin sites (Frim et al. 1990, Livingstone et al. 1987). The temperature of the skin is largely dictated by the thermal exchanges between the body core and the ambient environment. Thus skin temperature is thought to be time and body composition dependent (Frim et al. 1990, Chudecka et al. 2014).

Skin temperature has also been suggested to be a regulator of exercise intensity (Schlader et al. 2010, Schlader et al. 2011, Jay et al. 2009, Sawka et al. 2012). Yet, investigating the effects of skin temperature separately from the effects of T_{core} is potentially difficult, as changes elicited in T_{sk} are likely also to increase T_{core}. However, a novel study by Schlader et al. (2011) manipulated the skin temperature of participants using a water perfused suit during self-paced cycling exercise. Skin temperature either started cold (29.4°C) and was heated, or started hot (35.2°C) and was cooled throughout exercise. The change in magnitude of T_{sk} between the trials was similar in addition to similar T_{core} responses. In regards to exercise intensity, power output was significantly greater when T_{sk} was manipulated from cold to hot, thus suggesting that T_{sk} is capable of influencing the initial selection of exercise intensity. Schlader et al. (2011) reported that elevations in skin temperature and the associated thermal perceptions (i.e. thermal comfort and thermal sensation) prior to starting exercise are mainly responsible for the selection of the initial exercise intensity. However, the authors also stated that skin temperature appears to not have a sustained role, as after the initial stages of exercise (> 5 min) the change in skin temperature appears to play less of a vital role in self-paced exercise intensity (Schlader et al. 2011).

The majority of studies investigating thermoregulation have been conducted in the AB population. Aside from occupational population groups, a large proportion of studies have been conducted in the athletic population. An under-studied population group in this field of research is that of wheelchair athletes, in particular thermoregulatory impaired athletes with an SCI. Prior to discussing the importance of investigating thermoregulatory responses of these individuals, the sporting environments in which these athletes compete will be discussed. The section below depicts the development of wheelchair sport and focuses on the three wheelchair court sports of; wheelchair rugby (WCR), basketball and tennis.

2.5   Introduction to wheelchair sport

In 1948 Sir Ludwig Guttmann hosted the first wheelchair sport competition for the rehabilitation of World War II veterans at Stoke Mandeville Hospital. The Paralympic Games has subsequently undergone a remarkable growth and is now one of the largest multisport events in the world (Tweedy et al. 2010). Over the Paralympic history, the Games have increased in sports professionalism, included more sports and encompassed a larger range of impairments (Gold et al. 2007). For instance, at the London 2012 Paralympic Games, there were 20 sports, 164 nations and 4,237 athletes taking part in the event compared to just 16

athletes in 1948 (International Paralympic Committee 2013). Since 1988, the Olympics and Paralympics have been held in the same city, year and venue to enable greater relations between the two events to develop and help spread the message that sport is accessible for all. The recent advancements in elite competitive performance at the Paralympics Games have been supported by the evolution of both evidence-based sports science and medicine support (Webborn et al. 2012) and bespoke training/competition equipment (Burkett 2010).

It is beyond the scope of this thesis to introduce all these sports and the associated impairments. Instead, for the purpose of this thesis, the aim is to provide a brief background and physical demands of the wheelchair courts sports of basketball, tennis and rugby.

2.5.1 Wheelchair basketball

Wheelchair basketball was originally developed for World War II veterans in the United States of America in 1945. The sport made its first appearance at the Paralympic Games in 1960 in Rome and has grown dramatically, being practiced in nearly 100 countries. Players with a physical impairment which prevents them from being able to run, jump or pivot are eligible to compete. Therefore, players have a range of impairments, including individuals with PA. Players are classified according to their functional ability into 1 of 8 classification groups from 1.0 (most impaired) to 4.5 (least impaired). Five players make up a wheelchair basketball team and the total permitted classification point value for a team on court is 14 (Tweedy et al. 2010).

The game is played on a standard basketball court in manual wheelchairs and follows similar rules to the AB game, consisting of four 10 minute quarters with the game clock stopped during any stoppages or when the ball is out of play (Tweedy et al. 2010). During a match, players have been shown to cover around 5 km, with 10% of this activity being considered high intensity bursts of intermittent effort (Coutts 1992). In addition, 64% of the game has been shown to be spent in propulsive action and 36% in braking action, depicting the intermittent nature of the sport (Coutts 1992).

2.5.2 Wheelchair tennis

Wheelchair tennis was originally developed in the United States in the 1970's and made its first appearance at the 1992 Paralympic Games in Barcelona. In 1998 the sport became fully integrated with the International Tennis Federation (ITF), the first disability sport to become integrated with an AB world governing body, enabling wheelchair tennis to take place

alongside AB tennis tournaments, such as the Australian Open. The game is similar to the AB game apart from the ball is allowed to bounce twice. Players either compete in the open class or the tetraplegic class. For the tetraplegic class players must have a permanent physical impairment that affects either one or both upper extremities. Players are eligible to compete in the open class if they have a permanent mobility-related physical impairment that affects the lower body (Tweedy et al. 2010). The game consists of short, intermittent sprints combined with sub-maximal pushing and regular rest periods with matches typically lasting between 1-3 hours. In the open class, during a 52 ± 9 min match, the total distance covered has been shown to be 3191 ± 1124 m (Sindall et al. 2013).

2.5.3 Wheelchair rugby

Wheelchair rugby was first introduced for individuals with TP in 1977 and became a demonstration sport in 1996 at the Atlanta Games with six competing nations. Currently, over forty countries participate or are developing programs in the sport (International Wheelchair Rugby Federation 2015). The development of the sport has enabled any individual with an impairment that affects both the arms and legs the opportunity to compete. Although the majority of the players have TP, players with impairments such as cerebral palsy, muscular dystrophy, neurological disorders and amputations can also now compete (International Wheelchair Rugby Federation 2015).

The game of WCR is played in manual wheelchairs designed and built specifically for the sport. The game is played on a standard indoor basketball court with key areas and goal lines at each end and played with a regulation volleyball. The game consists of four 8 minute quarters with the game clock stopped during any stoppages or when the ball is out of play. A goal is scored when a player carries the ball across the opposing team's goal line. Full contact is permitted and wheelchair collisions are a major part of the sport (International Wheelchair Rugby Federation 2015). The sport consists of frequent intermittent activity superimposed on a background of aerobic activity (Goosey-Tolfrey et al. 2006). On average, players cover 4213 ± 626 m during a match and spend the majority of their time in low speed zones ($< 50\%$ mean peak speed, Rhodes et al. 2015).

As with wheelchair basketball, players are classified based on their functional ability into 1 of 8 classification groups from 0.5 (most impaired) to 3.5 (least impaired), determining their role on court. Classification has been shown to be closely related to the volume of activity elicited over a typical WCR quarter. For example, high point players (2.0-3.5 points) are able

to execute greater peak speeds and spend less time within low speed zones compared to low point players (0.5-1.5 points, Rhodes et al. 2015). Generally high point players have greater ball-handling skills, such as interceptions and passes made and caught (Molik et al. 2008, Morgulec-Adamowicz et al. 2010), most likely attributed to these players occupying offensive rather than defensive roles (Rhodes et al. 2015). Unlike wheelchair basketball and tennis, males and females play within the same teams. Each team can field 4 players on court at any one time with the total permitted classification point value of all players on court equally 8 per team (Molik et al. 2008).

Individuals with an SCI can compete in all three of the above wheelchair court sports, summarised in the table below, and are the population group of primary focus in this thesis. The following sections focus on the structure of the spinal cord and the physiological adaptations which occur as a consequence of an SCI, to illustrate how thermoregulatory control is altered for these individuals. Thus Table 2.2 also includes the heat stress risk associated with playing these sports, stated by Webborn (1996) and adapted by Goosey-Tolfrey and Diaper (2014).

Table 2.2 Summary of the sports of wheelchair basketball, tennis and rugby, including the heat stress risk of each sport.

	Sport		
	Wheelchair Basketball	**Wheelchair Tennis**	**Wheelchair Rugby**
Eligible athletes with an SCI	Paraplegia	Paraplegia/Tetraplegia	Tetraplegia
Indoor/ Outdoor sport	Indoor	Outdoor	Indoor
Average duration of a match	4 x 10 min quarters (game clock)	1-3 hours	4 x 8 min quarters (game clock)
Average distance covered during a match	~4.7 km	~3.2 km (52 min match)	~4.2 km
Heat stress level*	Intermediate risk	High risk	High risk

*Note: taken from Webborn (1996) and adapted by Goosey-Tolfrey and Diaper (2014).

2.6 Anatomy of the spinal cord

The human spinal cord functions as a bidirectional conduit through which sensory and motor information travels between the brain and body (Kirshblum et al. 2011). Evidence has also shown it acts as a 'command centre' involved in the control of several functions. For instance, controlling both simple motor functions, such as reflexes, and more complex motor actions, such as locomotion (Guertin et al. 2009).

The spinal cord is made up of 1 billion neurons and involves 31 segments (8 cervical, 12 thoracic, 5 lumbar, 5 sacral and 1 coccygeal, Figure 2.3A). Spinal nerves attach to the spinal cord by paired roots. Each nerve pair defines the 31 segments and passes superior to its corresponding vertebrae, travelling to the body region it supplies. A dorsal root and a ventral

root connect each spinal nerve to the spinal cord. The dorsal roots contain sensory fibres conducting impulses to the spinal cord from the peripheral receptors and the ventral roots contain motor fibres that extend to and innervate skeletal muscles (Figure 2.3B, Marieb et al. 2010). The majority of skeletal muscles are innervated by more than one root and most roots innervate more than one muscle (Kirshblum et al. 2011). The upper limbs are innervated by the cervical spinal nerves, the trunk by the thoracic spinal nerves and the lower limbs by the lumbar and sacral spinal nerves.

An analysis of the cross-section of the spinal cord depicts longitudinally orientated spinal tracts, known as white matter, surrounding central areas, known as grey matter. The white matter allows communication between the spinal cord and the brain and between different parts of the spinal cord through ascending and descending tracts. Ascending tracts contain sensory fibres that carry impulses up the spinal cord whilst descending tracts transmit impulses from the brain down the spinal cord. Within the grey matter, there are two dorsal projections, known as the dorsal and ventral horns. These horns form columns of grey matter, running the length of the spinal cord. Dorsal horns consist entirely of interneurons. The ventral horns house cell bodies of somatic motor neurons, which send their axons to the skeletal muscles via the ventral roots (Figure 2.3B). The amount of skeletal muscle innervated at a given level of the spinal cord reflects the amount of ventral grey matter present at that level. For instance, the ventral horns are largest in the cervical and lumbar region of the spinal cord as they innervate the limbs. In the thoracic and superior lumbar regions of the spinal cord an additional pair of grey columns is present, known as lateral horns, which are autonomic motor neurons that serve visceral organs (Marieb et al. 2010).

A

Cervical

(8 cervical nerve pairs)

Thoracic

(12 thoracic nerve pairs)

Lumbar

(5 lumbar nerve pairs)

Sacrum

(5 sacral nerve pairs)

1 coccygeal nerve
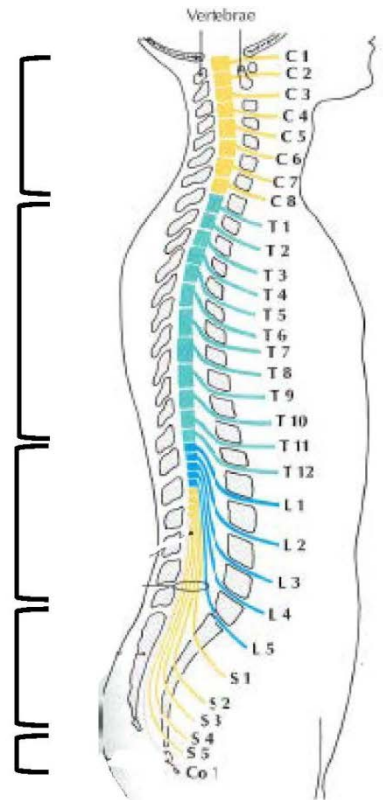
B
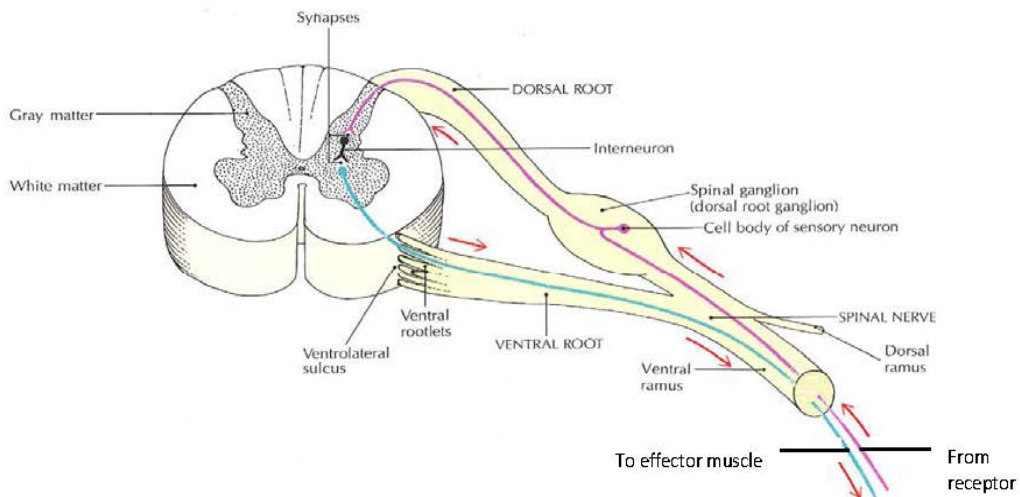
Figure 2.3 A) Right lateral view of the spinal cord, depicting spinal segments and the emergence of the spinal nerves (Carola et al. 1992) B) Cross section of spinal cord, depicting dorsal and ventral roots of spinal nerve (Carola et al. 1992).

2.7   Spinal cord injury

An SCI is a total or partial disruption to the structure and function of the spinal cord, usually caused by a form of trauma (Janssen et al. 2005). This results in impairments, such as autonomic nervous system dysfunction, sensation loss and paralysis. More than half the individuals with an SCI will experience varying degrees of sensory, motor and function loss (Jacobs et al. 2004). An impairment or loss of motor and/or sensory function of the cervical segments of the spinal cord results in tetraplegia (TP). Individuals with TP have impaired function of the arms, trunk, legs and pelvic organs. An impairment or loss of motor and/or sensory function of the thoracic, lumbar and sacral segments of the spinal cord, results in paraplegia (PA). Depending on the level of the injury, arm function is not affected whilst the function of the trunk, legs and pelvic organs may be involved (Kirshblum et al. 2011). Spinal cord injuries are further classified as being neurologically complete or incomplete in relation to motor or sensory function. The Standards for Neurological Classification published by the American Spinal Injury Association (ASIA), defines a complete injury as no motor and/or sensory function preserved in the lowest sacral segments (S4-S5, Waters et al. 1991), whilst a sensory or motor incomplete injury refers to the preservation of motor and/or sensory function in the lowest sacral segments (S4-S5, Kirshblum et al. 2011, American Spinal Injury Association 2002). Incomplete injuries are neurologically more complex and vary greatly between individuals.

Depending on the level of the SCI, varying degrees of disruption to the sympathetic and parasympathetic division of the autonomic nervous system are apparent. Individuals with PA have a partial loss to the sympathetic division of the autonomic nervous system and loss of the sacral portion of the parasympathetic division. Individuals with TP incur decentralisation of their sympathetic nervous system, due to the highest level of sympathetic outflow occurring at the T1 spinal level, potentially resulting in a loss of continuity between the central nervous system autonomic origins and the sublesional autonomic nervous system (Nash 1994, Figure 2.4.) An SCI above the thoracolumbar levels of sympathetic nerve outflow causing autonomic dysfunction are associated with reduced innervation of muscles below the lesion level (Bhambhani 2002), cardiac and circulatory dysfunction(Coutts et al. 1983, Campbell et al. 2004), reduced respiratory function (Krassioukov 2009, Baydur et al. 2001, Hopman et al. 1997), alternations to physical capacity (Coutts et al. 1983, Wicks et al.1983) and thermal dysfunction (Price 2006).
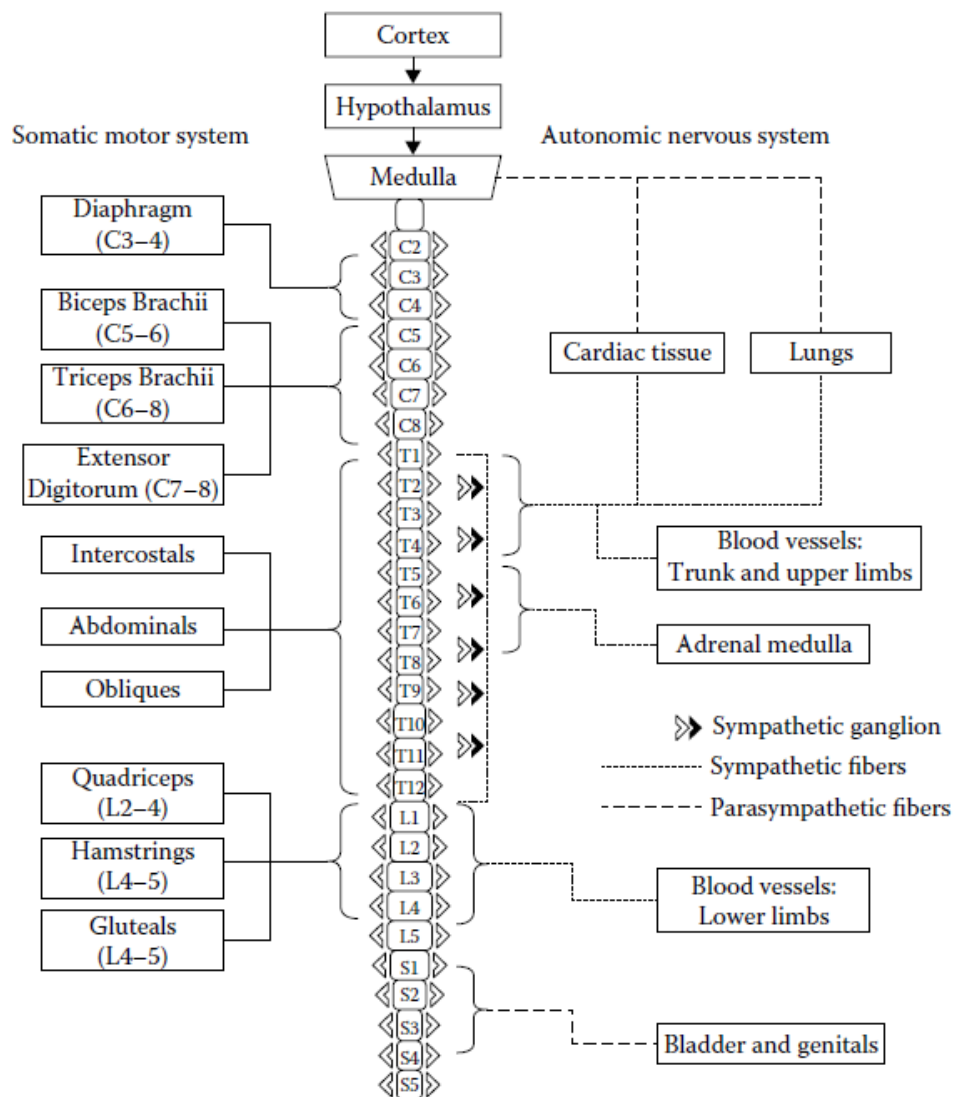
Figure 2.4 A schematic representation of the autonomic and somatic nervous systems (Krassioukov 2009).

2.8 Physiological adaptations following a spinal cord injury

2.8.1 Muscular system

The more complete and the higher the level of the SCI, the greater the loss of somatic and autonomic nervous system function (Janssen et al. 2005). Totally paralysed or weakened muscle prevent or limit the ability to sustain intense muscular contractions, due to the lack or reduction in neurological stimuli to paralysed muscle (Bhambhani 2002), in addition to the altered structural and contractile properties of the muscle (Jacobs et al. 2004). Studies of sublesional muscle following an SCI report fibres that produce lower peak contractile forces

(Rochester et al. 1995) and a cross-sectional area that declines within 1 month of attaining an SCI (Castro et al. 2000, Scelsi et al. 1982).

Studies have shown dramatic muscular atrophy in the lower limbs of individuals with an SCI, with as much as a 35-50% reduction in lower limb cross sectional area (Castro et al. 2000, Olive et al. 2003). The greater the amount of paralysed skeletal muscle, the less able an individual can perform voluntary exercise at metabolic rates large enough to stimulate the cardiorespiratory system (Janssen et al. 2005). For instance, individuals with lesions below T10 have a greater peak oxygen uptake ($\dot{V}O_{2peak}$) than those with a higher spinal lesion due to the ability to utilise a larger proportion of their trunk muscles during upper body exercise (Bhambhani 2002).

2.8.2   Cardiovascular system

The lack of sympathetic vasoconstriction and muscle pump inactivity below the level of the lesion, results in an inability to redistribute blood below the spinal lesion during exercise (Hopman et al. 1992). As a consequence there is a lower increase in mean systemic and ventricular filling pressure, at a given exercise intensity, resulting in a lower stroke volume compared to the AB. The heart has dual innervation from both the vagal nerve (parasympathetic) and the preganglionic neurons from thoracic segments T1-T5 of the spinal cord (sympathetic) shown in Figure 2.4 (Krassioukov 2009). In individuals with lesions below T5, the heart is fully innervated and maximal HR is similar to the AB (Bhambhani 2002). Subsequently, a similar cardiac output to an AB individual, at a given submaximal oxygen uptake ($\dot{V}O_2$) is attained, as the lower stroke volume is compensated by an increase in HR (Hopman et al. 1992). Individuals with cervical lesions possess a disrupted sympathetic stimulation to the heart, whilst parasympathetic control remains intact (Krassioukov 2009), resulting in a maximal HR of 110-130 b·min^{-1} (Jacobs et al. 2004, Bhambhani 2002, Hoffman 1986). Maximal cardiac output is therefore reduced, leading to a decrease in the amount of oxygen transported to the tissues. Although West et al. (2013) has shown that some athletes with TP with complete injuries can extend a maximum HR of 130 b·min^{-1}. Nonetheless, reduced cardiac output and impaired regional blood flow may not pose a primary risk for individuals with PA but appear to be a major limiting factor for individuals with TP (Hoffman 1986).

Vascular adaptations seem to occur within weeks after an SCI, with a significant reduction in systemic blood volume (Houtman et al. 2000) and a remodelling of the arterial wall (de Groot et al. 2006). Thus leading to changes such as a smaller diameter of the common femoral artery and resting blood flow in the leg being 30-50% lower than the AB (Nash et al. 1996, Hopman et al. 1996, Huonker et al. 1998). However, when diameter of the common femoral artery is expressed relative to muscle volume, no difference between SCI and AB is apparent, suggesting that decreases in arterial diameter may be matched to muscular atrophy (Olive et al. 2003). In contrast, in the active upper limb vasculature, the vasculature is relatively well preserved (de Groot et al. 2006) or an increased vessel diameter of the branchii artery may even occur (Shenberger et al. 1990). Therefore the structural adaptations that occur below the injury are reported to be primarily an adaptation to the reduced metabolic demands of the lower limb vasculature (West et al. 2013a).

The morphology of the heart is also changed following an SCI, particularly in individuals with TP (Janssen et al. 2005). For example both left ventricular heart mass and left ventricular dimensions have been found to be consistently smaller in individuals with TP (Kessler et al. 1986). A linear $\dot{V}O_2$- HR relationship has been shown to be non-existent in the majority of untrained individuals with TP (Valent et al. 2007). Yet, this may not be the case for highly trained athletes, as a study by Leicht et al. (2012b) showed that elite athletes with spinal lesions at C6-C7 were found to have a linear $\dot{V}O_2$- HR relationship. Nevertheless, the use of HR as a training prescription tool is still considered to be inappropriate for this population group, due to the markedly reduced HR range in which exercise can be prescribed (Leicht et al. 2012).

2.8.3 Respiratory system

The level and completeness of the lesion determines the loss of innervation of the respiratory muscles. Individuals with PA have a comparable respiratory function (forced vital capacity or forced expiratory flow in 1 s) to AB individuals, whilst individuals with TP have a reduced respiratory function (Haisma et al. 2006). For instance, individuals with cervical injuries (C6-C8) are able to breathe spontaneously, but have greater reductions in vital capacity, total lung capacity and an earlier onset of fatigue of the remaining innervated respiratory muscles, compared to individuals with a thoracolumbar injury (Krassioukov 2009, Baydur et al. 2001, Hopman et al. 1997). This is due to the partial or complete paralysis of the inspiratory muscle groups, such as the scaleni (C4-C8), parasternal intercostals (T1-T7) and the laternal external

intercostals (T1-T12, Krassioukov 2009). Individuals with TP have been shown to have a lower minute ventilation than the AB at rest, primarily attributed to a reduction in tidal volume without a change in breathing frequency (Spungen et al. 2009). However, this is not a consistent finding, as a similar minute ventilation in the AB and individuals with TP has also been reported (Loveridge et al. 1990).

2.8.4 Physical capacity

The effect of an SCI on the amount of innervated muscle and autonomic dysfunction, resulting in an altered haemodynamic response and respiratory function, influences the peak responses to exercise. During exercise where a small muscle mass is being utilised, i.e. during wheelchair propulsion, peripheral fatigue may occur before cardiovascular fatigue. Thus a plateau in maximal oxygen uptake ($\dot{V}O_{2max}$) is unlikely to occur and instead a $\dot{V}O_{2peak}$ is reached (Goosey-Tolfrey et al. 2010). Peak oxygen uptake and other physiological measures, such as peak power output, are inversely related to lesion level and completeness of injury; the higher the lesion, the lower the peak response (Coutts et al. 1983, Wicks et al. 1983). Activity status is also an important determinant of $\dot{V}O_{2peak}$ in individuals with an SCI, with reported values of 1.43 l.min^{-1} and 1.06 l.min^{-1} for trained and untrained individuals with TP, respectively (Bhambhani et al. 1995) and 2.24 l.min^{-1} and 1.56 l.min^{-1} for trained and untrained individuals with PA, respectively (Davis et al. 1988). At a given lesion level, the completeness of the injury also contributes to the peak exercise physiological responses of the individual (Bhambhani 2002). For instance, individuals with incomplete lesions may be able to recruit a larger proportion of their muscle mass, in addition to being able to attain higher heart rate (HR), resulting in a higher $\dot{V}O_{2peak}$ (Eriksson et al. 1988, Campbell et al. 1997). However, research investigating the effects of the completeness of a lesion is scarce.

Janssen et al. (2002) demonstrated that 48-80% of the variance in physical capacity in individuals with TP and PA can be explained by lesion level, completeness of an SCI, activity level, gender, age, body mass and time since injury (Janssen et al. 2002). Positive correlations were found between physical capacity and amount of sport participation, time since injury and body mass. Negative correlations were apparent between physical capacity and lesion level and age. Males and individuals with incomplete injuries also tended to have a greater physical capacity. The majority of these factors cannot be altered, yet activity level can be modified to enhance physical capacity in this population group.

2.8.5   Thermoregulation

Individuals with an SCI have a reduced afferent input to the thermoregulatory centre (Freund et al. 1984, Rawson et al. 1967, Tam et al. 1978) and a loss of both sweating capacity and vasomotor control below the level of the spinal cord lesion (Freund et al. 1984, Hopman 1994, Normell 1974). As blood redistribution and sweating are two major thermoregulatory effectors, individuals with an SCI have compromised thermoregulatory control and are at a greater risk of heat injury than the AB (Price 2006). Similarly to the physiological adaptations mentioned above, the magnitude of the thermoregulatory impairment is proportional to the level and completeness of the lesion. As a consequence, individuals with TP and a complete injury possess a smaller area of sensate skin, a lesser amount of afferent input regarding their thermal state and a reduced efferent response compared to individuals with PA (Normell 1974, Guttmann et al. 1958). Whilst individuals with incomplete lesions may have a greater amount of sensory information about their thermal state and a greater capacity to sweat (Webborn et al. 2010).

The following section reviews previous studies investigating thermoregulation in individuals with PA and TP.

2.8.5.1   Individuals with paraplegia

In cool-moderate conditions (15-21°C), trained individuals with PA, at the same relative intensity of exercise, demonstrate no difference in T_{core} compared to trained AB individuals (Dawson et al. 1994, Hopman et al. 1993, Price et al. 1997, Price et al. 1999b). When exercising for 60-90 minutes at 60% $\dot{V}O_{2peak}$, athletes with PA experience an increase in T_{core} of ~1°C, similar to the AB (Price 2006). Nevertheless, in these studies the majority of the individuals with PA possessed low level lesions (>T6), therefore, approximately half their body surface area would be available for sweating (Piwonka et al. 1965). In individuals with PA with lesions above T6 a greater thermal strain would be experienced, partly due to the smaller body surface area available for sweating and greater reduction in vasomotor control (Guttmann et al. 1958).

For the same relative exercise intensity (~60%$\dot{V}O_{2peak}$) in the heat (35-40°C) a greater increase in T_{core} over time may be apparent in athletes with PA, compared to the AB, signifying an imbalance between heat loss and heat gain, though exercise can still be maintained (Price 2006). Above exercise intensities of 60% $\dot{V}O_{2peak}$ in the heat, sweating and

heat production may become unbalanced potentially eliciting volitional exhaustion and a greater amount of thermal strain (Price 2006). Of note, wheelchair athletes often compete at exercise intensities above 60% $\dot{V}O_{2peak}$, for instance trained wheelchair athletes have been reported to be able to maintain ~75% $\dot{V}O_{2peak}$ during endurance races (Campbell et al. 2002). Hence previous studies have not reflected the "real-world" conditions of wheelchair sport. Trained wheelchair athletes could, therefore, be under significantly greater heat stress during competition in cool or hot conditions then stated in the current literature.

Another limitation of the current literature is the use of percentage of $\dot{V}O_{2peak}$ to match the exercise intensity for AB controls and individuals with an SCI. This experimental design is based on the premise that aerobic fitness influences T_{core} regulation. Recently this has been disapproved, with only a small percentage of variance in thermoregulatory responses explained by variations in fitness (i.e. $\dot{V}O_{2peak}$, Cramer et al. 2015). In the studies mentioned above (Dawson et al. 1994, Hopman et al. 1993, Price et al. 1997, Price et al. 1999b), individuals with PA had a lower $\dot{V}O_{2peak}$ value than the AB controls. In terms of heat production, the lower absolute work rate in PA would have led to a smaller production of heat. If the groups were matched for biophysical parameters related to heat production and body size, a difference in T_{core} between the groups in cool-moderate conditions and an even greater difference in hot conditions is likely apparent.

Mean skin temperature of individuals with PA has been investigated in previous studies (Dawson et al. 1994, Price et al. 1997, Fitzgerald et al. 1990). However, as there is no formula specifically for use in individuals with an SCI, T_{sk} could mask regional differences in skin temperature (Price 2006). Therefore, it is recommended that both T_{sk} and local skin temperatures are reported in SCI research. In addition, large inter-individual variation in thermoregulatory responses is common in the SCI population. Even when individuals that are neurologically similar are grouped together, a wide range of thermoregulatory responses may be apparent (Price et al. 2003). This may be potentially due to differences in the somatosensory and sympathetic pathways, in arrangements of sympathetic outflow and the type and degree of innervation (Normell 1974, Gass et al. 1988).

At rest in individuals with PA, thigh and calf skin temperatures (28-31°C) are lower than upper body skin temperatures (32-33°C) and in the AB (Hopman 1994, Price et al. 1997). During prolonged arm cranking calf skin temperature has been shown to increase, suggesting the lower body is a potential site for heat storage in individuals with PA (Hopman et al. 1993,

Price et al. 1997, Price et al. 1999b). However, the degree of sweating and blood flow redistribution in the lower limb may be dependent on the lowest intact part of the sympathetic chain, with the pathway for vasodilation in the lower limb located at or below T10 (Gass et al. 1988, Cooper et al. 1957). For instance, in individuals with lesions at T12, calf skin temperature has been shown to increase during exercise with little or no change for individuals with lesions at T10/T11 (Gass et al. 1988).

Differences between regional skin temperature sites may also exist due to the exercise modalities utilised. For instance, the difference in skin temperature of the upper limb between wheelchair propulsion and arm cranking. Wheelchair propulsion is less efficient (7-12%) (Goosey et al. 1998, Vanlandewijck et al. 1994) than arm cranking (14-20%, Goosey-Tolfrey et al. 2007, Powers et al. 1984, Marais et al. 2002) due to the intermittent application of force during wheelchair propulsion, occurring only during the forward swing, compared to the continuous application of force during arm cranking. Thus, more waste heat is produced in wheelchair propulsion compared to arm cranking. However, Price and Campbell (1999a) have shown that a lower heat storage is attained and thus a greater dissipation of heat is apparent in wheelchair propulsion compared to arm cranking (Price et al. 1999a). This is as a result of an increase in convective cooling, due to the arm moving relative to the body during propulsion of the wheelchair, causing an increase in peripheral heat loss. The increase in peripheral heat loss is clearly shown by a reduction in upper and lower arm skin temperature. Therefore it is imperative that future research uses the most appropriate mode of exercise to reflect the studied sport, i.e. wheelchair propulsion for wheelchair court sports.

2.8.5.2 Individuals with tetraplegia

Limited research has been conducted investigating the thermoregulatory responses of individuals with TP during rest and exercise. Two theories exist regarding the thermoregulatory responses of these individuals. Firstly, due to a reduced active muscle mass, individuals with TP may generate less metabolic heat and therefore a small increase in T_{core} may be apparent during exercise (Gass et al. 1992). In support of this theory, athletes with TP showed, on average, only a 0.3°C increase in T_{core} during a simulated 5 km wheelchair race in cool conditions (23°C dry bulb and 17°C wet bulb, Gass et al. 1992). However, a more credible theory is that athletes with TP may experience a disproportionate increase in T_{core} and heat storage, due to a minimal or loss in sweating capacity, despite potentially producing less metabolic heat. Thus an imbalance between heat production and heat loss will occur,

increasing the risk of exercise-induced heat injury (Gass et al. 1992). During 60 minutes of moderate intensity arm cranking exercise in cool conditions (21.5°C and 47% relative humidity), Price and Campbell (1997) demonstrated that one studied athlete with TP experienced a continuous increase in T_{core}, in contrast to a plateau in T_{core} for the AB and athletes with PA. Although the athlete with TP did not experience high thermal strain in these conditions, the continuous rise in T_{core} demonstrates thermal balance was not attained. The continual increase in T_{core} has also been found during both intermittent and continuous exercise in the heat (~32°C and ~50% relative humidity, Price et al. 2003, Webborn et al. 2005). However, similarly to studies conducted with individuals with PA, studies thus far have failed to reflect the mode and intermittent nature of wheelchair court sports, either using arm cranking or continuous protocols. Thus, a greater understanding of the thermoregulatory responses of individuals with TP is needed in "real-world" sporting environments.

Minimal or a loss in sweating capacity is demonstrated by individuals with TP as the cervical spinal lesion is above the sympathetic outflow (Guttmann et al. 1958, Webborn et al. 2005). Any minimal sweat that does occur is considered to cover only a small area of the skin's surface leading to limited evaporative heat loss (Gass et al. 1992). Pritchett et al. (2015) found no differences between sweat output per gland in individuals with PA compared to AB individuals, suggesting a compensatory increase in sweating in the upper body, to counteract the lack of active sweat glands present at the lower body, does not exist (Pritchett et al. 2015). Yet, training status may influence the sweat rate and sweat gland density of individuals with an SCI, similarly to the AB. Yaggie et al. (2002) investigated sweat production above and below the lesion level and between trained and untrained individuals with TP. Sweat production was induced by pilocarpine iontophoresis in untrained AB, untrained individuals with TP and trained individuals with TP (Yaggie et al. 2002). Findings showed that in the AB the lower extremities produced less sweat and had a lower sweat gland density than the extremities of the upper body. Sweat rate and sweat output per gland were both higher in the AB in both the upper and lower extremities compared to individuals with TP. But active sweat gland density and sweat rate in the upper extremities were higher in the trained than the untrained individuals with TP. The authors suggested that this was caused by a localized mechanism at the level of the eccrine gland in the trained individuals. Core and dermal temperature acclimatisation may occur due to the consistent physiological and environmental thermal exposure in relation to training and competition (Yaggie et al. 2002). Nevertheless, this is an area greatly under-studied in the SCI population, but does highlight that studies

should be conducted using highly trained and motivated individuals to ensure research findings can be translated to elite wheelchair athletes.

A summary from the current literature of some of the physiological adaptations as a consequence of an SCI, and how these may contribute to impaired thermoregulatory control at rest and during exercise is shown in Figure 2.5. Yet the extent of the changes in the heat exchange pathways and heat balance as a result of an SCI and the effect lesion level has on this response are currently unknown.
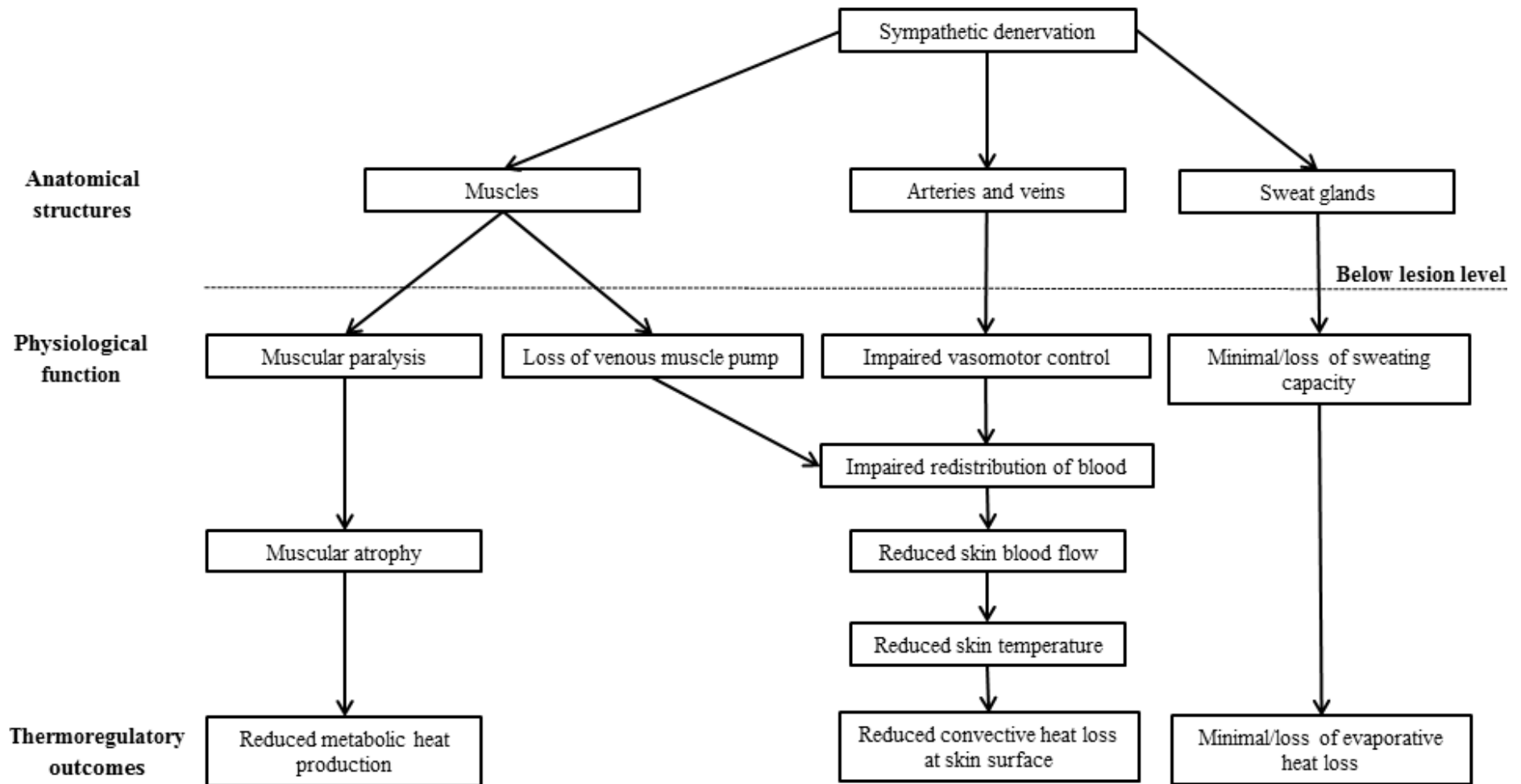
Figure 2.5 Physiological adaptations as a consequence of a spinal cord injury and how they may contribute to impaired thermoregulatory control.

2.9   Future exercise studies

Based on the current literature, future research needs to ensure that exercise employed is reflective, both in mode, intensity and type, of "real-world" sporting environments. This also extends to conducting studies in ambient environments representative of the sporting arenas wheelchair athletes would compete in. The thermoregulatory responses of athletes with TP have been under-studied to date, despite physiologically being at a greater thermoregulatory disadvantage compared to athletes with PA. Once the extent of the thermoregulatory impairment in athletes with TP in sporting scenarios is established, the application of practical strategies, for example cooling strategies, which could reduce thermal strain, is of particular importance.

2.10   Application of cooling strategies

Cooling strategies that reduce the attenuation of athletic performance have been investigated over the past three decades with increasing interest in the AB population, particularly in the lead up to a relatively hot Olympic Games, such as Athens 2004 or Beijing 2008. Despite the interest in the application of cooling strategies for the AB athlete, little is known regarding this for wheelchair bound thermoregulatory impaired athletes with an SCI. In an athletic setting, it is imperative that the appropriate training practices, such as cooling strategies, are applied to support athletic performance for athletes with an SCI, but more importantly, that the health of the individual is also considered.

Examining the scientific literature addressing application of cooling strategies to individuals with an SCI, with specific reference to the practical and logistical issues associated with each method, to date, ten studies have been published. Methods consist of hand/foot cooling (Goosey-Tolfrey et al. 2008b, Hagobian et al. 2004), water sprays (Pritchett et al. 2010) and cooling garments (Webborn et al. 2010, Webborn et al. 2005, Armstrong et al. 1995, Bongers et al. 2015, Trbovich et al. 2014, Diaper et al. 2009, Goosey-Tolfrey et al. 2008a). However, it is beyond the scope of this thesis to discuss each technique. Instead the review will focus on current cooling practices used by athletes with an SCI for pre-cooling and cooling between exercise/rest periods (Table 2.3 and Table 2.4). For a thorough review of all ten studies refer to Griggs et al. (2015).

Table 2.3 Summary of participants and methods of reviewed studies employing cooling practices currently use in wheelchair court sports.

	Participants			Method				Cooling procedure	
Study	No. of participants [a]	Sport (n)[b]	Impairment (n)	T_a, RH	T_{core} measure(s)	Exercise protocol	Description of protocol	Cooling method	Timing (duration)
Pritchett et al.(2010)	7 (4F)	WB	PA	22°C, 45%	T_{re} + T_{es}	INC	7 min stages on WERG, separated by 1 min passive rest, increasing by 20 W each stage. Test terminated if T_{es} rose more than 0.2°C/min or voluntarily terminated	1) WS(~17°C water) 2) CON	1) DUR (1 min rest periods)
Armstrong et al. (1995)	6	WR	TP (1) PA (4) Polio (1)	32.9°C, 75%	T_{re} + T_{au}	SS	30 min on WERG, simulated 10 km race pace	1) H 2) V 3) CON	1) DUR 2) DUR
Webborn et al.(2005)	8	WCR (4) + WT (4)	TP	32°C, 50%	T_{gi}	INT	28 min on ACE consisting of fourteen 2-min periods (10 s passive rest, 5 s max sprint and 105 s of active recovery at 35% $\dot{V}O2peak$)	1) V 2) V 3) CON	1) PRE (20 min) 2) DUR
Webborn et al.(2010)	8	WCR (4) + WT(4)	TP	32°C, 50%	T_{gi}	INT	60 min on ACE consisting of thirty 2-min periods (10 s passive rest, 5 s max sprint and 105 s of active recovery at 35% $\dot{V}O_{2peak}$)	1) V 2) V 3) CON	1) PRE (20 min) 2) DUR
Bongers et al. (2015)	10	n/a	PA	25.4°C, 41%	T_{gi}	SS	45 min of ACE at 50% $\dot{V}O_{2peak}$	1) CV 2) CON	1) DUR
Trbovich et al. (2014)	17	WB (11) + WCR (6)	TP (6) PA (11)	21.1-23.9°C, n/a	T_{gi}	INT	60 min match play of respective sport (WB or WCR)	1) CV 2) CON	1) DUR
Diaper and Goosey-Tolfrey (2009)	1 (F)	WT	PA	30.4°C, 54%	T_{au}	INT	See above for Goosey-Tolfrey et al.	1) V 2) V + HN	1) PRE (30 min) 2) PRE with V (30 min) +DUR with HN
Goosey-Tolfrey et al.(2008)	8 (3F)	WT	TP (2) PA (5) AMP (1)	30.4°C, 54%	None	INT	60 min on WERG, 5 x 10 min blocks followed by 2 min recovery (each block included 5 s max sprint, 105 s active recovery, followed by 10 s rest)	1) HN 2) CON	1) DUR

[a] all male participants unless stated otherwise   [b] all trained participants *ACE* arm crank ergometry, *AMP* amputation, *F* female, CON no cooling intervention, CV cooling vest DUR during exercise, H refrigerated headpiece, HN cooling hat and neckband, *INC* incremental, *INT* intermittent, *n/a* not available, *PA* paraplegia, PRE pre-cooling, RH relative humidity, *SCI* spinal cord injury, *SS* steady state, T_a ambient temperature, T_{core} core temperature, T_{au} aural temperature, T_{es} oesophageal temperature, T_{gi} gastrointestinal temperature, TP tetraplegia, T_{re} rectal temperature, *TT* time trial, $\dot{V}O_{2peak}$ peak oxygen uptake, *WB* wheelchair basketball, *WERG* wheelchair ergometer, W_{peak} Peak power output, V ice vest, WS water spray *WR* wheelchair racing, *WCR* wheelchair rugby, *WT* wheelchair tennis

2.11 Cooling methods

In the AB the majority of exercise-related cooling methods are applied externally, either in isolation or as a combination of methods. Widespread use of various cooling methods and techniques in research include; cold air exposure, (Olschewski et al. 1988, Lee et al. 1995) wearing of ice/cooling vests (Arngrimsson et al. 2004, Duffield et al. 2003, Duffield et al. 2007), whole body water immersion (Booth et al. 1997, Booth et al. 2001, Kay et al. 1999), water immersion of the extremities (Grahn et al. 2008, House et al. 1997) and ice slurry or cold water ingestion (Ross et al. 2011, Siegel et al. 2010). These methods influence the body in different ways by either reducing T_{core} and T_{sk} (water immersion); reducing T_{core} with no effect on T_{sk} (ice slurry or cold water ingestion) or primarily reducing T_{sk} (ice/cooling vests, cold air exposure, water sprays). Methods differ greatly in terms of their physiological effects, cooling power and, importantly, the timing of application. Moreover, the duration of the cooling strategy employed is also crucial to ensure maximum benefit to the athlete's performance without compromising athlete comfort or pre-event/half-time routine. Depending on the method used, in the AB population, the time required to achieve a significant reduction in T_{core} has been shown to range from 15-60 minutes of cooling (Barwood et al. 2009, Quod et al. 2008). In assessing the practicality of a cooling method for an athletic population the effectiveness, sporting regulations, staffing/assistance, logistics, cost and athlete comfort need to be considered. Although, there is still debate regarding which strategy provides the greatest performance benefit, recent meta-analysis data in the AB population has shown that pre-cooling, especially mixed method cooling (Bongers et al. 2014) can improve subsequent intermittent and prolonged exercise performance in the heat (Tyler et al. 2015). During exercise, meta-analysis data has revealed the use of ice vests to have the largest effect on performance (Bongers et al. 2014).

Table 2.4 summaries the cooling method and results of reviewed studies employing current cooling practices used in wheelchair court sports.

Table 2.4 Summary of cooling method and results of reviewed studies employing cooling practices currently used in wheelchair court sports

Study	Cooling procedure		Results	
	Method	Timing (duration)	Performance effect	Thermal effect
Pritchett et al. (2010)	3) WS(~17°C water) 4) CON	2) DUR (1 min rest periods)	Mean total work done and time was similar between conditions	No significant differences between conditions in T_{re}, T_{es}, T_{sk}, RPE and TS
Armstrong et al. (1995)	4) H 5) V 6) CON	3) DUR 4) DUR	No performance measure	No significant differences in T_{re}, T_{au}, T_{sk}, RPE and TS H had a smaller absolute and relative cooling potential than V
Webborn et al. (2005)	4) V 5) V 6) CON	3) PRE (20 min) 4) DUR	No performance measure	T_{gi} was lower during the ISP in PRE and DUR T_{sk} was lower in DUR compared to CON but no different between CON and PRE RPE was lower during PRE and DUR TS was lower in DUR than CON but not different to PRE
Webborn et al. (2010)	4) V 5) V 6) CON	3) PRE (20 min) 4) DUR	Mean exercise duration was increased by PRE and DUR More sprints were completed in DUR Significant reductions in peak power output across time in PRE and CON but not DUR	T_{gi} was lower in PRE and DUR T_{sk} was similar between CON and PRE but DUR was lower than CON RPE was lower during PRE and DUR TS was lower in DUR but not different between PRE and CON
Bongers et al. (2015)	3) CV 4) CON	5) DUR	No performance measure	No significant differences between conditions for T_{gi} and RPE T_{sk} was lower in V than CON Trend for lower TS in V than CON
Trbovich et al. (2014)	3) CV 4) CON	1) DUR	No performance measure	T_{gi} was not different between CV and CON for athletes with TP or PA
Diaper and Goosey-Tolfrey (2009)	3) V 4) V + HN	3) PRE (30 min) 4) PRE with V (30 min) +DUR with HN	Average peak speed higher in HN	Change in T_{au} from baseline over the 60 min trial was higher in CON TS was lower for each exercise block during HN
Goosey-Tolfrey et al.(2008)	3) HN 4) CON	2) DUR	No performance measure	Participants consumed 42% less water on average during HN TS and RPE tended to be lower in HN, though not significant

CON no cooling intervention, CV cooling vest DUR during exercise, H refrigerated headpiece, HN cooling hat and neckband, ISP intermittent sprint protocol, PRE pre-cooling, RPE rating of perceived exertion, T_{au} aural temperature, T_{core} core temperature, T_{es} esophageal temperature, T_{gi} gastrointestinal temperature, T_{re} rectal temperature, TS thermal sensation T_{sk} mean skin temperature, V ice vest, WS water spray

2.11.1 Water Sprays

Players in wheelchair court sports with an SCI tend to use water sprays during rest periods to cool themselves, partly due to their ease of use. The concept of using water sprays is to partially mimic the sweat response that an AB individual would experience (Pritchett et al. 2010). Despite this, only one study to date has investigated the use of water sprays in individuals with an SCI, in particular athletes with PA. Pritchett et al. (2010) conducted an incremental arm cranking protocol involving seven minute stages interspersed with 1 minute breaks, when participants sprayed themselves *ad libitum*. The protocol was terminated voluntarily or when oesophageal temperature (T_{es}) rose by more than 0.2°C/min^{-1}, despite the value of the end T_{core}. There were no differences between water spraying and no cooling in HR, T_{es}, rectal temperature (T_{re}), T_{sk}, mean total work performed, rating of perceived exertion (RPE) or thermal sensation (Pritchett et al. 2010). Although the lack of positive findings may be due to the limited skin surface area covered by the water sprays (back of head, neck, forearm and face), due to the obstruction of clothing, this reflects the typical water spraying habits of wheelchair athletes. It is unknown which factor plays the greatest role in a cooling method's ability to dissipate heat; the amount of body surface area cooled or the specific body location (Young et al. 1987).

The absence of positive findings in the work of Pritchett et al. (2010) may be due to a number of limitations of the study. Although the authors stated that the protocol and ambient conditions (22°C, 45-50% relative humidity) were used to maintain high ecological validity, the exercise mode of arm cranking is not reflective of wheelchair court sports of an intermittent nature. Secondly, players only experienced a slight increase in T_{core} by the end of the protocol (0.5°C). This could be because exercising at an air temperature of 22°C, trained individuals with PA may be able to regulate heat loss in the absence of external heat gains similarly to an AB counterpart (Price 2006). Whether a more demanding exercise protocol, akin to a wheelchair basketball match, may have elicited a larger cooling improvement from water spraying or whether a similar outcome would be observed for players with TP is unknown.

Remarkably, Pritchett et al. (2010) found no improvement in perceptual measures (thermal sensation and RPE) in the cooling condition. Evidence for the responsiveness of the face to cooling in the AB population has shown a two to fivefold suppression of thermal discomfort in the face compared to cooling other body regions (Cotter et al. 2005), indicating that water

spraying the face may be beneficial for thermal comfort. Although considered to be a practical method frequently used by many wheelchair athletes, caution is needed if thermal comfort is improved but there is no equivalent reduction in T_{core}, as athletes could potentially override signs of high levels of heat strain, putting them at risk of heat injury.

2.11.2 Cooling Garments

Lightweight cooling garments have received considerable interest in the AB athletic population (Arngrimsson et al. 2004, Duffield et al. 2003, Duffield et al. 2007, Quod et al. 2008, Bogerd et al. 2010a, Hornery et al. 2005, Cotter et al. 2001, Faulkner et al. 2015). An advantage of these garments is their potential use prior to or during exercise. However, a disadvantage is the trade-off between a lightweight garment with a sufficient cooling capacity, in relation to the amount and type of coolant contained in the garment. Recent developments in design features include; close-fitting designs, silica based gels to promote greater evaporative cooling, phase change materials that operate close to normal skin temperature (Tate et al. 2010) and wet cooling to increase heat transfer between torso and vest (Ross et al. 2013). Cooling garments typically weigh ~1-4 kg (Barwood et al. 2009). For wheelchair athletes, bulkier cooling systems would be counter-active to the technology of the modern sports wheelchair, produced to reduce mass and improve aerodynamics (Armstrong et al. 1995).

In the AB athletic population, research into the use of cooling garments has predominantly focused on ice vests as a pre-cooling method prior to endurance exercise (Ross et al. 2013). Pre-cooling using an ice vest, usually results in relative reductions in T_{sk} (Quod et al. 2008) and body temperature (Bogerd et al. 2010a), in addition to skin blood flow (Bogerd et al. 2010a), with no change in T_{core} (Bogerd et al. 2010a, Minett et al. 2011). This suggests that the transfer of heat mainly occurs at the skin and less so at the core. The use of cooling garments prior to intermittent exercise has produced mixed results, being dependent upon the ambient condition, with positive effects found in warm environments (30-34°C, Wegmann et al. 2012, Cheung et al. 2004). The use of ice vests as a pre-cooling method has been shown to improve performance by 4.8% (Wegmann et al. 2012), but also provide limited efficacy compared to ice slurry ingestion (Jones et al. 2012). Meta-analysis data has found wearing ice vests during exercise has a significantly larger effect (ES = 4.64) than other cooling techniques, such as cold water ingestion (ES = 1.75) and cooling packs (ES = 0.39, Bongers et al. 2014). However, research into wearing these garments during sport is still limited, due

to sporting regulations and difficulty in incorporating such garments into athletic clothing worn during competition.

Although not as heavily researched, cooling devices for the head and neck, such as cooling hats, neckbands and headpieces, are also commercially available (Diaper et al. 2009, Goosey-Tolfrey et al. 2008a, Tyler et al. 2011, Tyler et al. 2010). The rationale for garments that cool the head is based on the concept that this body region contains a high concentration of thermoreceptors (Nakamura et al. 2008), as demonstrated by the head feeling warmer than the rest of the body in warm environments (Arens et al. 2006). It should be noted, however, that the influence of head cooling and the extent to which brain temperature increases during exercise in the heat is unknown and needs to be further investigated (Brengelmann 1993, Cabanac et al. 1979). The neck area is a region of high thermosensitivity for both sudomotor and discomfort responses (Cotter et al. 2005), yet few studies in the AB have investigated cooling this region during exercise. The limited number of studies that have investigated the use of cooling neck collars have found a performance improvement whilst exercising in the heat (~30°C) and wearing the collars for 90 minutes during exercise (75 minutes at 60% $\dot{V}O_{2peak}$ followed by a 15 minute time trial, Tyler et al. 2011, Tyler et al. 2010). However, a shorter cooling exposure (during a 15 minute time trial) had no effect on time trial performance (Tyler et al. 2010). This suggests that the small surface area of cooling provided by the neck collars may only have an ergogenic effect under high levels of thermal strain and when worn for a long duration, below which a performance benefit cannot be achieved (Tyler et al. 2010).

In the athletic SCI population, the use of a refrigerated headpiece and an ice vest used to cool during 30 minutes of wheelchair exercise at 10 km race pace (~70% maximal aerobic power) has shown to provide no thermal, perceptual or performance benefit compared to no cooling (Armstrong et al. 1995). The lack of a performance benefit observed may be due to the cooling potential of the two garments (75 W and 117 W for the headpiece and ice vest, respectively) being considerably lower than the metabolic heat generated during the exercise (704-766 W). From thermal manikin work, this commercially available vest has been found to extract only ~70 W of heat from the torso over 45 minutes at 26°C (Bogerd et al. 2010b). A greater cooling potential may have been achieved with additional ice packets in the vest covering a greater skin surface area (Armstrong et al. 1995). However, this would increase the mass of the 3 kg garment, potentially hindering athletic performance. Practically, the length of time the ice vest stays cold also needs to be considered as once the ice strips of the

vest have melted, cooling effectiveness is reduced. Therefore, applying this cooling method prior to exercise may be more practical and increase cooling effectiveness when compared to wearing the vest for a longer period of time during exercise.

Webborn et al. (2005, 2010) demonstrated promising results using ice vests prior to and during intermittent arm cranking exercise for athletes with TP. Twenty minutes of pre-cooling (PRE) and cooling during exercise (DUR, warm-up and intermittent sprint protocol (ISP)) using an ice vest was shown to elicit lower gastrointestinal (T_{gi}) and thermal sensation throughout exercise, compared to no cooling. Despite T_{gi} being greater in DUR throughout exercise, compared to PRE, a lower rate of increase resulted in similar T_{gi} at the end of exercise. Pre-cooling demonstrated central cooling through an offset in the absolute increase in T_{gi}. Upon removal of the vest T_{sk} increased at a greater rate than the other conditions, due to the greater thermal gradient between the environment and the skin, but still remained lower than the no cooling condition. In contrast, in DUR, initial peripheral cooling may have been apparent as direct heat transfer from the body core to the periphery was facilitated, demonstrated by the lower rate of increase in T_{gi} resulting in a cooling of the skin. Therefore, whether cooling before or during exercise is the most appropriate form of cooling may depend on whether peripheral or core cooling is of importance. In terms of sprint performance, whilst there were no differences in overall work done during the 14 sprint protocol (Webborn et al. 2005), the extended protocol of 30 sprints exhibited substantial differences between the conditions (Webborn et al. 2010). In Webborn et al. (2010) athletes were able to complete more sprints in PRE and DUR than no cooling, with the greatest number of sprints completed in the latter. Peak power output significantly decreased in PRE (~15%) and the no cooling condition (~13%) over time, whilst this was not observed for DUR (~3%). The peak power output of the initial sprints in DUR were lower than the other conditions, which could be linked to the ability of the athletes to exercise for longer in DUR. Consequently, during the initial sprints the metabolic processes of the muscle will not have been stressed as greatly in DUR compared to the other two conditions, potentially allowing better recovery between sprints. This implies that cooling during exercise with an ice vest may not be ideal when the initial power output of sprints is essential to the overall performance. Participants also commented on the initial coldness of the vest, which may have affected their initial sprint performance from a psychological perspective.

Similar results were not found when using a cooling vest (HyperKewl[TM], TechNiche) with athletes with PA in a cooler ambient environment (25.4°C, 41% relative humidity, Bongers et

al. 2015). After 45 min of arm cranking at 50% $\dot{V}O_{2peak}$ Bongers et al. (2015) found the increase or maximum T_{gi} was not significant different between cooling and no cooling. A lower T_{sk} and a trend for a lower thermal sensation value were apparent during the cooling condition, yet this result may be unsurprising given the surface area covered by the vest. In addition to the lack of a performance measure, the ecological validity of the protocol and training status of the participants could be questioned limiting the application of the study's findings.

To date, only one study has investigated the use of a cooling garment in a field based environment (Trbovich et al. 2014). Trbovich et al. (2014) studied the use of a cooling vest, containing renewable phase change materials, reported to maintain at 15°C for 2-3 hours, during 60 minutes of wheelchair basketball or WCR (21.1-23.9°C environmental temperature) in athletes with PA and TP, respectively. A greater rise in T_{gi} was experienced by the athletes with TP at the end of the 60 min compared to athletes with PA, yet the cooling vest had no effect on T_{gi} for either group. Even though this study may appear novel by exploring a cooling strategy in a field based environment for athletes with an SCI, a number of limitations are apparent which affects the application of the findings. Firstly, there was no control of or recording of exercise intensity. Secondly, although the sports are both of an intermittent nature using court sports wheelchairs, the kinematics of the wheelchair basketball and WCR differ (Coutts 1992, Sarro et al. 2010), and a player's function and classification affects their speed and distance covered (Sarro et al. 2010), limiting the comparative nature of the study. Finally, irrespective of any thermal benefit, it is unclear if any performance benefit was provided by the cooling vest, or whether T_{sk} or perceptual responses were affected.

To ensure an athlete gets the most benefit from a cooling strategy, methods need to be practiced prior to major competitions. Diaper et al. (2009) investigated pre-cooling using an ice vest and the combination of pre-cooling using an ice vest and cooling hats and neckbands during intermittent exercise (~30°C environmental temperature) for a wheelchair tennis player prior to a Paralympic Games. The player exhibited a lower T_{au}, thermal sensation and faster average peak speed using the combination of methods compared to pre-cooling alone (Diaper et al. 2009). However, the study did not measure any other thermal or physiological parameters or provide a control condition to determine whether pre-cooling only had any thermal benefit compared to no cooling. The thermoregulatory and physiological effects of pre-cooling have been shown to wane after 30-40 min (Hessemer et al. 1984, Wilson et al. 2002), therefore at the end of the 60 min exercise protocol, the pre-cooling condition may

have had limited benefit compared to no cooling. During a similar protocol and ambient conditions, Goosey-Tolfrey et al. (2008) demonstrated the combined use of cooling hats and neckbands versus no cooling elicited lower RPE and thermal sensation during intermittent sprint exercise in eight wheelchair tennis players (Goosey-Tolfrey et al. 2008). Although 42% less water was consumed during the cooling condition and sweat rates did not differ between conditions, athletes did maintain euhydration. Limited findings can be drawn in respect to the thermal benefit of this cooling strategy, as no thermal measures were taken, yet practically the cooling hats could be dual purpose (additional sun protection) during outdoor sports.

2.12 Timing of cooling application

2.12.1 Pre-cooling

Pre-cooling is based on the concept of starting exercise with a lowered body temperature to widen the temperature margin before reaching a critical limiting T_{core} contributing to fatigue (Quod et al. 2006). It is generally accepted, in the AB, that cooling prior to endurance and intermittent exercise elicits a performance improvement (ES = 0.52 and ES = 0.43, respectively, Wegmann et al. 2012, Tyler et al. 2015, Ross et al. 2013), yet performance benefits are limited when cooling occurs prior to sprint exercise (ES = 0.03, Wegmann et al. 2012). The extent of the performance improvement may also be dependent on the exercise duration, with the effect of pre-cooling decreasing for exercise durations over 60 minutes, potentially due to the limited duration of the cooling effect (Wegmann et al. 2012). To enhance the cooling effect, a combination of methods could be used. Applying these methods simultaneously could also limit the time before an event that needs to be dedicated to pre-cooling (Ross et al. 2013).

To maintain a physiological advantage and enhance performance pre-cooling needs to be provided as close to the start of exercise as possible and potentially during the warm-up (Webborn et al. 2005, Arngrimsson et al. 2004). In light of this, previous cooling research in the AB has sometimes failed to account for the effect of athletes' warm-up prior to competition thus limiting its application in a field environment. Nevertheless, pre-cooling during a warm-up will depend on the body area cooled and the method of cooling. A heavy cooling garment worn during the warm-up may also affect the metabolic cost of exercise, with the intensity of the warm-up needing to be adjusted accordingly (Arngrimsson et al. 2004). Lastly, the cooling intensity of the strategy is particularly important as a sharp

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decrease in T_{core}, T_{sk} or muscle temperature prior to exercise may have a detrimental effect on performance (Wegmann et al. 2012, Faulkner et al. 2013, Sleivert et al. 2001).

Two of the three studies reviewed utilising cooling with ice vests prior to intermittent sprint exercise observed a performance and thermal benefit compared to no cooling (Webborn et al. 2010, Webborn et al. 2005). A combination of pre-cooling using ice vests and cooling hats and neckbands during exercise, to attenuate the rise in T_{core} and thermal sensation, has also been shown to be effective as a case study (Diaper et al. 2009). Therefore, there may be some justification for pre-cooling using ice vests in athletes with an SCI, though further work is greatly needed.

2.12.2 Cooling during exercise/ rest periods

To offset the gains in heat throughout exercise, cooling during exercise has been utilised, predominantly through the use of ice vests. As previously mentioned, the difficulty with this cooling technique is to avoid an adverse effect on performance due to the size, coverage and weight of the cooling garment. Hence, due to this complexity, cooling during exercise has received less research attention than pre-cooling. Although research in the AB shows that it could be just as effective as pre-cooling in improving performance (Bongers et al. 2014).

In addition to cooling during exercise, cooling provided during rest periods between multiple bouts of exercise could be viable for many team sports, i.e. wheelchair courts sports. Strategies employed during these rest periods need to ensure minimal influence on athlete preparation. Due to the limited time athletes are allowed during rest periods/half-time (2-15 minutes depending on the wheelchair court sport) this may not allow for enough cooling exposure, but may provide some benefit compared to no cooling at all. Therefore, to enhance the cooling effect, a combination of both pre-cooling and cooling during rest periods/half-time may be more effective at reducing thermal strain by offsetting heat storage during the subsequent bout of exercise (Price et al. 2009).

Cooling during exercise was utilised in seven reviewed studies (Webborn et al. 2010, Webborn et al. 2005, Armstrong et al. 1995, Bongers et al. 2015, Trbovich et al. 2014, Diaper et al. 2009, Goosey-Tolfrey et al. 2008b) with mixed results. Either performance was improved or T_{core} reduced when using ice vests, cooling vests and cooling hats and neckbands during intermittent exercise for trained wheelchair athletes (Webborn et al. 2010, Webborn et al. 2005, Bongers et al. 2015, Diaper et al. 2009). Though, in a field based environment a

cooling vest had no effect on T_{core} during a game of wheelchair basketball or WCR (Trbovich et al. 2014). During continuous exercise, a refrigerated headpiece and ice vest provided no benefit to trained wheelchair athletes, due to the low cooling potential of the garments (Hagobian et al. 2004, Armstrong et al. 1995). The use of water sprays during rest periods had no thermal or performance effect (Pritchett et al. 2010).

2.12.3 Summary of cooling methods and timing of cooling application

In comparison to the advice that can be gathered from the literature for AB athletes it is difficult to establish the optimal cooling method for athletes with an SCI. This is predominantly due to the lack of studies that have investigated the use of cooling strategies in this population leading to a lack of evidence for each method (Table 2.3). Nevertheless, from the studies reviewed it would appear that wearing an ice vest during intermittent sprint exercise has beneficial effects both in terms of decreasing thermal strain and enhancing performance (Webborn et al. 2010), though contrasting findings have been observed during steady state exercise (Armstrong et al. 1995). Drawing on findings from the AB, the use of ice vests has been shown to be a feasible method of pre-cooling, with a 4.8% improvement in performance (Wegmann et al. 2012). A combination of pre-cooling and cooling during exercise or half-time cooling might also be an effective strategy (Bongers et al. 2014).

2.13 Practical Implications

2.13.1 Exercise Protocol

Only three of the eight studies reviewed mentioned the use of a warm-up and the application of cooling during this time (Webborn et al. 2005). Often an athlete's warm-up is performed at intensities (~40-60% $\dot{V}O_{2max}$, AB research, Woods et al. 2007) that result in an increase in T_{core}. Therefore, excluding a warm-up from the experimental design could affect the practical application of the findings of the reviewed studies. Prospective studies need to ensure the inclusion of a warm-up and, if pre-cooling is being administered, the wearing of cooling garments during this time, if appropriate.

The different cooling strategies combined with the different types of exercise and ambient temperatures used in the reviewed studies makes it difficult to combine results regarding the effectiveness of cooling strategies in an SCI population group. Similarly to research in the AB, the majority of the reviewed studies have neglected to employ a measure of performance specific to the sport, making it difficult to determine if there is a clear performance benefit

associated with a cooling strategy. For application in wheelchair court sports future research should consider employing an ISP that reflects the nature and exercise intensity of the sport in an attempt to mimic a "real-world" sporting environment. Of particular importance is the mode of exercise as differences in thermal strain are elicited depending on the modality, i.e. arm crank vs. wheelchair ergometry (Price et al. 1999a).

2.13.2 Ambient Conditions

Future studies are required to establish the transferability of practical cooling strategies in a laboratory to the field environment (Ross et al. 2013). To achieve this future studies in the SCI athletic population need to be as closely matched as possible to the intended environmental playing conditions. In addition, participants of a highly trained and motivated nature need to be recruited to ensure research findings can be translated into meaningful performance enhancements (Ross et al. 2013). For instance, even in relatively moderate temperatures of 21°C, only 1-2°C higher than an air conditioned sports hall, exercise capacity is reduced and T_{core} is increased compared to in 11°C in the able-bodied (Galloway et al. 1997).

In relation to wheelchair court sports, athletes with an SCI predominantly compete in: i) wheelchair tennis, ii) WCR or iii) wheelchair basketball. The latter two sports are played indoors, suggesting that it should be possible to closely control the ambient playing conditions. How strictly these indoor conditions are regulated is unclear, i.e. air conditioned, with anecdotal evidence suggesting playing conditions vary greatly between training centres and competition venues. In addition to this, the increased potential for thermal strain owing to the intermittent sprint nature of the sports and the impaired thermoregulatory response of individuals with an SCI suggest that cooling strategies could be highly beneficial for athletes with an SCI in these sports. Logistically, due to the practical problems of travelling to venues if athletes with an SCI arrive at venues with an already elevated T_{core}, without sufficient cooling or recovery this may limit their temperature margin before reaching a critical T_{core} during exercise.

For future studies, it is therefore imperative that as well as the exercise protocol and mode of exercise, the ambient conditions match the sport specific playing environment. Practically, when administering any cooling method for athletes with an SCI in wheelchair court sports, in addition to its effectiveness, the specific sporting regulations and logistics of administering

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the cooling method needs careful consideration and co-operation from support staff.

2.14 Conclusions

Upon reviewing the literature, the following points have been highlighted as areas for further investigation.

1. Able-bodied individuals are able to attain heat balance in a wide range of environmental conditions, known as the "prescriptive zone". Yet, the physiological adaptations that occur as a result of an SCI (Figure 2.5) will alter heat loss by dry and, in particular, wet (evaporative) heat exchange. Currently the extent of the changes in evaporative heat loss and heat balance, as a result of an SCI, and the effect lesion level has on this response is unknown. To gain a greater understanding of the thermoregulatory consequences as a result of an SCI, it is essential that the additional metabolic heat production from exercise is removed and studies are conducted at rest.

2. Athletes with TP are an under-studied population group in relation to their thermoregulatory responses during exercise. Even though athletes with TP are known to have a greater thermoregulatory impairment compared to individuals with PA during continuous steady state exercise, the extent of this difference during intermittent sprint wheelchair exercise is not known.

3. To determine the extent of the thermoregulatory impairment for athletes with TP, conducting studies that replicate a "real-world" sporting environment is imperative. For instance, the use of an ISP, wheelchair propulsion and an ambient environment representative of an indoor sports hall.

4. Although laboratory studies can be used to replicate sporting scenarios, field testing enables thermoregulatory responses during actual match play to be determined, taking into account activity profiles and players roles on court. Once the extent of the thermoregulatory impairment in athletes with TP in sporting scenarios (both laboratory and field) is established, the application of practical strategies, for example cooling strategies, which could reduce thermal strain, is of particular importance.

5. The effectiveness of practical cooling strategies for athletes with TP, especially those currently used by wheelchair athletes, warrants further investigation. Fundamental issues that have not been accounted for in the existing literature, such as the inclusion of a warm-up, appropriate mode of exercise, highly trained individuals, ambient

environment representative of the playing environment and a protocol that mimics a "real-world" sporting environment need to be addressed.

Chapter 3

General methods

Several experimental chapters required the use of similar methods. To avoid repetition, methods used in more than one experimental chapter (Chapters 4-7) are described below and are only described in brief in the following experimental chapters.

3.1   Measurement of core temperature

For all experimental chapters, a telemetric pill (HQ Inc, Palmetto, Florida, accuracy = ± 0.1°C, resolution = 0.01°C) was used to measure T_{gi} as an indicator of T_{core}. To ensure consistency between experimental chapters, this method was chosen due to its practicality in field based settings (see Table 2.1) and ease of use in the SCI population. To avoid the influence of ingested food or fluid on the temperature reading (Wilkinson et al. 2008), in accordance with previous recommendations (ingestion of the pill 6 h before data collection) (Byrne et al. 2007), participants ingested a telemetry pill ~8 h prior to the start of each test. Similarly to the AB, gastric mobility and colonic transit times will vary greatly between individuals, however in the SCI population, these have been shown to be delayed compared to the AB (Kao et al. 1999, Williams et al. 2012). Thus, ingesting the pill ~8 h before arriving for testing should have been sufficient time to ensure the telemetric pill was in the gastrointestinal tract. In addition, before each test, participants were asked to take a sip of water to check if the fluid was influencing the temperature reading.

Prior to the experimental chapters, a telemetry pill was calibrated against a mercury filled thermometer (accuracy ±0.1°C) by immersion in a water bath (Camlab Clifton water bath, Cambridge, UK). The pill was immersed at a set of temperatures within the expected physiological range (36-39.7°C thermometer readings) and recorded via the Cortemp data logger (HQ Inc, Palmetto, Florida). The difference between the Cortemp data logger and thermometer values, at the temperatures employed, were all below 0.1°C.

3.2　Measurement of skin temperature

In Study 2 (Chapter 5) skin thermistors were used for the measurement of skin temperature at seven regional sites, whereas iButtons were used in Study 3 (Chapter 6) at the same regional sites. IButtons were also used in Study 1 (Chapter 4) and Study 4 (Chapter 7) with additional skin sites. In Studies 1 and 4 (Chapters 4 and 7), an additional iButton was placed at the abdomen (5 cm adjacent to the umbilicus). In Study 1 (Chapter 4) iButtons were also placed at the hand (middle of dorsal side of the hand) and foot (middle of dorsal side of the foot) to enable a greater representation of the whole body skin surface. These skin temperature measurement sites are shown in Figure 3.1.
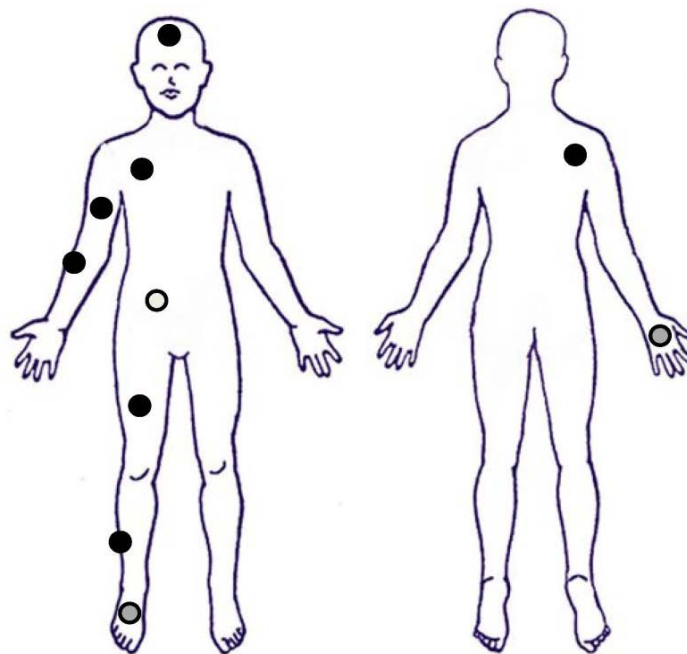
Figure 3.1 Skin temperature measurement sites depicted by black circles (used in Studies 1-4), light grey circle (additional skin site used in Studies 1 and 4) and dark grey circles (additional skin sites used in Study 1).

Both skin thermistors (Grant Instruments, Cambridge, UK, accuracy ± 0.1°C) and iButtons (DS1922T, Maxim Integrated Products, Inc., Sunnyvale, CA, USA) were attached to the skin using strips of soft cloth surgical tape (3M Medipore, Loughborough). They were placed on the forehead (centre of forehead 1cm below hairline) and right side of the body on the forearm (junction of the proximal one-third and distal two-thirds of the extensor aspect in the midline of the forearm), upper arm (midline of the muscle belly of biceps), upper back (centre of the superior border of the scapula in the midclavicular line), chest (centre of the

muscle belly of pectoralis major in the midclavicular line), thigh (junction of the distal one-third and proximal two-thirds of the anterior quadriceps muscle belly) and calf (mid-point of the calf on the lateral aspect. These measurement sites have been used previously in SCI research (Price et al.1999a, Price et al. 1999b, Price et al. 2003, Price et al. 2008). Skin thermistors were connected to a Grant Squirrel logger (Series 2010, Grant Instruments, Cambridge, UK). Prior to the experimental conditions, the thermistors were calibrated against a mercury filled thermometer (accuracy $\pm$ 0.1°C) by immersion in a water bath (Camlab Clifton water bath, Cambridge, UK). The thermistors were immersed at a set of temperatures within the expected physiological range; (25-40°C thermometer readings). The difference between the Grant Squirrel logger and thermometer values and the iButtons and thermometer values at the temperatures employed, were all below 0.1°C and 0.3°C, respectively.

3.3 Calculation of mean skin temperature

Although a formula for T_{sk} has not been developed specifically for individuals with an SCI, in all experimental chapters T_{sk} was estimated in accordance with the formula by Ramanathan (Ramanathan 1964). The Ramanathan formula is a recommended method, especially in field studies (Mitchell et al. 1969) and has been used previously for individuals with an SCI and so would allow comparison between studies (Pritchett et al. 2010, Webborn et al. 2010, Webborn et al. 2005). In addition the formula uses skin sites above and below the lesion level.

$$T_{sk} = 0.3t_{chest} + 0.3t_{arm} + 0.2t_{thigh} + 0.2t_{calf} \qquad (1)$$

Where: t_{chest} = chest skin temperature, t_{arm} = upper arm skin temperature, t_{thigh} = thigh skin temperature, t_{calf} = calf skin temperature.

3.4 Laboratory based exercise testing

A motorised treadmill was used in Studies 2-4 (Chapters 5-7) for the determination of $\dot{V}O_{2peak}$ (Figure 3.2). For the ISP's described in Studies 2 and 4 (Chapters 5 and 7) a wheelchair ergometer (WERG) was used. These devices are described below.

3.4.1 $\dot{V}O_{2peak}$ testing – treadmill

In Studies 2-4, a continuous speed incremental test on a motorised treadmill (HP Cosmos, Traunstein, Germany) was conducted to determine $\dot{V}O_{2peak}$. For this test, participants used their own sports wheelchair which was mounted on the treadmill (Figure 3.2). The

wheelchair was secured to a safety bar running half way down the side of the treadmill, allowing the wheelchair to move freely back and forth, but preventing movement sideways. The back end of this safety bar was fitted with a spring. Since tyre pressure can influence rolling resistance (Sawatzky et al. 2005) pressure was set to normal training/competition levels for each individual (80-150 psi). Firstly, a self-selected 5-10 min warm-up was performed, followed by 5 min passive recovery. For the $\dot{V}O_{2peak}$ test, the starting speed varied between 1.2 m·s^{-1} and 2.0 m·s^{-1} and was chosen according to disability, classification and previous test results (if available). The gradient of the treadmill was held at 1% (Mason et al. 2014) throughout the test. The workload was increased by 0.2 or 0.3 m·s^{-1} every 3 min (dependent on the individual's classification), to achieve a test time of 8-14 min. The test was terminated when the participant reached volitional exhaustion and could no longer maintain the speed of the treadmill (Leicht et al. 2014). Repeatedly touching the spring, fitted to the safety bar, served as a further indication of exhaustion. A slower starting speed and smaller speed increments were adopted for participants with an SCI with higher lesion levels (Studies 2 and 4) and for lower point players (Study 3).

Figure 3.2 Treadmill used for $\dot{V}O_{2peak}$ preliminary testing.

During the $\dot{V}O_{2peak}$ test, heart rate was recorded continuously at 5-s intervals using a heart rate monitor (Polar PE 4000, Kempele, Finland). Participants were also asked to indicate their RPE on a 6-20 scale at the end of each 3 min stage (Borg 1970). A small capillary blood sample (20 µl) was obtained from the earlobe to measure blood lactate (BLa) at the end of each 3 min stage. Lactate concentration in haemolysed whole blood was assessed using the lactate analyser, YSI 1500 SPORT (YSI Incorporated, Ohio, USA) in Study 2 and the Biosen

C-Line (EKF Diagnostic GmbH, Barleben, Germany) in Studies 3 and 4 (Chapters 6 and 7). Both lactate analysers were calibrated before each test using a lactate standard solution of 5 mmol·l^{-1} and 12 mmol·l^{-1} for the YSI and Biosen, respectively.

Ventilatory data were recorded continuously using an online gas analysis system in breath by breath mode (MetaLyzer 3B, Cortex Biophysik GmbH, Leipzig, Germany). Before each test, gases were calibrated using a two-point calibration (O_2 = 17.0 %, CO_2 = 5.0 % against room air) and volumes with a 3 L syringe at flow rates of 0.5–3.0 L·s^{-1}, according to the manufacturer's recommendations. Peak values for all ventilatory data were defined as the highest 30 s rolling average of the test.

3.4.2   Intermittent sprint protocol - Wheelchair ergometer

For the ISP in Studies 2 and 4 (Chapters 5 and 7), a wheelchair ergometer (WERG) was used. A single cylinder WERG (Bromakin, Loughborough, UK) interfaced with a computer (Compaq Armada 1520, Series 2920A, Compaq Computer Corporation, Taiwan) was used in Study 2. A flywheel sensor connected to the roller and interfaced to a computer calculated wheelchair velocity and displayed it visually on a computer monitor. Due to changes in laboratory equipment, for Study 4 a dual-roller WERG comprising of two pairs of independent rollers was used (VP Handisoft-25, Medical Developpment Hef Groupe, Andreziuex Boutheon, France). The WERG was equipped with two electromagnetic brakes, which have the capabilities to produce a braking torque of 0 Nm to 4 Nm, on both the left and right sides of the roller system. Before each test the sensor of each brake was calibrated with a known weight. On this WERG, following recommendations for wheels with camber (Devillard et al. 2001), all testing was performed on the rear roller on the left and right side to minimise resistance. The left and right rollers were independently capable of real time measuring velocity, torque and the angle of rotation at 100 Hz, which was fed back in real time through a computer monitor (HP Compaq LA1951g, Hewlett Packard, California, USA). Both WERG systems are shown in Figure 3.3.

For testing on both WERG's, participants were set up in their own sports wheelchair and tyre pressure was set to normal training/competition levels for each individual (80-150 psi). During the warm-up participants performed a deceleration test, to allow resistance to be calculated according to the principles described by Theisen et al. (1996). The deceleration test also ensured equal resistance on each side of the dual roller by calculating individual residual torque for both left and right rollers. To perform the deceleration test, the participant

accelerated the wheelchair for 5 pushes, then adopted an upright position with their hands placed on their knees, during which time the roller system decelerated to a complete standstill. The velocity was recorded as the chair slowed to a standstill and the average deceleration calculated from the slope of this velocity-time data. This enabled residual torque to be calculated, which is representative of rolling resistance. For the single roller WERG used in Study 2, typical rolling resistance values have been previously shown to be 22 ± 5 N for wheelchair athletes with a body mass of 74.8 ± 19.6 kg (Lenton et al. 2008). During the deceleration test in Study 4 using the dual roller, in accordance with physiological assessments in our laboratory, the braking load was kept at an individual residual torque that was sport-specific and representative of the wheelchair-user interface of WCR (proportional to the mass of the participant and wheelchair combined), ranging from 0.5-1.12 Nm. Power output was calculated by multiplying the average speed by the rolling resistance of the wheelchair-user combination (Mason et al. 2015).
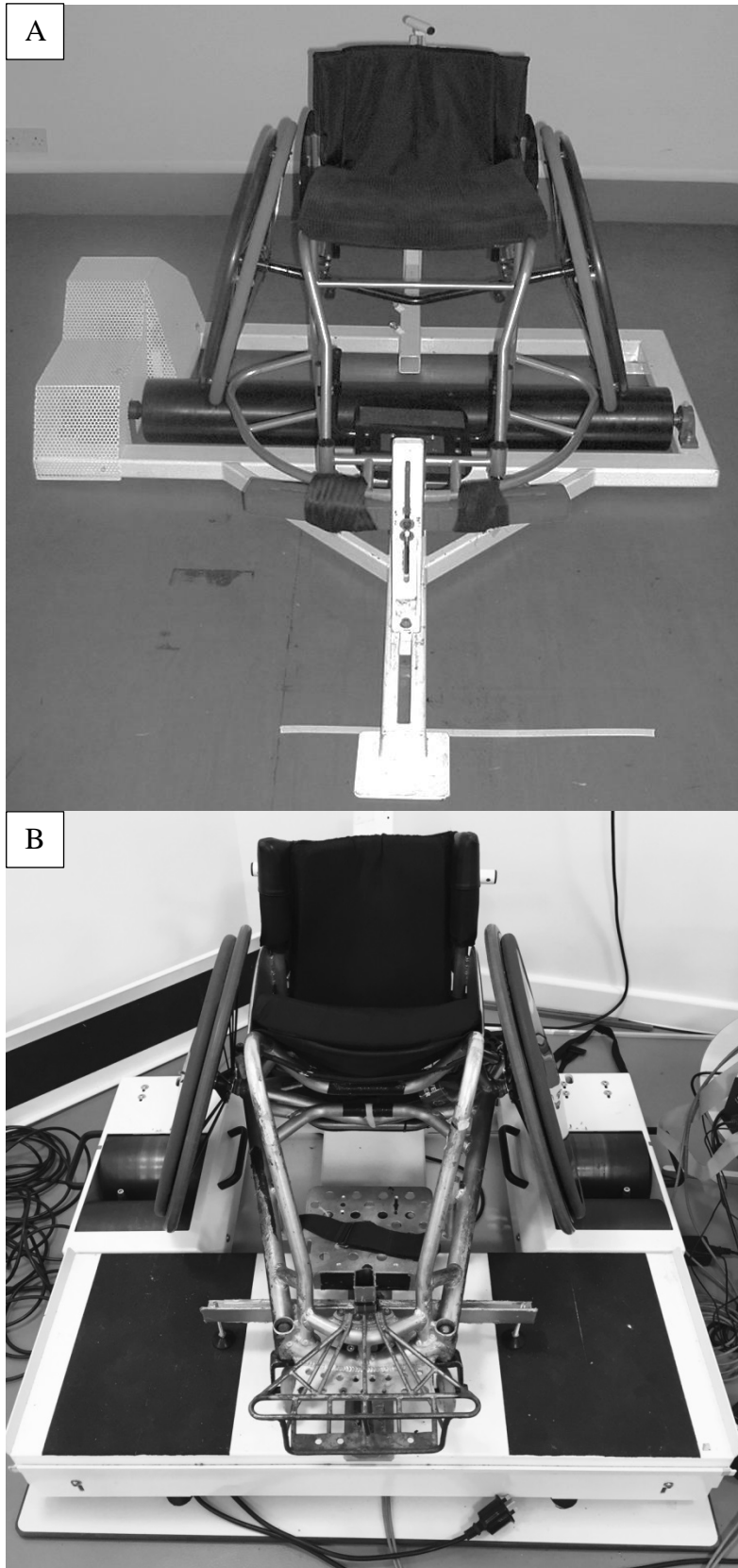
Figure 3.3 Wheelchair ergometers used in A) Study 2 (single cylinder wheelchair ergometer, Bromakin) and B) Study 4 (dual-roller wheelchair ergometer, VP Handisoft-25).

Chapter 4

Study 1: Differences in evaporative heat loss between the able-bodied and individuals with a spinal cord injury of different lesion level

4.1 Abstract

Purpose: Individuals with an SCI have a loss of sweating capacity and vasomotor control below their lesion level. No previous study has investigated how the heat exchange avenues, in particular evaporative heat loss, are altered in individuals with an SCI and the thermoregulatory consequences as a result. Thus the purpose of this study was to determine the extent of the changes in evaporative heat loss and heat balance at rest as a result of an SCI and the effect lesion level has on this response.

Methods: A total of 23 male participants volunteered for this study, consisting of eight able-bodied individuals (AB), eight individuals with PA and seven individuals with TP. Participants rested in a climatic chamber set at 37°C and 20% relative humidity (RH) for 20 mins. The RH was then increased by 5% every 7 minutes, (ambient temperature remained constant), until the participant's T_{gi} showed a clear inflection or increased by 1°C from initial values. Gastrointestinal temperature, skin temperatures, HR and respiratory and perceptual responses (thermal sensation, thermal comfort and wetness sensation) were measured throughout.

Results: Metabolic heat production was similar between groups (p = 0.20, ES = 0.4-0.8) and so the required rate of evaporative cooling for heat balance (E_{req}) was also similar (p = 0.92, ES = 0.1-0.2). TP had a greater change in T_{gi} compared to AB (p = 0.01, ES = 1.5), whilst HR was not different between groups (p = 0.43). Both PA (p = 0.01, ES = 1.45) and TP (p = 0.01, ES = 1.98) had a greater change in T_{sk} than AB. There was no difference between groups for any of the perceptual responses.

Conclusions: Despite metabolic heat production and thus E_{req} being similar between groups, the present resting study provides evidence that evaporative heat loss in TP is not large enough to balance the heat load in order to attain heat balance. Although PA possesses a greater sweating capacity than TP, the continual increase in both T_{gi} and T_{sk} signifies at temperatures above T_{sk} latent heat loss is insufficient to attain heat balance compared to AB. Consequently both PA and TP require effective heat loss strategies when evaporation is the primary avenue for heat loss.

4.2 Introduction

Body core temperature is regulated within a narrow range in humans, with severe health consequences if there are more than a few degrees deviation (Parsons 2003). Thus the body maintains a dynamic balance between internal heat production and the rate of heat dissipation to the environment. The latter being through the heat exchange avenues of convection, conduction, radiation and evaporation. Any imbalance between heat production and heat dissipation results in an increase in T_{core} (Parsons 2003), leading to increases in HR, skin temperature and sweat rate.

Over a wide range of environments, T_{core} of the able-bodied is able to equilibrate at levels proportional to metabolic rate, known as the "prescriptive zone" (Lind 1963, Figure 2.2) and is thus independent of ambient conditions. Above this designated zone, T_{core} is forced out of equilibrium, resulting in a continuous rise in T_{core} and the attainment of a critical environmental limit (Kenney et al. 2002). In contrast, the physiological adaptations that occur as a result of an SCI, shown in Figure 2.5, such as a loss of sweating capacity and vasomotor control below their lesion level, indicate that heat balance may be difficult to attain for individuals with an SCI across the same range of environments. The higher the lesion level the smaller the surface area of sensate skin (Normell 1974, Guttmann et al. 1958), resulting in a reduction in sweating capacity and hence evaporative heat loss. Thus the avenues of heat exchange, in particular evaporative heat loss, will be altered as a result of an SCI, but the extent of this compared to the able-bodied and its subsequent effect on heat balance is currently unknown.

Individuals with an SCI are largely reported to have a lower resting energy expenditure than the able-bodied (Liusuwan et al. 2007, Monroe et al. 1998), due to the muscular atrophy of the lower limbs and a reduction in the available sympathetic nervous system (Buchholz et al. 2004). Thus, while these individuals may be less efficient at dissipating heat, due to a lower resting energy expenditure they would produce less heat than the able-bodied. To gain a greater understanding of the thermoregulatory consequences as a result of an SCI, it is imperative that studies are conducted at rest, removing the additional metabolic heat production from exercise.

In regards to the dissipation of heat, no previous study has investigated how the heat exchange avenues are altered as a result of an SCI and the thermoregulatory consequences as

a result. One would expect that lesion level is likely to play an important role in the rate of heat dissipation and the subsequent attainment of heat balance. For instance, individuals with PA, who have a greater sweating capacity than individuals with TP, may be able to attain heat balance within a "prescriptive zone", but may reach a critical environmental limit prior to the able-bodied, i.e. a shift in prescriptive zone would be expected.

Therefore, the aim of this study was to determine how evaporative heat loss and heat balance are altered as a result of an SCI compared to the able-bodied and the effect lesion level has on this response. Experimental sessions were conducted at rest, in hot conditions (37°C) using a stepwise protocol, based on the experimental design of previous studies (Kenney et al. 2002, Kamon et al. 1976, Kamon et al. 1978, Kenney et al. 1993, Ravanelli et al. 2016). The chosen experimental design aimed to minimise heat loss from dry heat exchange, remove the additional heat load from exercise and reduce the water vapour pressure gradient throughout the protocol, progressively increasing the thermal stress of the environment by hindering evaporative heat loss. It was hypothesised that the able-bodied group (AB) would be able to attain heat balance for the majority of the protocol with clear critical environmental limits, whilst in individuals with PA heat balance would be attained initially but a critical limit would be reached prior to AB. In contrast, evaporative heat loss would be greatly hindered for individuals with TP and individuals would experience a continual increase in T_{core} starting during the early stages of the protocol.

4.3 Methods

4.3.1 Participants

A total of 23 male participants were recruited for this study, consisting of eight able-bodied individuals (AB), eight individuals with PA and seven individuals with TP (Table 4.2). All participants were recreationally active and participated in exercise at least three times a week. Participants gave their written informed consent to participate in this study, approved by the Loughborough University Research Ethics Committee.

4.3.2 Experimental design

Participants were instructed to refrain from alcohol, caffeine and strenuous exercise 24 h prior to testing. All trials were conducted at the same time of day to negate circadian variation (Winget et al. 1985). Prior to arrival at the laboratory, participants ingested a telemetric pill (HQ Inc, Palmetto, Florida) 6-8 hours prior to experimental sessions for the measurement of T_{gi}, as an indicator of T_{core}, previously described in Section 3.1. Upon arrival at the laboratory, participants completed both a health and heat tolerance questionnaire (Appendix B). The heat tolerance questionnaire was used to check if participants had previously experienced hot and/or humid environmental conditions plus how they usually felt in these conditions. Skinfold measurements (Harpenden Skinfold Callipers, Baty International, West Sussex, UK) were taken from the biceps, triceps, subscapular and suprailliac sites to calculate a sum of skinfolds (mm). Body fat percentage, using the Durnin and Wormsley four site method (Durnin et al. 1974), plus fat and fat free mass were calculated using age appropriate equations stated below.

$$20\text{-}29 \text{ yrs} \tag{1}$$
$$\text{Body density (g/ml)} = 1.1631 - (0.0632 \cdot \log(\text{sum of four skinfolds})$$

$$30 - 39 \text{ yrs} \tag{2}$$
$$\text{Body density (g/ml)} = 1.1422 - (0.0544 \cdot \log(\text{sum of four skinfolds})$$

$$40 - 49 \text{ yrs} \tag{3}$$
$$\text{Body density (g/ml)} = 1.1620 - (0.0700 \cdot \log(\text{sum of four skinfolds})$$

$$> 50 \text{ yrs} \tag{4}$$
$$\text{Body density (g/ml)} = 1.1715 - (0.0779 \cdot \log(\text{sum of four skinfolds})$$

$$\text{Body fat (\%)} = \left(\frac{457}{\text{body density}}\right) - 414.2 \tag{5}$$

$$\text{Fat mass (kg)} = \text{body mass} \cdot \left(\frac{\text{body fat \%}}{100}\right) \tag{6}$$

$$\text{Fat free mass (kg)} = \text{body mass} - \text{fat mass} \tag{7}$$

Skin temperature was measured at 10 sites using iButtons (DS1922T, Maxim Integrated Products, Inc., Sunnyvale, CA, USA), which were applied to the forehead and on the right side of the body at the forearm, upper arm, chest, abdomen, upper back, thigh, calf, hand and foot, previously described in Section 3.2. Prior to entering the climatic chamber (T.I.S.S.

Peak Performance, Series 2009), measures of blood pressure (Model M2 Basic, Omron Healthcare Co Ltd, Kyoto, Japan), HR (Polar PE 4000, Kempele Finland), T_{gi} and perceptual measures of thermal comfort, thermal sensation and wetness sensation were taken in the preparation room (25.8 ± 0.4°C and 30.5 ± 4.1 %). The thermal sensation scale, comprised of categories ranging from 0 ("unbearably cold") to 8 ("unbearably hot") in 0.5 increments (Toner et al. 1986). The thermal comfort scale ranged from 1 ("comfortable") to 4 ("very uncomfortable") in 1 increments (Gagge et al. 1969). The wetness sensation scale ranged from 0 ("dry") to 6 ("dripping wet") in 1 increments (modified scale from Ha et al. 1995).

To standardise clothing, all participants were given a pair of shorts and short sleeved t-shirt to wear during testing. Participants wore their own socks and sports shoes. Euhydration was confirmed for all participants (urine specific gravity <1.025, Meta Scientific Ltd, Surrey, UK) and participants were weighed (Mettler Toledo KCC 150, Leicester, UK, resolution 1g) before entering the climatic chamber.

Throughout the protocol, PA and TP remained in their daily wheelchair, whilst AB participants remained seated in a similar wheelchair provided. The climatic chamber was initially set at 37°C and 20% RH. Participants sat for an initial 20 min stabilisation period, after which the RH was increased stepwise by 5% every 7 minutes, whilst the ambient temperature was kept constant (37.2°C ± 0.2°C throughout all trials). The ambient temperature and RH inside the climatic chamber were measured throughout (Testo 435, Testo AG, Germany, resolution 0.1°C and 0.1% RH). The mean ± SD of RH across all trials are shown in Table 4.1. The RH settings of the climatic chamber will be used in the results section (both in the text and figures). The duration of each stage, starting RH and climatic chamber settings were determined through pilot work, using the stepwise protocols noted previously (Kenney et al. 2002, Kamon et al. 1976, Kamon et al. 1978, Kenney et al. 1993, Ravanelli et al. 2016). Each participant was informed that the RH would increase during the protocol but were not told the initial starting RH or when the RH was being increased.

Table 4.1 The relative humidity of all trials measured inside the climatic chamber (Testo 435) and the set climatic chamber settings. All data are shown as mean ± SD.

Relative humidity (%) measured by the Testo 435	Climatic chamber settings (%)[a]
29 ± 0	25
33 ± 0	30
38 ± 0	35
43 ± 1	40
49 ± 2	45
54 ± 1	50
58 ± 2	55
62 ± 2	60
66 ± 1	65
70 ± 2	70
74 ± 2	75
78 ± 2	80
82 ± 2	85
84 ± 1	90

[a]The RH inside the chamber and the RH of the climatic chamber settings were not significantly different ($p = 0.95$).

4.3.3 Thermoregulatory and perceptual responses

Gastrointestinal temperature, skin temperatures and HR were measured continuously throughout the protocol. Expired air was recorded continuously throughout the test using a calibrated online gas analysis system in breath by breath mode (Metamax, Cortex Biophysik GmbH, Leipzig, Germany). Measurements of thermal comfort, thermal sensation and wetness sensation were taken during the last minute of each 7 min stage. Blood pressure was taken during the last minute of each 7 min stage.

Mean arterial pressure (MAP) was calculated from the following equation:

$$\text{MAP(mmHg)} = \frac{\text{systolic blood pressure} + 2 \cdot (\text{diastolic blood pressure})}{3} \quad (8)$$

Participants were removed from the chamber when their T_{gi} displayed a clear inflection point (critical environmental limit, Kenney et al. 2002), shown in Figure 4.1, or their T_{gi} increased by 1°C from their initial T_{gi} upon entering the chamber. Figure 4.1 displays pilot data, hence the participant was not removed directly after the inflection point in T_{gi} was reached.
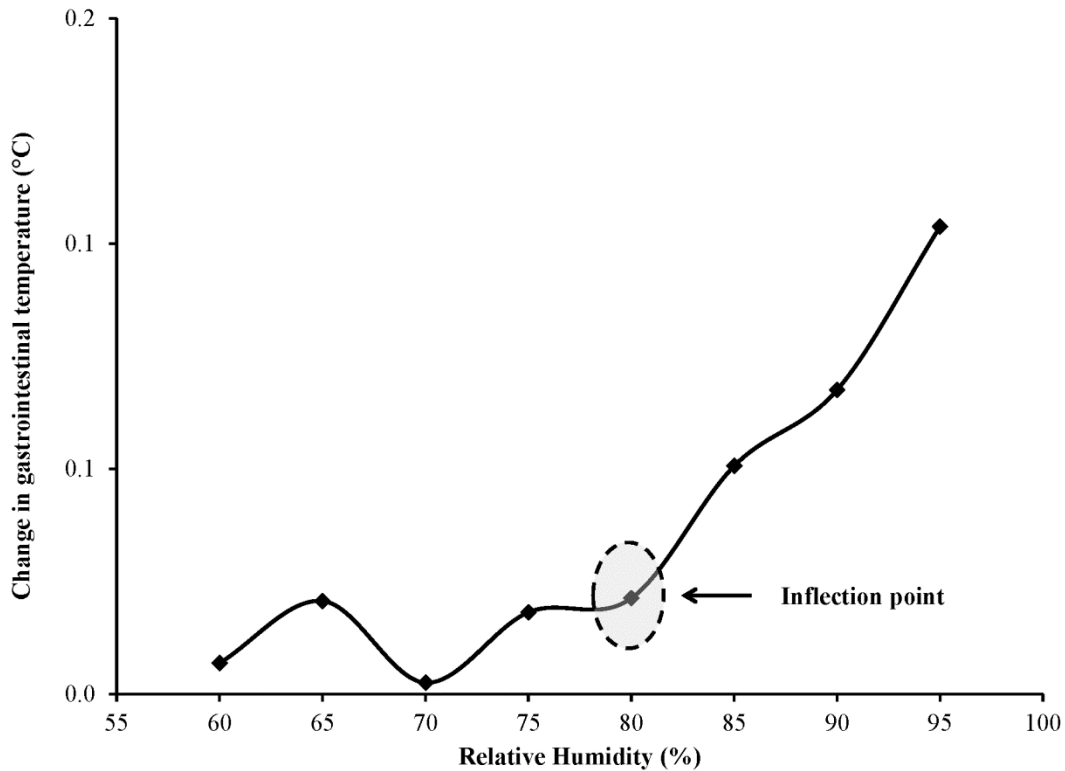
Figure 4.1 Determination of the inflection point from gastrointestinal temperature data of an able-bodied participant during pilot work. Each data point represents the average value during the last minute of each stage. The pilot work was conducted at rest in constant environmental temperature (37°C) and increasing humidity. The inflection in gastrointestinal temperature is depicted by the grey shaded circle at 80% relative humidity. Note: for the pilot work, relative humidity was increased, following a 20 min stabilisation period at 55%, whereas in the actual trial relative humidity was increased after a 20 min stabilisation period at 20% relative humidity.

Mean skin temperature was calculated in accordance with the formula by Ramanathan (Ramanathan 1964), previously described in Section 3.3.

Mean body temperature (Tb) was estimated using the formula below:

$$T_b \ (°C) = (0.8 \cdot T_{gi} + 0.2 \cdot T_{sk}) \tag{9}$$

4.3.4 Fluid balance

Participants were allowed to drink water *ad libitum* except for during the last minute of each 7 min stage to prevent interference with respiratory measures. Fluid consumption was measured and the temperature of the water was kept at the temperature of the chamber to prevent any cooling effect of the fluid on the participant. Upon removal from the climatic chamber and towel drying their skin, participants were re-weighed and another urine sample was taken to measure urine specific gravity. In addition to the absolute change in body mass ($Mass_{pre}$ - $Mass_{post}$), the change in body mass relative to fluid consumed (total mass loss) was also calculated (($Mass_{pre}$ - $Mass_{post}$) + fluid consumed).

4.3.5 Ventilatory data and heat balance calculations

Saturated water vapour pressure (P_{sa}), saturated skin vapour pressure (P_{sk}) and partial pressure of water in ambient air (P_a) were calculated using the following equations (Parsons 2003).

$$P_{sa}(kPa) = \frac{e^{(18.956-(4030.18 \div T_a+235))}}{10} \tag{10}$$

$$P_{sk}(kPa) = \frac{e^{(18.956-(4030.18 \div T_{sk}+235))}}{10} \tag{11}$$

$$P_a(kPa) = (\Phi \cdot 0.01) \cdot P_{sa} \tag{12}$$

Where: Ta is the ambient temperature and Φ is the RH.

Tidal volume, minute ventilation, breathing frequency, respiratory exchange ratio (RER), oxygen consumption ($\dot{V}O_2$) and volume of exhaled carbon dioxide ($\dot{V}CO_2$) were calculated for the end of each stage. Metabolic energy expenditure (M) was obtained from minute-average values for $\dot{V}O_2$ in litres per minute and RER collected with the metabolic cart. The calibration process is previously described in Section 3.4.1. Metabolic energy expenditure was calculated using the equation below:

$$M \ (W \cdot m^2) = \dot{VO_2} \frac{\left(\frac{RER - 0.7 \ \cdot e_c}{0.3}\right) + \left(\frac{1 - RER \ \cdot e_f}{0.3}\right)}{60 \ \cdot BSA} \cdot 1000 \tag{13}$$

Where: e_c is the caloric equivalent per litre of oxygen for the oxidation of carbohydrates (21.13 kJ), and e_f is the caloric equivalent per litre of oxygen for the oxidation of fat (19.62

79

kJ). Body surface area (BSA) was calculated using the Dubois formula (Dubois et al. 1916). Since the rate of external work (W) was assumed to be 0 W·m² (i.e. any work on surrounding objects was negligible, Parsons 2003), metabolic energy expenditure was taken to be equal to metabolic heat production (M-W).

Radiative heat exchange (R), convective heat exchange (C), evaporative (E_{res}) and convective respiratory heat exchange (C_{res}) and required rate of evaporative cooling (E_{req}) were also calculated using the following equations:

$$R(\text{W·m}^2) = h_r \cdot (T_{sk-}T_a) \tag{14}$$

$$C\ (\text{W·m}^2) = h_c \cdot (T_{sk} - T_a) \tag{15}$$

$$C_{res} + E_{res}\ (\text{W·m}^2) = (0.0014 \cdot M \cdot (34 - T_a) + 0.0173 \cdot M \cdot (5.87 - P_a)) \tag{16}$$

$$E_{req}\ (\text{W·m}^2) = M - W + C + R + C_{res} + E_{res} \tag{17}$$

Where: h_c is the convective heat transfer coefficient (estimated at 3.1 W·m^{-2} k^{-1} when air velocity is less than 0.2 m/s$^-$1, Mitchell 1974) and h_r is the radiative heat transfer coefficient (estimated at 4.7 W·m^{-2} k^{-1} for typical indoor conditions, ASHRAE 1997).

4.3.6   Statistical Analysis

All data were analysed using the Statistical Package for Social Sciences (version 19, SPSS Chicago, IL). Delta HR, T_{gi}, T_{sk} and individual skin temperatures were calculated from the change from the last minute of the 20 min stabilisation period. Data analysis for T_{gi}, T_{sk}, individual skin temperatures, HR, ventilatory data and heat balance calculations were conducted on the average value during the last minute of each stage (data points shown in figures). Statistical analysis was conducted for repeated measures up to 65% RH. All 23 participants were tested up until 65% RH after which a number of participants from PA and TP were removed due to a ≥ 1°C change in T_{gi}. The number of participants at each time point are noted in Figure 4.2, 4.3 and 4.6. To account for the reduced number of participants tested at 70-90% RH, corrected lines were calculated in Figure 4.2, Figure 4.3 and Figure 4.6 for the change in T_{gi}, T_{sk} and HR to indicate the expected trend if participants had not been removed

from the chamber. To calculate the corrected data the difference between each time point (after 65% RH) for each individual was calculated. The average differences for each time point were then added to the previous time point to estimate data points for 70-90% RH. For AB an inflection point in T_{gi} was determined grapically. A line was drawn between the data points starting from 25% RH. When the T_{gi} slope started to deviate upward, a second line was drawn from the point of departure from the first line. This point was defined as the inflection point, a method previoulsy used in Kenney and Zeman (2002). For ventilatory data and the heat balance calculations, data from six AB participants were used due to missing data as a result of equipment error.

Distribution and normality of data were assessed using the Shapiro–Wilk test. For data violating normality and homogeneity assumptions, logarithmic or square-root conversions were applied. For one way ANOVA analysis, if these conversions failed to correct the skew and heterogeneity, a Kruskal-Wallis test was used. To analyse any between group differences in participant characteristics, fluid balance, T_{gi}, T_{sk}, individual skin temperatures sites, HR and MAP at both the start and at 65% RH, a one way ANOVA was used. Thermoregulatory responses, HR, MAP, respiratory responses and perceptual responses during the protocol were analysed using a mixed method ANOVA. Where significance was obtained, post hoc pairwise comparisons with a Bonferroni correction were conducted. Main effects and interactions were accepted as statistically significant when $p \leq 0.05$. A main effect of time corresponded to a step increase in RH. Confidence intervals (95% CI) for differences are presented, alongside effect sizes (ES) to supplement important findings. Effect sizes were calculated as the ratio of the mean difference to the pooled standard deviation of the difference. The magnitude of the ES was classed as trivial (<0.2), small ($0.2–0.6$), moderate ($0.6–1.2$), large ($1.2–2.0$) and very large (≥ 2.0) based on previous guidelines (Batterham et al. 2006). All data are expressed as mean ± SD. An *a priori* power analysis, conducted in G*Power 3.1, revealed a minimum sample size of 6 participants was required per group, with 90% power and an α of 5%, based on findings from Price et al. (2008). Given the heterogeneity of the population group, additional participants were recruited to increase statistical power.

4.4 Results

4.4.1 Participant characteristics

Participant characteristics for all three groups are shown in Table 4.2. Individuals with PA were significantly older than both AB ($p < 0.01$, ES = 2.8) and TP ($p < 0.01$, ES = 1.0). Compared to AB, sum of skinfolds and percentage body fat were larger in PA ($p = 0.02$, ES = 1.4 and $p < 0.01$, ES = 2.0 for sum of skinfolds and percentage body fat, respectively) and TP ($p = 0.04$, ES = 2.3 and $p < 0.001$, ES = 2.5 for sum of skinfolds and percentage body fat, respectively). Compared to AB, fat mass was larger ($p < 0.001$, ES = 1.5) and fat free mass smaller ($p = 0.04$, ES = 0.9) in PA.

Table 4.2 Participant characteristics for able-bodied individuals (n = 8), individuals with paraplegia (n = 8) and individuals with tetraplegia (n = 7).

	Age (years)	Height (m)	Body mass (kg)	Sum of four skinfolds (mm)	Body fat (%)	Fat mass (kg)	Fat free mass (kg)	Body surface area (m^2)	Body surface area/mass (cm^2·kg^{-1})	Lesion level (range)	Completeness of lesion (number of participants)
Able-bodied	28 ± 5	1.88 ± 0.07	75.99 ± 2.86	31.5 ± 9.4	14.4 ± 3.3	11.0 ± 2.9	65.0 ± 2.0	1.96 ± 0.05	259 ± 10	n/a	n/a
Paraplegia	45 ± 7 [§#]	1.77 ± 0.06	77.41 ± 7.26	61.8 ± 28.2 [§]	25.5 ± 7.3 [§]	17.5 ± 9.8 [§]	57.1 ± 4.6 [§]	1.94 ± 0.11	251 ± 12	T3-T12	Complete (5), Incomplete (3)
Tetraplegia	32 ± 3	1.80 ± 0.09	73.78 ± 12.24	58.3 ± 13.7 [*]	21.5 ± 2.1 [*]	16.0 ± 3.8	57.8 ± 8.6	1.92 ± 0.20	263 ± 19	C5/6-C6/C7	Complete (2), Incomplete (5)

§ = significant difference between individuals with paraplegia and able-bodied individuals, # = significant difference between individuals with tetraplegia and individuals with paraplegia, * = significant difference between individuals with tetraplegia and able-bodied individuals. Sum of skinfolds from biceps, triceps, subscapular and suprailliac sites. Body fat percentage, was calculated using the Durin and Wormsley four site method (Durnin et al. 1974), whilst body surface area was calculated using the Dubois formula (Dubois et al. 1916).

4.4.2 Thermoregulatory responses

Gastrointestinal temperature was not significantly different at the start of the 20 min stabilisation period (37.22 ± 0.29°C, 36.91 ± 0.40°C and 37.11 ± 0.45°C for AB, PA and TP, respectively, $p = 0.18$). The change in T_{gi} over the stabilisation period was also not significantly different between groups (0.05 ± 0.06°C, 0.16 ± 0.14°C, 0.23 ± 0.24°C for AB, PA and TP, respectively, $p = 0.08$). There was a main effect of time ($p < 0.001$) and an interaction effect ($p < 0.001$) for change in T_{gi} during the stepwise protocol. The change in T_{gi} was smaller in AB than for TP ($p = 0.01$, 95% CI $= 0.07$ to 0.47, ES $= 1.5$, Figure 4.2) from 30% to 65% RH. Despite not being statistically significant, a moderate ES was revealed between AB and PA for the change in T_{gi} (ES $= 0.8$). Gastrointestinal temperature at 65% RH was significantly cooler in AB (37.43 ± 0.25°C, $p < 0.001$, ES $= 2.6$) and PA (37.53 ± 0.45°C, $p = 0.01$, ES $= 1.5$) than in TP (38.16 ± 0.37°C). The inflection point for T_{gi} for AB occurred at 80% RH.

Mean skin temperature was not significantly different at the start of the 20 min stabilisation period (34.34 ± 0.65°C, 34.27 ± 0.90°C and 34.14 ± 1.05°C for AB, PA and TP, respectively, $p = 0.91$). The change in T_{sk} over the stabilisation period was also not significantly different between groups (1.54 ± 0.46°C, 1.45 ± 0.22°C and 1.88 ± 0.33°C for AB, PA and TP, respectively, $p = 0.07$). There was a main effect of time ($p < 0.001$) and an interaction effect ($p < 0.001$) for change in T_{sk}. The change in T_{sk} was significantly greater, compared to AB, for PA ($p = 0.01$, 95% CI $= 0.14$ to 0.98, ES $= 1.5$) and TP ($p = 0.01$, 95% CI $= 0.29$ to 1.03, ES $= 2.0$) across all humidity levels (Figure 4.3). Mean skin temperature at 65% RH was significantly warmer, compared to AB (36.25 ± 0.36°C), in PA (36.91 ± 0.56°C, $p = 0.05$, ES $= 1.3$) and TP (37.45 ± 0.58°C, $p < 0.001$, ES $= 2.5$).

Mean body temperature was significantly cooler in AB ($p = 0.02$, ES $= 1.6$) and PA ($p = 0.04$, ES $= 1.2$) than TP throughout the protocol. Mean body temperature was significantly cooler in AB (37.19 ± 0.24°C, $p = 0.001$, ES $= 2.5$) and PA (37.40 ± 0.46°C, $p = 0.02$, ES $= 1.4$) compared to TP (38.01 ± 0.41°C) at 65% RH.

Figure 4.2 Change in gastrointestinal temperature at rest in constant environmental temperature (37°C) and increasing humidity for able-bodied individuals (AB), and those with paraplegia (PA) and tetraplegia (TP). Inflection point for able-bodied participants was graphically determined at 80% relative humidity. *= significant difference between individuals with tetraplegia and able-bodied individuals, † = statistical analysis was not conducted on this data, due to a reduced number of participants. The number of participants for each group for each time point are listed underneath the x axis. To calculate the corrected data, the difference between each time point (after 65% RH) for each individual was calculated. The average differences for each time point were then added to the previous time point to estimate data points for 70-90% RH.

Figure 4.3 Change in mean skin temperature at rest in constant environmental temperature (37°C) and increasing humidity for able-bodied individuals (AB), and those with paraplegia (PA) and tetraplegia (TP). [*] = significant difference between individuals with tetraplegia and able-bodied individuals, [§] = significant difference between individuals with paraplegia and able-bodied individuals, [†] = statistical analysis was not conducted on this data, due to a reduced number of participants. The number of participants for each group for each time point are listed underneath the x axis. To calculate the corrected data, the difference between each time point (after 65% RH) for each individual was calculated. The average differences for each time point were then added to the previous time point to estimate data points for 70-90% RH.

The chest, upper back, abdomen, forehead, hand and foot skin temperatures were all similar between groups at the start of the stabilisation period. The forearm ($p = 0.01$) and upper arm ($p = 0.04$) were significantly cooler in AB than PA at the start of the stabilisation period. Both thigh and calf skin temperatures were significantly warmer in AB than PA ($p = 0.04$ and $p < 0.001$ for thigh and calf skin temperature, respectively) and TP ($p = 0.03$ and $p < 0.001$ for thigh and calf skin temperature, respectively) at the start of the stabilisation period. The abdomen, thigh and foot were similar between groups at the end of the stabilisation period whereas the forearm ($p = 0.02$), upper arm ($p = 0.01$), chest ($p < 0.001$) and upper back ($p = 0.01$) were all significantly cooler in AB than TP at the end of the stabilisation period. Hand skin temperature was significantly cooler in AB ($p = 0.02$) and PA ($p = 0.03$) than in TP, whilst the forehead skin temperature was significantly cooler in AB ($p < 0.001$) than TP at the end of the stabilisation period. The calf was significantly warmer in AB than PA ($p = 0.02$) and TP ($p < 0.001$), whilst PA was warmer than TP ($p = 0.03$).

For individual skin temperatures, there was a main effect of time at all skin sites (all $p < 0.001$). There were no differences between groups for the change in chest ($p = 0.07$, ES = 0.1 - 1.0, Figure 4.4C), hand ($p = 0.68$, ES = 0.1 - 0.2, Figure 4.4I) and foot skin temperature ($p = 0.87$, ES = 0.1 - 0.4, Figure 4.4J). The change in forearm skin temperature was smaller in AB ($p = 0.01$, ES = 1.3) and PA ($p = 0.01$, ES =1.4) than TP across all humidity levels (Figure 4.4A). The change in upper arm skin temperature was smaller in AB than TP across all humidity levels ($p = 0.01$, ES = 1.5, Figure 4.4B), whilst a moderate ES revealed a smaller change for AB compared to PA ($p = 0.74$, ES = 1.1). The change in forehead skin temperature was smaller in AB than TP from 45% RH ($p = 0.04$, ES = 0.2, Figure 4.4G). The change in upper back (Figure 4.4D) and abdomen (Figure 4.4E) skin temperature was smaller for both AB ($p < 0.001$, ES = 1.7) and PA ($p < 0.02$, ES = 1.2) compared to TP. The change in thigh (Figure 4.4F) and calf (Figure 4.4H) skin temperatures were smaller in AB than both PA ($p < 0.01$, ES = 1.6) and TP ($p < 0.01$, ES = 1.6 -1.7) across all humidity levels. Absolute thigh and calf skin temperatures are shown in Figure 4.5.
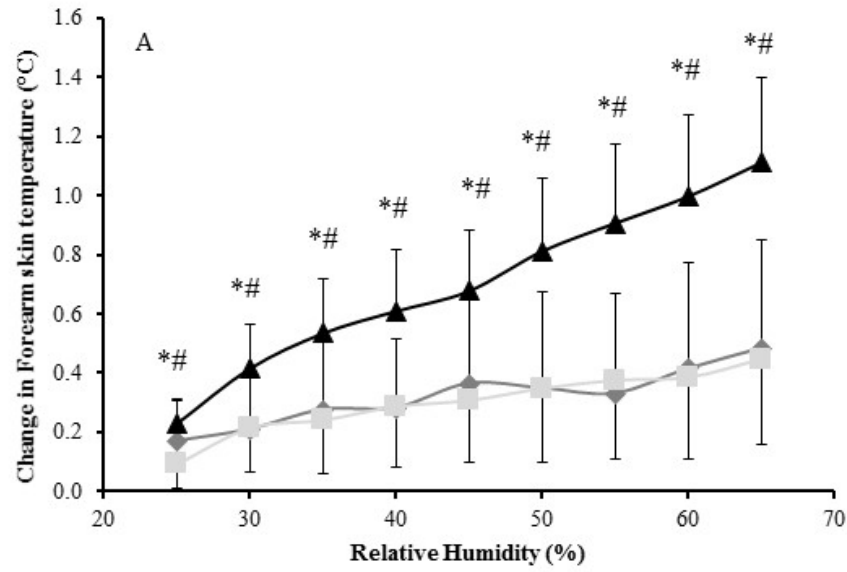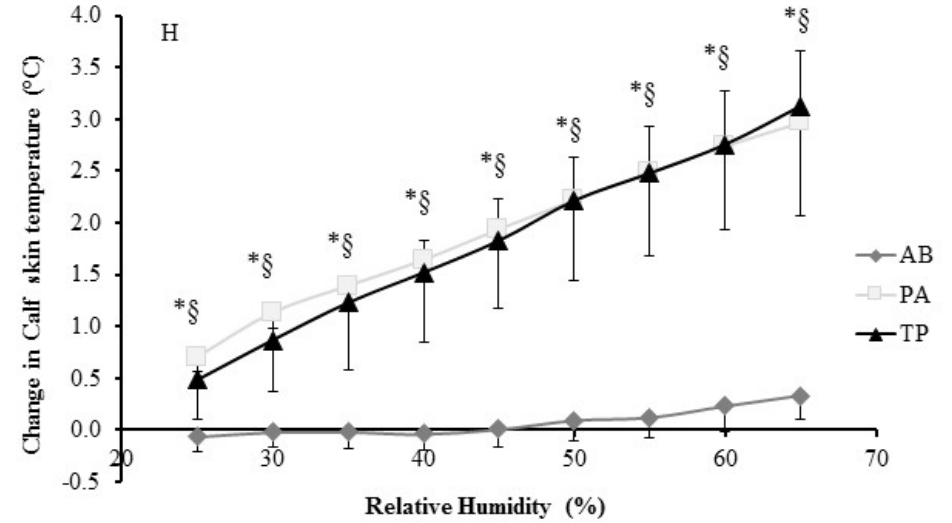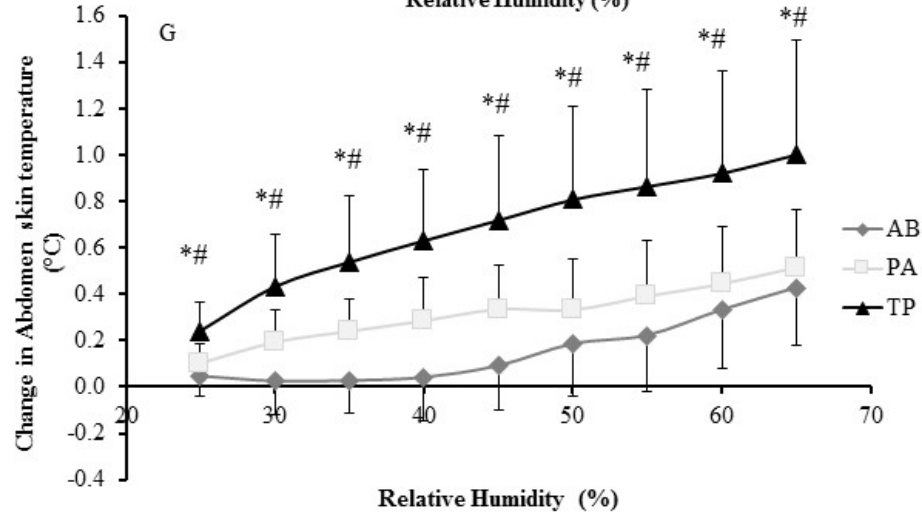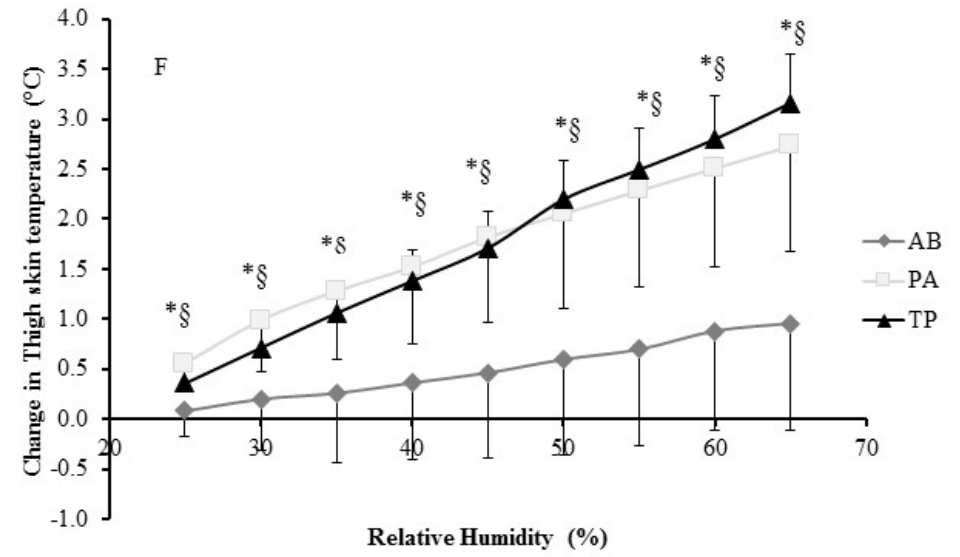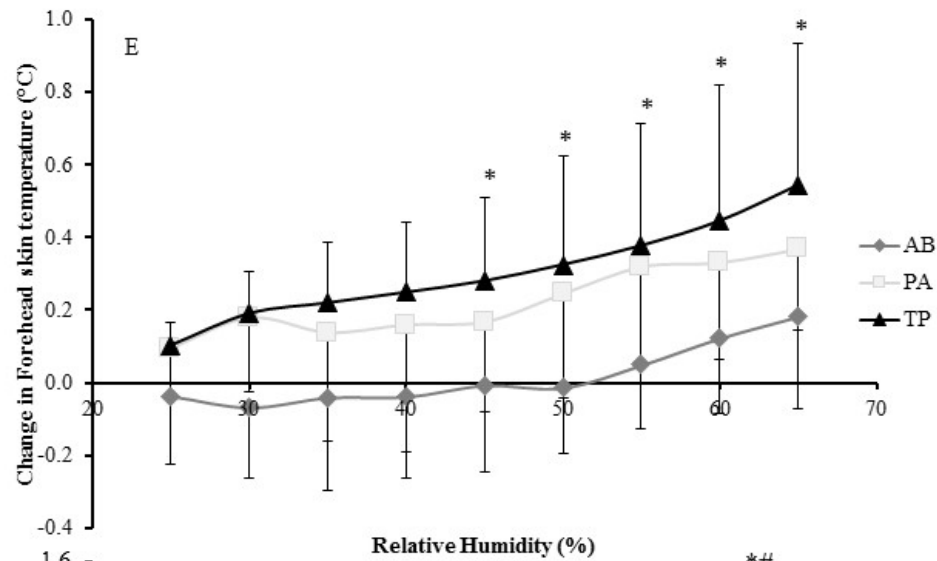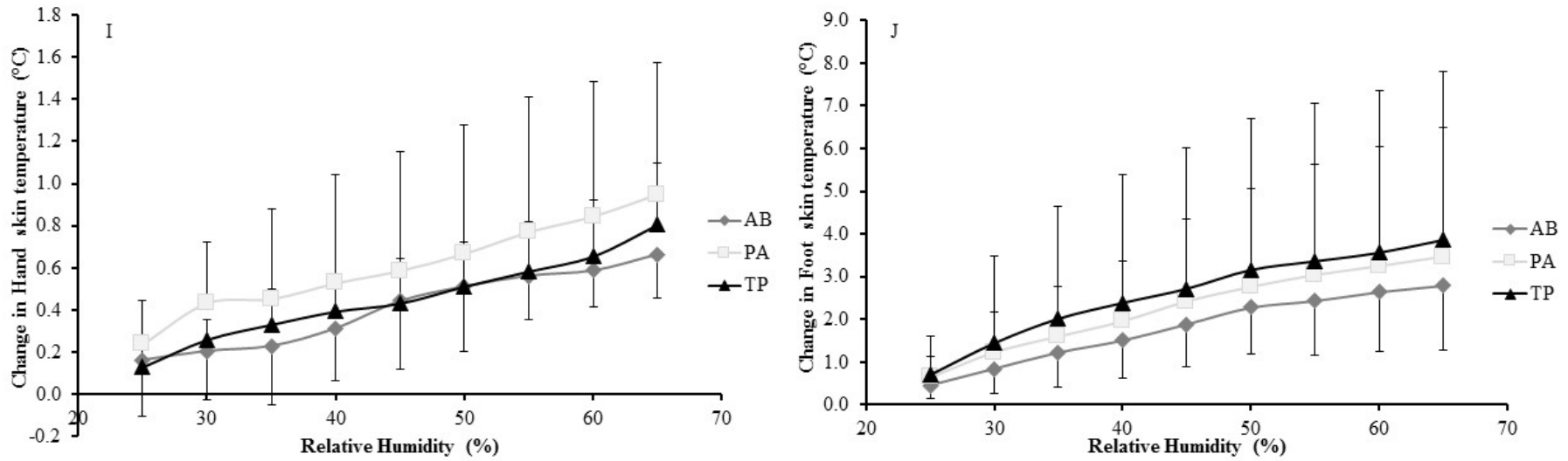
Figure 4.4 Change in (A) forearm, (B) upper arm, (C) chest, (D) upper back, (E) abdomen, (F) thigh, (G) forehead, (H) calf, (I) hand and (J) foot skin temperature at rest in constant environmental temperature (37°C) and increasing humidity for able-bodied individuals (AB), and those with paraplegia (PA) and tetraplegia (TP). [§] = significant difference between individuals with paraplegia and able-bodied individuals, [#] = significant difference between individuals with tetraplegia and individuals with paraplegia, [*] = significant difference between individuals with tetraplegia and able-bodied individuals. [†] = statistical analysis was not conducted on this data, due to a reduced number of participants.
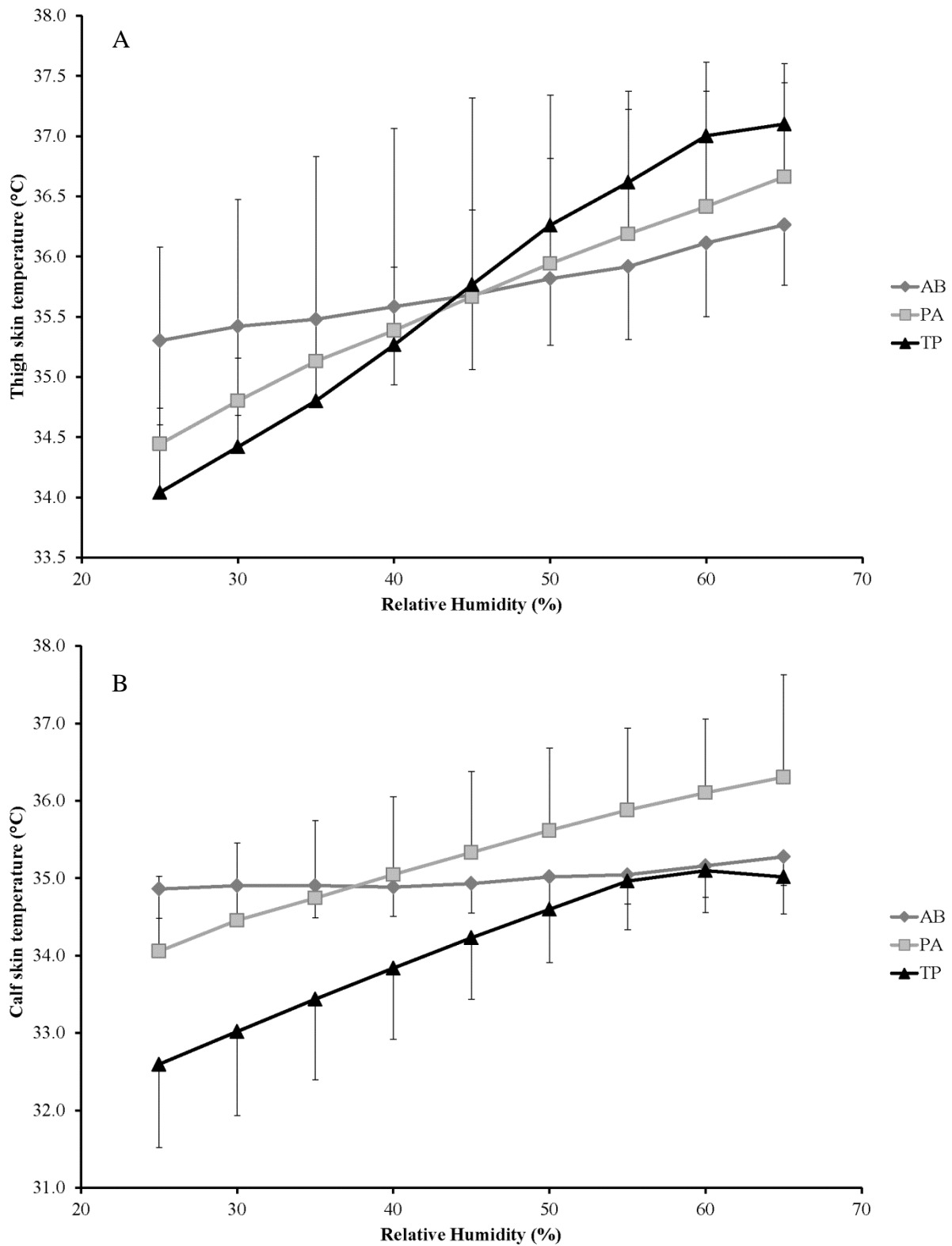
Figure 4.5 Absolute (A) thigh and (B) calf skin temperatures at rest in constant environmental temperature (37°C) and increasing humidity for able-bodied individuals (AB), and those with paraplegia (PA) and tetraplegia (TP).

Heart rate was not different at the start of the 20 min stabilisation period (62 ± 7 b·min^{-1}, 74 ± 19 b·min^{-1} and 71 ± 4 b·min^{-1} for AB, PA and TP, respectively, p = 0.18). The change in HR during the stabilisation period was not significantly different between groups (1 ± 3 b·min^{-1}, 3 ± 7 b·min^{-1} and 6 ± 5 b·min^{-1} for AB, PA and TP, respectively, p = 0.16). The change in HR was not significantly different between groups during the protocol (p = 0.43, Figure 4.6), though there was a significant increase over time (p < 0.001). Heart rate at 65% RH was not significantly different between groups, though, compared to AB (68 ± 10 b·min^{-1}), ES were moderate for PA (86 ± 26 b·min^{-1}, p = 0.16, ES = 0.9) and very large for TP (89 ± 8 b·min^{-1}, p = 0.09, ES = 2.3). Mean arterial pressure was significantly higher in AB (90 ± 8 mmHg, p < 0.001, ES = 2.3) and PA (83 ± 9 mmHg, p = 0.03, ES = 1.2,) compared to TP (73 ± 7 mmHg) throughout the protocol, though there was no main effect of time (p = 0.56).

4.4.3 Perceptual responses

There were no significant differences between groups for thermal sensation or comfort, though participants became hotter and were in greater thermal discomfort throughout the course of the protocol (p < 0.001, Figure 4.7). At 65% RH, thermal sensation corresponded to "hot" for all groups and "slightly uncomfortable" for thermal comfort. Wetness sensation was significantly higher in AB at 30-35% RH and 50-65% RH (p < 0.001) than TP. Wetness sensation significantly increased over time (p < 0.001). Wetness sensation at 65% RH corresponded to 3 (in between "moist" and "wet") for AB and PA, whilst in TP a 1 (in between "dry" and "moist") was recorded.

Thermal sensation (r = 0.94, p < 0.001, r = 0.94, p < 0.001 and r = 0.96, p < 0.001 for AB, PA and TP, respectively) was significantly correlated with T_{sk} in all three groups. Thermal comfort was significantly correlated with T_{sk} in AB (r = 0.81, p < 0.001) and TP (r = 0.75, p < 0.001), but not in PA (r = 0.57, p = 0.08). Thermal comfort was not significantly correlated with T_{gi} in AB or PA (r = 0.54, p = 0.13, r = 0.42, p = 0.27 for AB, PA and TP, respectively) but was for TP (r = 0.71, p = 0.03). Thermal comfort was significantly correlated with wetness sensation in AB (r = 0.82, p < 0.001) and PA (r = 0.74, p < 0.001) but not in TP (r = 0.31, p = 0.02).
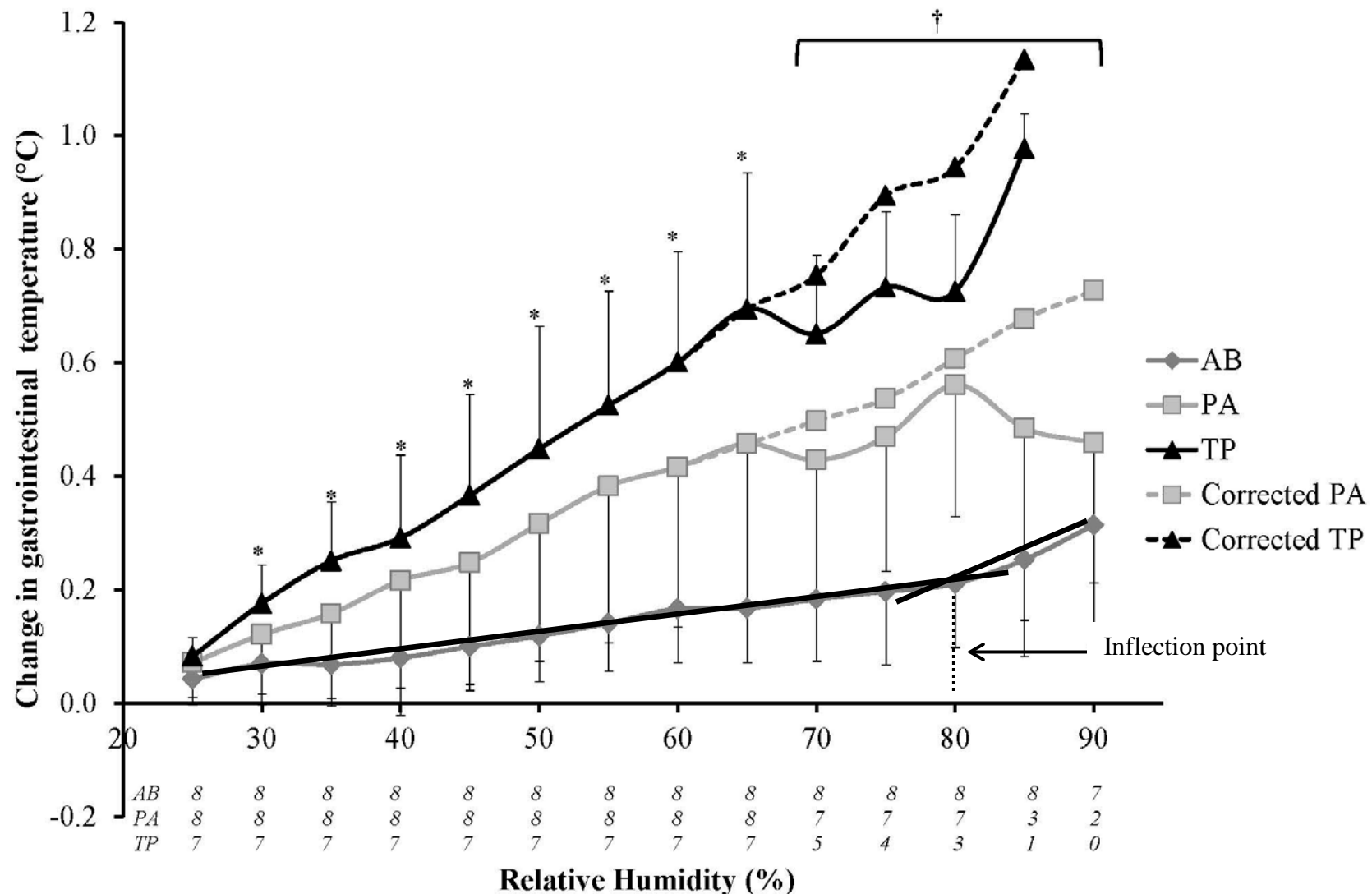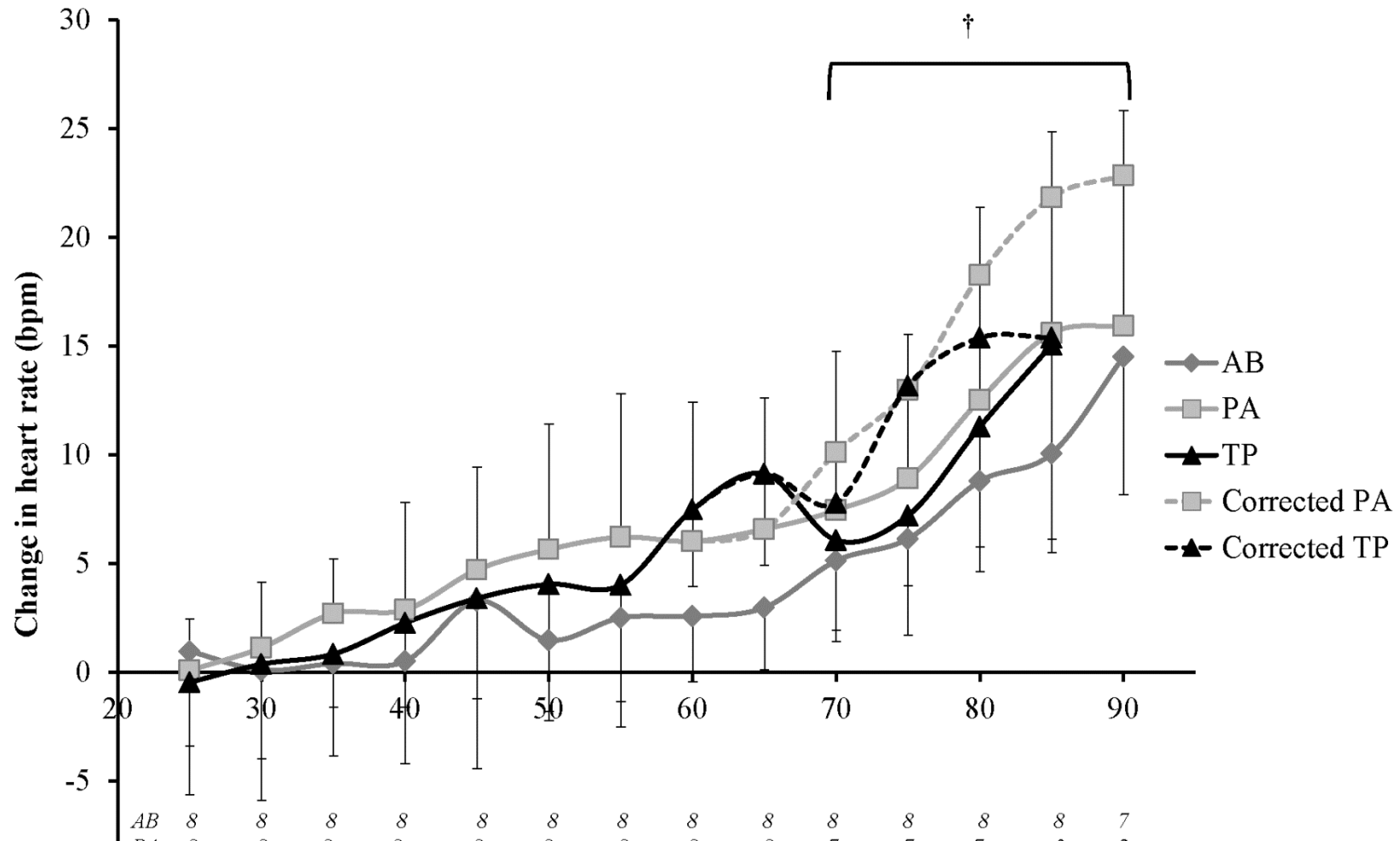
Figure 4.6 Change in heart rate at rest in constant environmental temperature (37°C) and increasing humidity for able-bodied individuals (AB), and those with paraplegia (PA) and tetraplegia (TP). † = statistical analysis was not conducted on this data, due to a reduced number of participants. The number of participants for each group for each time point are listed underneath the x axis. To calculate the corrected data, the difference between each time point (after 65% RH) for each individual was calculated. The average differences for each time point were then added to the previous time point to estimate data points for 70-90% RH.
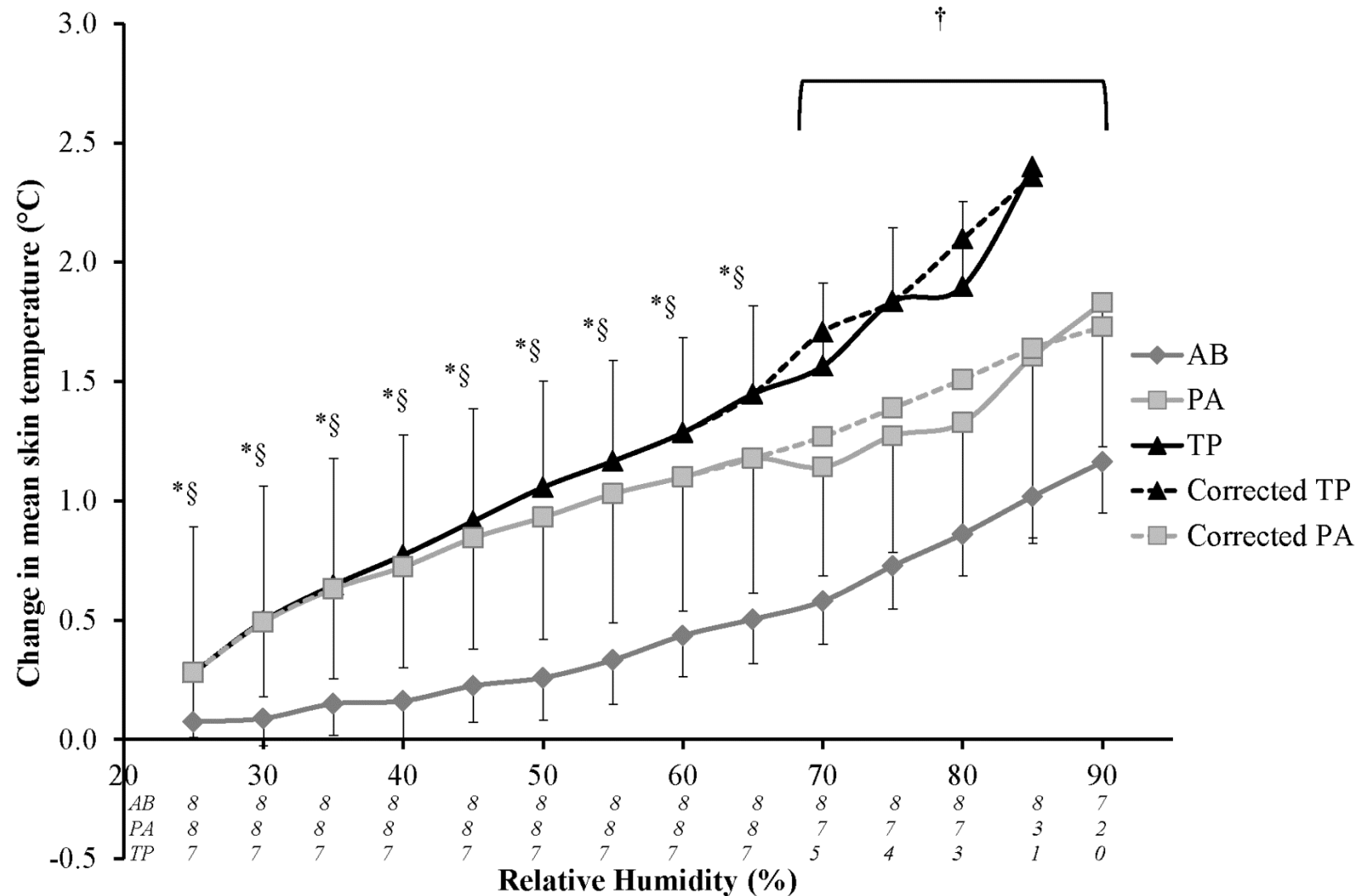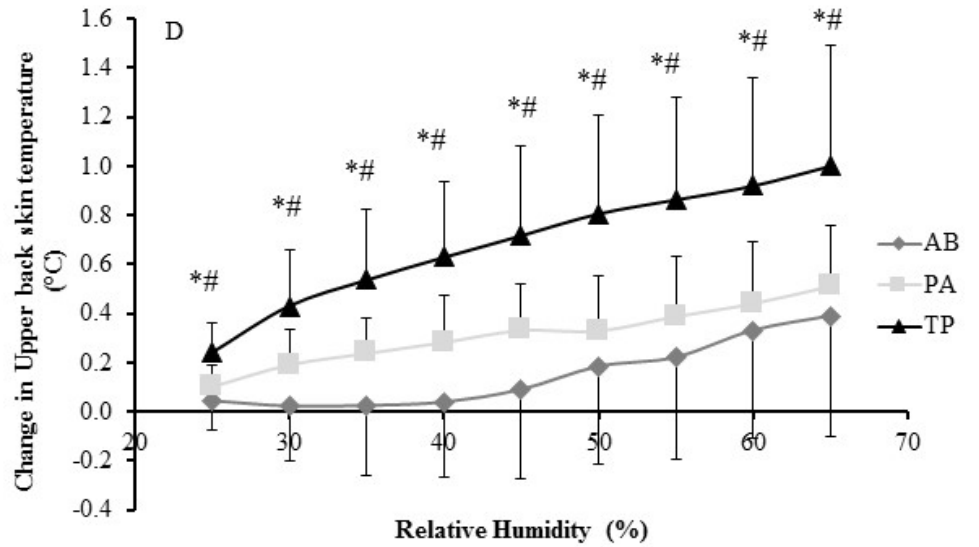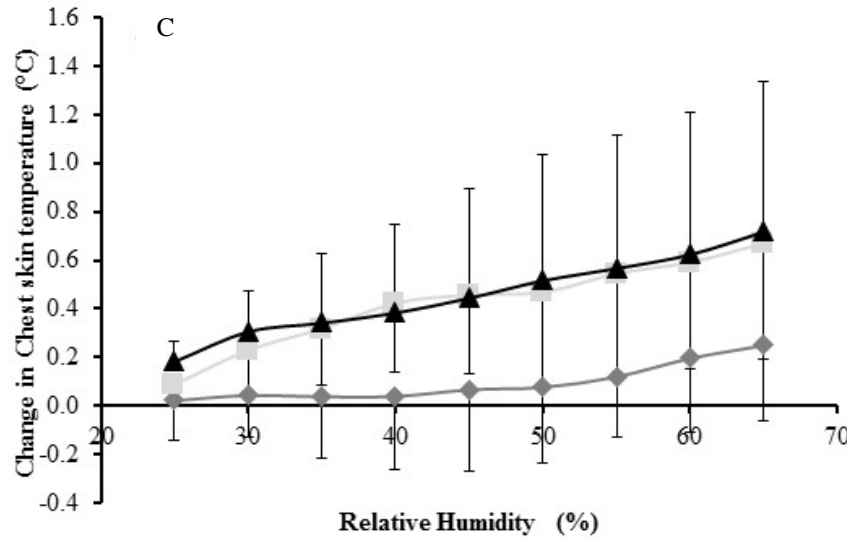
3
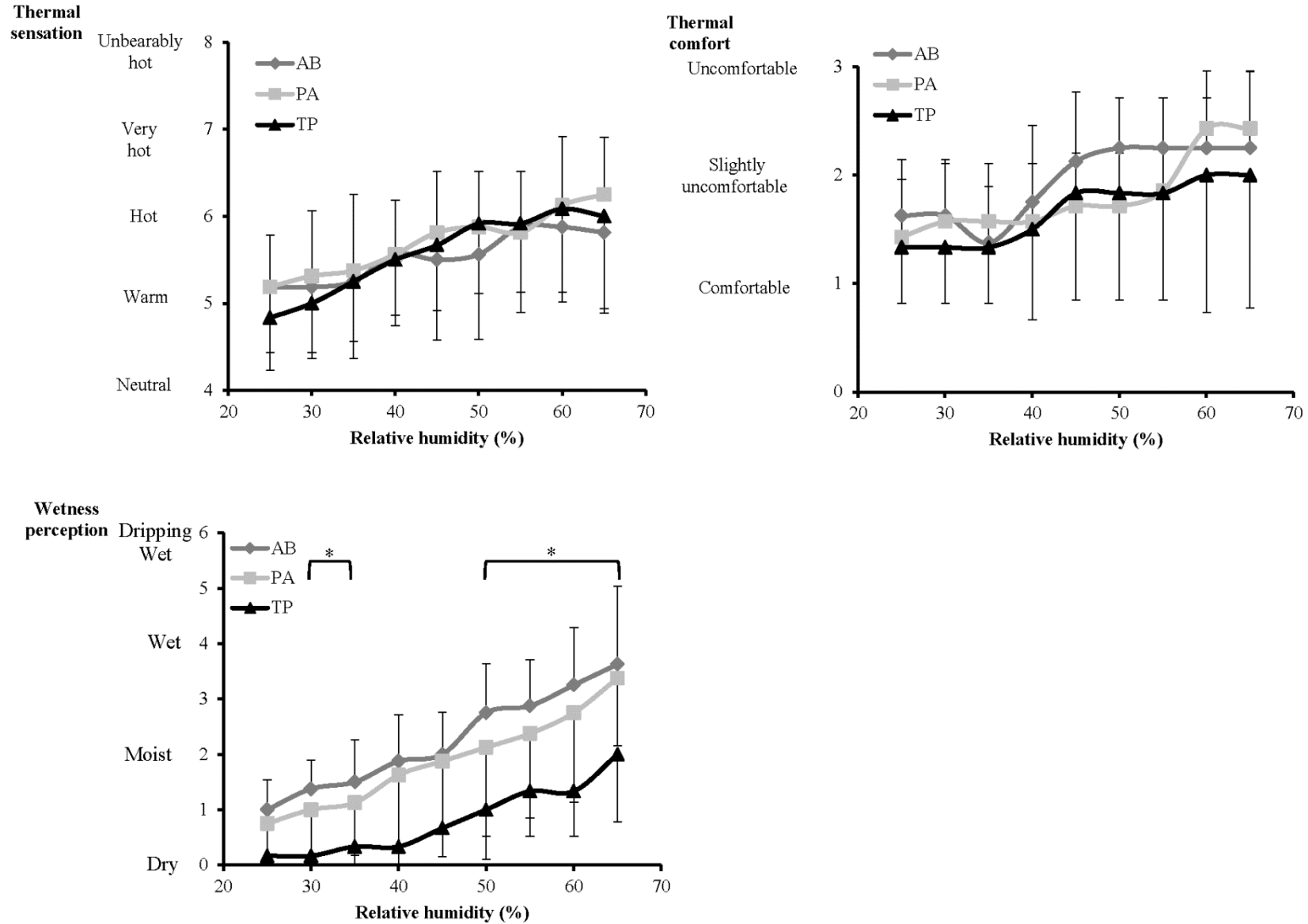
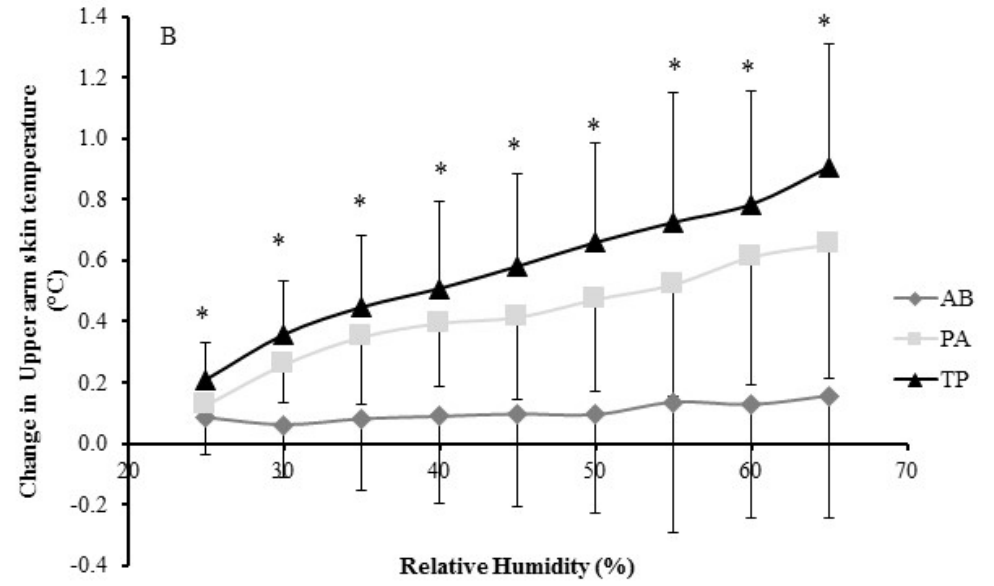**Figure 4.7** Thermal sensation, thermal comfort and wetness perception at rest in constant environmental temperature (37°C) and increasing humidity for able-bodied individuals (AB), and those with paraplegia (PA) and tetraplegia (TP). [*] = significant difference between individuals with tetraplegia and able-bodied individuals.

4.4.4 Fluid balance

Urine specific gravity was not significantly different between groups (1.018 ± 0.009, 1.016 ± 0.006 and 1.019 ± 0.006 for AB, PA and TP, respectively, p = 0.67) before the protocol, but was significantly greater in AB (1.025 ± 0.008) compared to both PA (1.015 ± 0.006, p = 0.02) and TP (1.016 ± 0.003, p = 0.04) at the end of the protocol. The absolute change in body mass (p = 0.11) and amount of fluid consumed (p = 0.31) was not significantly different between groups. Total mass loss and sweat rate were significantly greater in AB than PA (p < 0.001, ES = 1.4 - 1.7) and TP (p < 0.001, ES = 1.7 - 2.0, Table 4.3).

Table 4.3 Fluid balance during the stepwise protocol for able-bodied individuals, individuals with paraplegia and individuals with tetraplegia.

	Able-bodied	Paraplegia	Tetraplegia
Absolute change in body mass (kg)	0.04 ± 0.33	-0.28 ± 0.31	-0.13 ± 0.19
Amount of fluid consumed (L)	0.41 ± 0.36	0.46 ± 0.27	0.24 ± 0.21
Total mass loss (kg)	0.45 ± 0.05	0.18 ± 0.11[§]	0.11 ± 0.12[*]
Sweat rate (L·h^{-1})	0.23 ± 0.09	0.10 ± 0.06[§]	0.07 ± 0.07[*]

[§] = significant difference between individuals with paraplegia and able-bodied individuals, [*] = significant difference between individuals with tetraplegia and able-bodied individuals.

4.4.5 Ventilatory data

There were no significant differences between groups for tidal volume (p = 0.56), breathing frequency (p = 0.99), $\dot{V}O_2$ (p = 0.14), RER (p = 0.21) or minute ventilation (p = 0.14). Only RER had a main effect of time (p = 0.05).

4.4.6 Heat balance calculations

Metabolic heat production was not significantly different between groups (62 ± 10 W·m^2, 58 ± 9 W·m^2 and 54 ± 12 W·m^2 for AB, PA and TP, respectively, p = 0.20) or over time (p = 0.44). Radiative heat exchange (p = 0.11), C (p = 0.11), C_{res} and E_{res} (p = 0.14) were not significantly different between groups with increases in R and C and decreases in C_{res} and E_{res} as humidity increased (p < 0.001). E_{req} (57 ± 9 W·m^2, 55 ± 9 W·m^2 and 55 ± 12 W·m^2 for AB, PA and TP, respectively, p = 0.92, Figure 4.8) was not significantly different between groups.
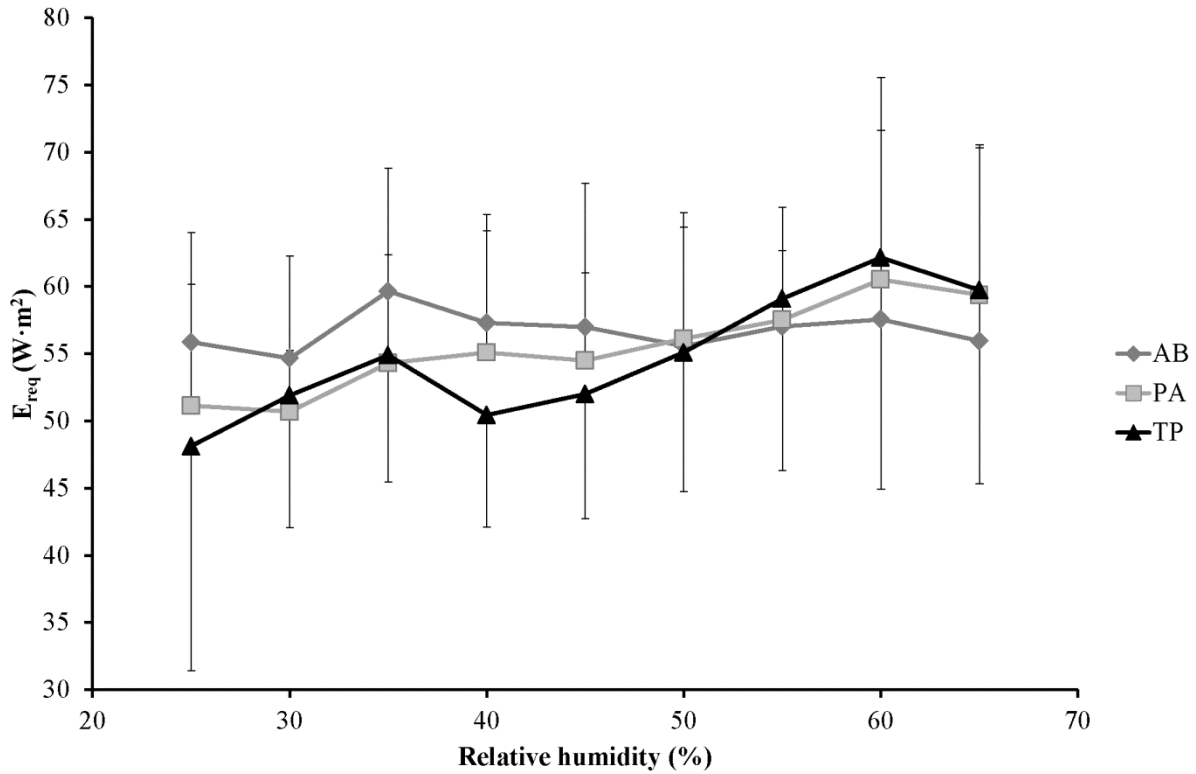
Figure 4.8 Required rate of evaporative cooling (E_{req}) at rest in constant environmental temperature (37°C) and increasing humidity upto 65% relative humidity for able-bodied individuals (AB), and those with paraplegia (PA) and tetraplegia (TP).

4.4.7 Completeness of lesion

Although statistical analysis cannot be conducted to determine if differences exist between complete and incomplete lesions in both PA and TP due to the small numbers, Figure 4.9 and 4.10 show mean and individual responses for the change in T_{gi} and T_s, respectively.
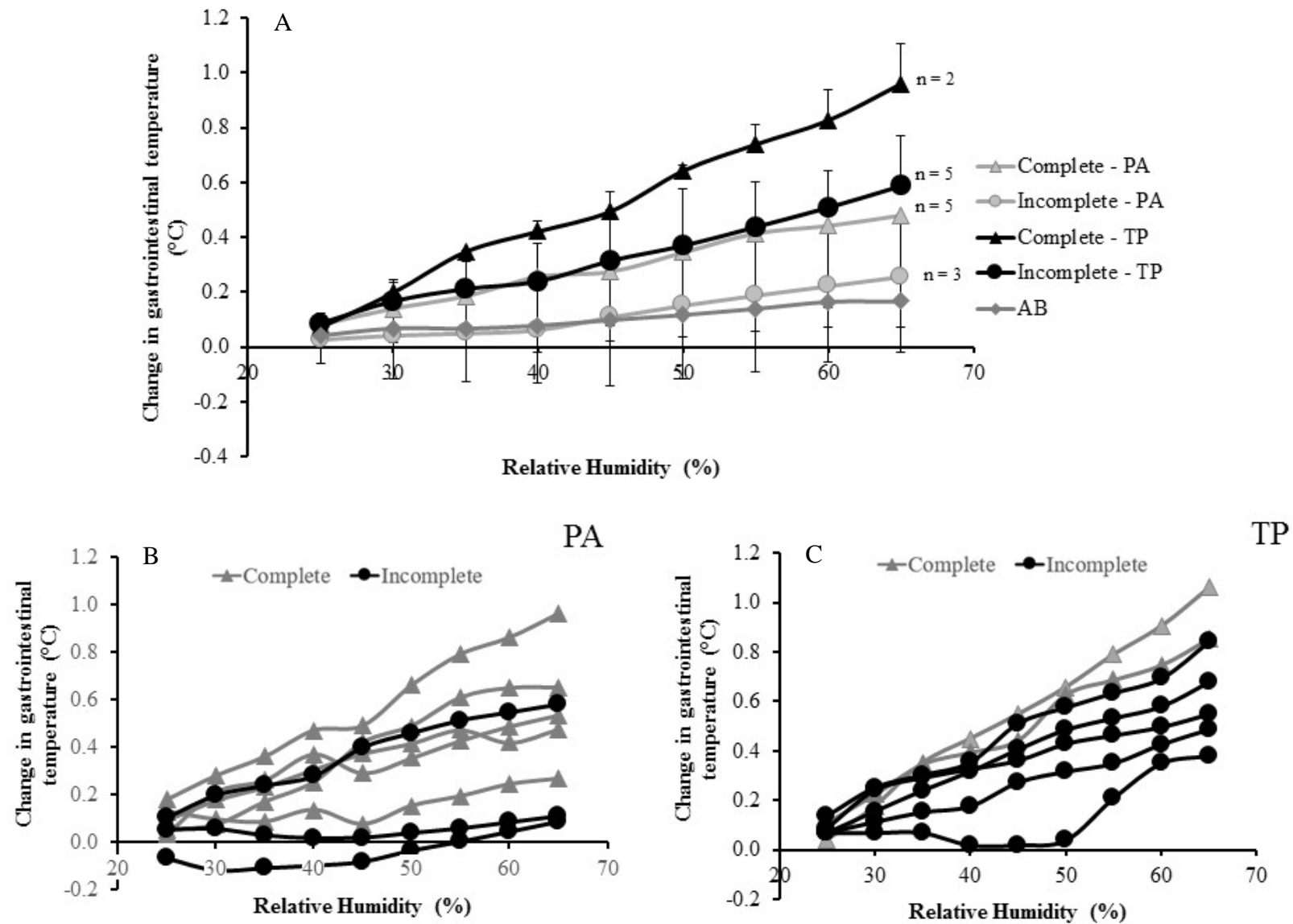
Figure 4.9 (A) The comparison between complete and incomplete lesions for individuals with paraplegia (PA) and individuals with tetraplegia (TP) for the change in gastrointestinal (T_{gi}). (B) and (C) Individual responses for complete and incomplete lesions for PA and TP. Note: five individuals with paraplegia had complete lesions and three with incomplete lesions. Two individuals with tetraplegia had complete lesions and two with incomplete lesions.
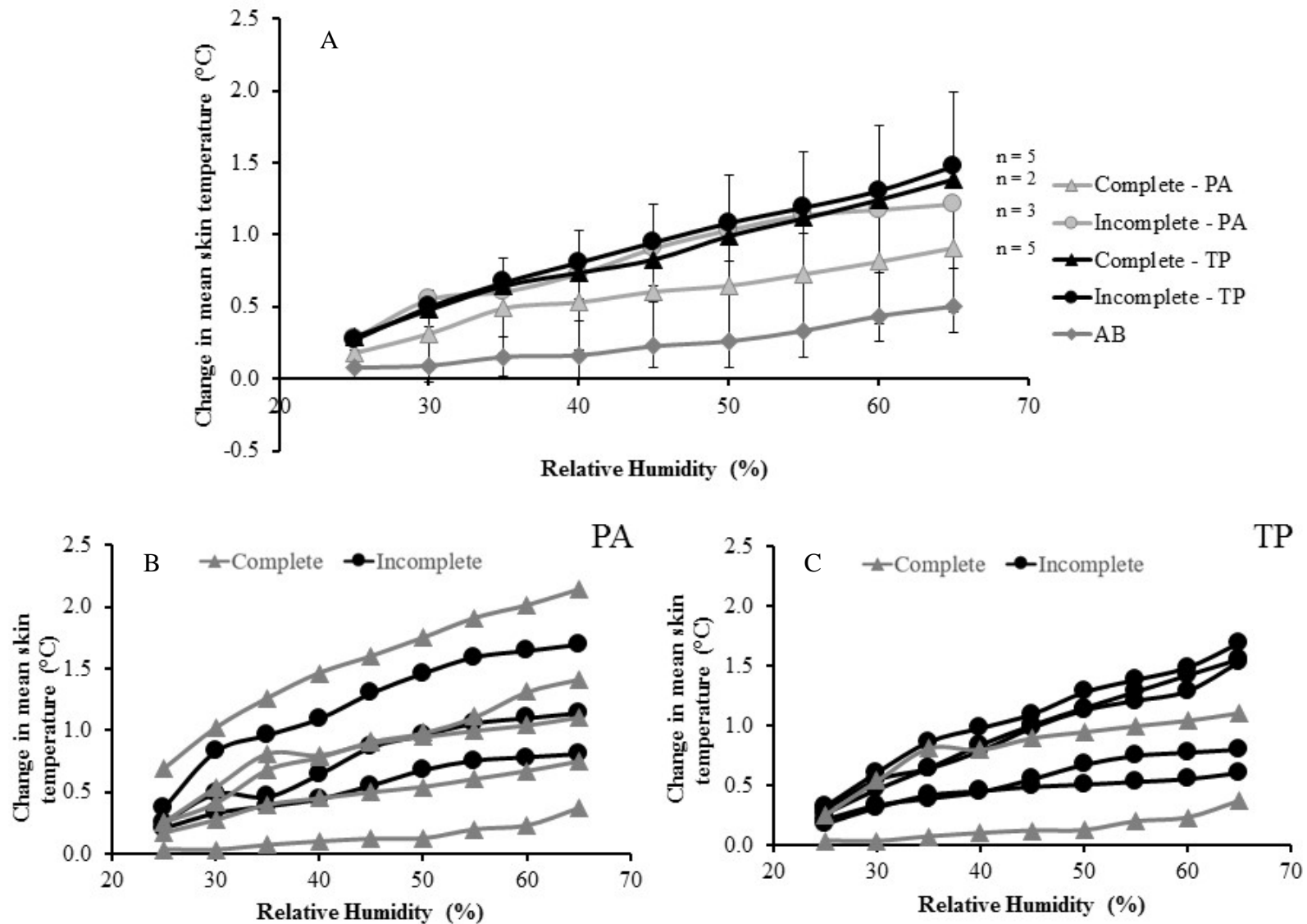
Figure 4.10 (A) The comparison between complete and incomplete lesions for individuals with paraplegia (PA) and individuals with tetraplegia (TP) for the change in mean skin temperature. (B) and (C) Individual responses for complete and incomplete lesions for PA and TP. Note: five individuals with paraplegia had complete lesions and three with incomplete lesions. Two individuals with tetraplegia had complete lesions and two with incomplete lesions.

4.5   Discussion

4.5.1   Main findings

The stepwise protocol used in the present study manipulated the water vapour pressure gradient between the skin and environment, leading to a reduction in evaporative heat loss and an eventual increase in T_{core}. This manipulation of evaporative heat loss enabled the extent of the differences in evaporative capacity between AB, PA and TP and the resulting thermoregulatory responses to be determined. The high ambient temperature (37°C) reduced heat loss by the dry heat exchange pathways, forcing evaporation to be the principle pathway for the dissipation of heat.

All three groups in the present study produced similar amounts of metabolic heat and calculated dry heat exchange at rest. Therefore, in accordance with the heat balance equation, the rate of evaporative cooling required for heat balance was also similar between groups, suggesting all individuals should have similar thermoregulatory responses to the environment. Despite this, a key finding of the study was that TP were unable to achieve heat balance even at the start of the protocol, signifying that even at rest, the heat load was greater than evaporative heat loss in these individuals, accepting part of the hypothesis. Although in PA the change in T_{gi} was of a lesser magnitude than TP and statistically similar to AB, a continual increase in T_{gi} and T_{sk} from the start of the protocol was apparent (Figure 4.2 and 4.3), partially disproving of the hypothesis. Thus even in PA, despite possessing a sweating capacity proportional to their lesion level, evaporative heat loss was not large enough to fully balance the heat load at rest.

Considering the three groups were statistically producing similar amounts of heat, neither PA nor TP attained a steady T_{gi} response (Figure 4.2), and hence heat balance, during the protocol. For instance, at 65% RH, the change in T_{gi} was 0.29°C and 0.51°C higher than AB in PA and TP, respectively. The corrected data lines for T_{gi}, T_{sk} and HR depict how these responses would have continually increased if all individuals had been kept in the environmental conditions of 70-90% RH. Conversely T_{gi} was stable for AB, suggesting the humidity range used for statistical analysis (25% - 65% RH) was within the prescriptive zone for AB, based on a critical limit of ~80% RH (Lind 1963). Thus this data provides comprehensive evidence that evaporative heat loss in both PA and TP is insufficient to

maintain a stable T_{gi} in hot conditions, where evaporation is the primary pathway for the dissipation of heat, even at rest.

The attenuation in evaporative heat loss in persons with an SCI is also shown by the greater change in T_{sk} and smaller total mass loss in PA and TP compared to AB throughout the protocol. To calculate $T_{sk,}$ the Ramanathan formula, utilizing the skin temperature at the chest, upper arm, thigh and calf, was used to compare to previous SCI literature. In the present study, both the change in thigh and calf skin temperature, i.e. skin sites below the lesion level, were significantly greater in PA and TP than AB throughout the protocol (Figure 4.4 F and H), contributing to the greater T_{sk} response. In PA the small amount of evaporated sweat, depicted by the smaller total mass loss and lower sweat rate compared to AB, may not have been large enough to lower T_{sk}. Hence the results of the present study suggest that latent heat loss is greatly reduced and insufficient to attain heat balance for both PA and TP, compared to AB, at rest in ambient conditions above T_{sk}.

4.5.2 Heat balance

The latent heat loss required for heat balance (E_{req}) is calculated through a re-arrangement of the heat balance equation. Metabolic heat production is the primary contributor of E_{req}, since the calculated dry heat exchange will vary relatively little between individuals under similar environmental conditions (Bain et al. 2011). Thus, the similar metabolic heat production (and metabolic energy expenditure) between groups led to similar values for E_{req}. This result was unexpected and in contrast to the lower energy expenditure found in TP compared to AB and PA in previous studies (Liusuwan et al. 2007, Monroe et al. 1998, Mollinger et al. 1985). Nevertheless, in the present study due to their inability to achieve evaporative heat balance requirements (i.e. E_{req}), a heightened T_{gi} response was attained by TP.

4.5.3 Body composition

Although historically body fatness has been thought to be a predictor of individual T_{core} and sweating responses to exercise (Havenith et al. 1998, Havenith et al. 1990, Havenith et al. 1995), recent studies have found body fatness actually explains little of the variance. Instead heat production (in W/kg of total body mass) and E_{req} explain the majority of the variance in T_{core} and whole body sweat loss, respectively (Cramer et al. 2015). Whether body fatness explains a similar amount of variance in T_{gi} in individuals with an SCI is unclear. Since individuals with an SCI not only have a thermal dysfunction, but as a result of the inactivity

of the lower limbs and skeletal muscle denervation, have adverse changes to their overall body composition. In the current study, similar body composition characteristics to previous studies (Spungen et al. 2003, Maggioni et al. 2003) were observed, with moderate-large ES depicting a greater body fat percentage, greater fat mass and smaller fat free mass in both PA and TP compared to AB. Despite these findings, equations to calculate body fat percentage have not been developed for the SCI population and the Durnin and Wormsley four site method used in the present study has been shown to under predict body fat percentage compared to dual energy x-ray absorptiometry (DXA) in wheelchair athletes by 4.2% (Goosey-Tolfrey et al. 2016, Willems et al. 2015). Thus differences in body fat percentage between AB and both PA and TP are likely to be greater than reported. For instance using the mean values for each group and the 4.2% underestimation for SCI, body fat percentage would be 14.4%, 26.6% and 22.4% for AB, PA and TP, respectively. In addition, the use of the Dubois formula to calculate body surface area has limitations in the SCI population as body mass distribution is altered compared to AB due to muscular atrophy of the lower body as a result of an SCI. Despite this, a larger data set would be needed to determine in the SCI population how much variance in T_{gi} body fatness could explain.

4.5.4 Skin temperatures

Physiological adaptations that occur as a result of an SCI, such as a lack of sympathetic vasoconstriction, muscle pump activity and sweating capacity below the lesion level, lead to a variance in regional skin temperatures (Griggs et al. 2015). Thus it is imperative that regional skin temperature responses are investigated in individuals with an SCI, as T_{sk} is likely to mask these regional differences (Price 2006). At the extremities, both the change in hand and foot skin temperatures were not significantly different between groups (Figure 4.4 I and J). Both skin sites have been shown to have a low sweat rate in AB (Smith et al. 2011). Thus, the lower evaporative cooling effect of sweat in AB may not have led to skin temperature differences between the groups, despite the foot being below the lesion level for both PA and TP. Furthermore, the foot had the largest change in skin temperature compared to the other skin temperature measurement sites, which may have been due to the participants wearing both socks and shoes during the protocol, decreasing the dissipation of heat. In contrast, in the lower limbs, the change in thigh and calf skin temperatures were greater in both PA and TP than AB, due to the disrupted blood flow, vascular atrophy and skeletal muscle denervation below the level of the lesion (Hopman 1994). According to Figure 4.5, both thigh and calf skin temperatures were lower in PA and TP at the start of the protocol,

increasing throughout, compared to stable thigh and calf skin temperatures in AB. Thus depicting that the lower body is a potential site for heat storage in hot conditions (Price et al. 1997), due to the combination of a reduced capacity to dissipate heat and lower initial thigh and calf skin temperatures, leading to a greater thermal gradient between the skin and environment.

A non-significant difference in the change in chest skin temperature was reported between groups. However, Figure 4.4C depicts a heightened response for both PA and TP compared to AB, suggesting the large standard deviation within groups could have masked a significant difference between groups. The site is below the lesion level for TP so one would expect a greater increase in chest skin temperature in TP compared to AB and PA. However, compared to other regions of the torso, the chest has a lower regional sweat rate (Smith et al. 2011), thus the sweat response may have had a lower evaporative cooling effect, leading to a similar skin temperature for all three groups. In addition, a clear difference between groups may have been masked by the potential differences in skin response between individuals with complete and incomplete lesions.

Similarly at the upper arm, a similar skin temperature was observed for PA and TP, despite the site being above the lesion level for PA. Nevertheless a moderate ES was revealed for PA compared to AB, signifying a meaningful difference between the two groups, whilst a significant result may have been masked by the large inter-individual variation, due to the range and completeness of the lesion levels (Figure 4.4B).

Conversely, the change in abdomen skin temperature in PA was not significantly different to AB, even though the site is below the lesion level for both PA and TP (Figure 4.4C). A heightened abdomen skin temperature response in TP compared to PA may have been due to postural variations or differences in wheelchair design (Price et al. 2003). Individuals with TP have limited trunk function (Tweedy et al. 2010) so are unable to hold their torso upright, potentially changing the microclimate around the abdomen skin temperature site, decreasing air flow to the region and leading to a greater increase in abdomen skin temperature than PA. Despite the results of the chest, upper arm and abdomen skin temperatures, the other upper body skin temperatures of the upper back and forearm reflected the remaining sweating capacity of the two groups (Figure 4.4A and D). Thus for these regions lesion level determined the degree of increase in skin temperature.

Lastly for individual skin temperature responses, the change in forehead skin temperature was significantly greater in TP than AB (Figure 4.4E), though the magnitude of the effect was small (ES = 0.2). Petrofsky (1992) reported that individuals with TP produced a sweating response above their lesion level which was so great it dripped off the skin surface. Yet, no study since has found this response (Price 2006). Anecdotally, in the current study beads of sweat on the foreheads of TP were not visible, thus supporting the notion that TP do not have a compensatory increase in sweating above their lesion level. However, it also suggests that these individuals do not have a similar skin temperature response to the AB, even though the site is above the lesion level. Unfortunately, regional sweat rates were not measured in this study, which would have enabled the regional sweat rates to be quantified and potentially provide further evidence to help explain why the change in forehead skin temperature was significantly higher in TP than AB. At the level of the sweat gland, Yaggie et al. (2002) previously reported a lower active sweat gland density and sweat rate above the lesion level in untrained individuals with tetraplegia. Nonetheless, limited research has been conducted in this area and further investigation is needed to gain insight into the extent of the sweating capacity above the lesion level in both PA and TP and the reasons behind this.

4.5.5 Cardiovascular responses

As a result of the body having to contend with an extra exogenous heat load, alterations in cardiac and vascular function also occur at rest during heat stress. Two main causes of cardiovascular drift appear to be an increase in HR and T_{core}, causing a decrease in ventricular filling and end diastolic volume (Coyle et al. 2001). Consequently this leads to a reduction in stroke volume and a maintenance of cardiac output (Coyle et al. 2001). In the present study cardiovascular drift is clearly shown by the significant increase in HR (Figure 4.6) and T_{gi} (Figure 4.2) over the duration of the protocol in all three groups. In TP cardiovascular drift likely occurred earlier due to the greater increase in $T_{gi.}$ In contrast to T_{gi} and T_{sk}, the change in HR during the protocol was similar between groups. In athletes with TP, there is a reduced pre load on the heart, as a result of venous pooling and a subsequent reduction in stroke volume. Thus, in athletes with TP changes in HR are the primary mechanism for increasing cardiac output to meet oxygen demands (Currie et al. 2015). Although participants were not elite athletes in the present study they were recreationally active, suggesting TP were able to sufficiently increase their HR during the protocol in line with AB and PA in an attempt to maintain cardiac output.

Another indication of cardiovascular drift is a reduction in MAP (Ekelund 1967). In the present study, MAP was lower in TP compared to AB and PA throughout the protocol, consistent with previous studies (Gondim et al. 2004), but MAP did not decrease over time. Mean arterial pressure remained fairly constant in AB but a decrease from the start to 65% RH of 5mmHg and 4 mmHg was apparent for PA and TP, respectively. Therefore, as a result of an increased demand for blood flow to the skin surface to dissipate heat and the smaller portion of their body in which they have sympathetic control, stroke volume likely decreased in TP and PA compared to AB. Subsequently a reduction in cardiac output would be apparent. Whereas in AB, throughout the majority of the protocol, due partly to their ability to dissipate the heat load, they were able to prevent an increase in T_{gi} and a decrease in MAP.

Regardless of alterations in cardiac and vascular function, there was no difference between groups or over time for the respiratory responses of tidal volume, breathing frequency, $\dot{V}O_2$ or minute ventilation. While in support of findings by Loveridge and Dubo (1990), the similar minute ventilation between SCI and AB is in contrast to other studies (Spungen et al. 2009). In cool conditions, previous results show a reduction in minute ventilation in TP compared to AB at rest. This is primarily attributed to a reduction in tidal volume without a change in breathing frequency (Spungen et al. 2009). Although further disparities between studies in relation to respiratory measures in TP have been found (Spungen et al. 2009, Loveridge et al. 1990, Bodin et al. 2003), these are potentially due to methodological differences. In the able-bodied, a T_{core} threshold of ~38˚C has been reported, above which minute ventilation will increase in both passive heating and during exercise (Saxton 1975, Fujii et al. 2008, Cabanac et al. 1995). Our findings may partially support this notion as T_{gi} at 65% RH was only 37.43°C, without an increase in minute ventilation.   Whether a similar threshold for minute ventilation, but at a different T_{gi} value, exists for PA and TP is currently unknown.

4.5.6   Perceptual responses

In addition to physiological measures, perceptual measures of thermal sensation, thermal comfort and wetness sensation were also investigated. Thermal sensation was not significantly different between PA and TP, even though TP were under greater thermal strain. Thermal sensation is largely dictated by skin temperature, independent of T_{core} (Schlader et al. 2011), thus one would expect a greater thermal sensation in TP and PA compared to AB. Strong significant correlations were apparent between T_{sk} and thermal sensation in all three groups, suggesting that PA and TP may not be able to perceive the magnitude of thermal

strain compared to AB. Whether PA and TP are able to perceive dynamic changes in T_{sk}, instead of a continual increase, is unknown.

The small body surface area of sensate skin in TP (Attia et al. 1983) implies the role of skin temperature for reporting thermal sensation may be limited for these individuals. Though a smaller magnitude, a similar correlational response to thermal sensation was also apparent for thermal comfort for AB and TP, but not PA. Core temperature and T_{sk} have been reported to contribute equally to thermal comfort in the able-bodied (Frank et al. 1999). Yet TP had a greater change in T_{gi} and T_{sk} suggesting they should have been in greater thermal discomfort than AB. Interestingly, thermal comfort was only significantly correlated to T_{gi} in TP and not AB or PA, which may be due to the larger change in T_{gi} in this group. Similarly to thermal sensation, whether TP are able to detect dynamic changes in T_{gi} is unknown.

As expected, due to the small body surface area of sensate skin and loss/minimal sweating capacity, wetness sensation was lower in TP compared to AB and PA. The upper body has a greater proportion of high sweat rate regions than the lower body (Smith et al. 2011), thus despite a lower total mass loss and sweat rate in PA, perceived wetness of the sensate areas of PA led to a similar wetness sensation score to AB. Strong and significant correlations were apparent between thermal comfort and wetness sensation for both AB and PA, signifying the influence of sweat production on thermal comfort. Further work is needed to understand whether perceptual responses in individuals with an SCI can be used as a tool to determine the degree of thermal strain.

4.5.7 Complete and incomplete lesion responses

The large variance in thermoregulatory responses in SCI, is further complicated by the completeness of the lesion. Research investigating whether completeness of a lesion influences physiological or perceptual responses of individuals with an SCI is limited (Song et al. 2015). In the current study for the T_{gi} response, AB and individuals with incomplete PA had a similar response, whilst the same was true for complete PA and incomplete TP (Figure 4.9). A heightened T_{gi} response compared to the rest of the participants was observed for individuals with a complete TP. Individuals with incomplete lesions may have a greater amount of sensory information in relation to their thermal state and a greater body surface area available for sweating (Webborn et al. 2010). Yet Webborn et al. (2010) has shown an incomplete lesion to have little effect on whole body sweat loss. In terms of T_{sk}, both

incomplete and complete TP and incomplete PA had a similar response, with an attenuated response in complete PA (Figure 4.10). If completeness of a lesion leads to a lower sweating capacity, one would expect complete PA to have a greater T_{sk} response than incomplete PA. In relation to HR, no clear pattern can be seen in terms of the effect of the completeness of the lesion depicting variations between individuals in cardiac control. To fully understand what effect completeness of the lesion has on thermoregulatory responses, a larger number of participants, plus separate groups of individuals with complete PA and TP and incomplete PA and TP of comparable lesion levels (between complete and incomplete PA etc.) should be tested.

4.6 Practical applications

The storage of heat in TP, due to the lack of evaporative heat loss, has applications for athletes when travelling to hot countries. While a large majority of athletes with an SCI compete indoors in air conditioned venues, competitions are increasingly being hosted by countries with hot climates. The additional thermal strain these individuals will experience at rest from being outdoors aside from competition or in rooms with no air conditioning, is thus of concern. Using data from the present study, guidance should state that, in environments where evaporation is the primary source of heat dissipation and evaporation is fully permitted, these athletes should only spend short periods of time in these conditions, use effective cooling strategies and request air conditioned rooms to avoid a large change in T_{core} outside of competition and minimise the risk of heat related illnesses.

Caution should additionally be given to PA as despite an attenuated T_{gi} response compared to TP, the continual increase in T_{gi} and T_{sk} suggests they were also unable to attain heat balance throughout the protocol. Yet due to PA in the present study encompassing a large range of lesion levels (T3-T12), differences in thermoregulatory responses may have likely occurred between individuals with high (T1-T6) and low (T7 and below) lesions (Price et al. 2003). In future research, separate groups of participants with sufficient numbers of high and low PA should be studied.

Conversely, whether short periods of exposure to these environments as a form of heat acclimation would be of benefit to athletes is unknown. Only one published study, to date, has investigated the effect of a period of heat acclimation on the thermoregulatory responses of athletes with an SCI (Castle et al. 2013). The authors stated that after 7 days of heat

acclimation in 33°C, 65% RH, athletes with PA, TP, spina bifida and Polio experienced partial heat acclimation, signified by a reduction in resting aural temperature and perception of effort and increased plasma volume. Despite this, subsequent observations (Price et al. 2011) have found a lack of heat acclimation, using a protocol similar to Castle et al. (2013) in athletes with PA and TP.

4.7 Conclusions

In conclusion, despite producing similar amounts of metabolic heat and thus requiring the same rate of evaporative cooling for heat balance, TP had a heightened T_{gi} and T_{sk} response compared to AB. The results provide evidence that in TP, even at rest, evaporative heat loss is not large enough to balance the heat load. Even though PA possesses a greater sweating capacity than TP and T_{gi} increased by a smaller magnitude, the continual increase in both T_{gi} and T_{sk} signifies at temperatures above T_{sk} latent heat loss is insufficient to attain heat balance, compared to AB. Based on the study's findings, both PA and TP require effective heat loss strategies when evaporation is the primary avenue for heat loss in an attempt to attain heat balance.

Chapter 5

Study 2: Thermoregulation during intermittent exercise in athletes with a spinal cord injury

This chapter has been published in a slightly modified form in the *International Journal of Sports Physiology and Performance.*

Study 1 (Chapter 4) highlighted that at rest both individuals with PA and TP are unable to attain heat balance when evaporative heat loss is the main source of heat dissipation. Study 2 (Chapter 5) aims to represent a "real-world" sporting scenario and investigate the thermoregulatory responses of athletes with PA and TP during intermittent sprint wheelchair exercise.

5.1 Abstract

Purpose: Previous research has not simulated the intermittent nature and modality of wheelchair court sports, or replicated typical environmental temperatures. Hence, the purpose of this study was to investigate the thermoregulatory responses of athletes with PA and TP during intermittent wheelchair exercise and passive recovery in conditions representative of an indoor playing environment for WCR and basketball.

Methods: Sixteen wheelchair athletes; 8 with TP (body mass 65.2 ± 4.4 kg) and 8 with PA (body mass 68.1 ± 12.3 kg) completed a 60 min intermittent wheelchair sprint protocol (ISP) in $20.6 \pm 0.1°C$, $39.6 \pm 0.8\%$ relative humidity, on a WERG, followed by 15 min of passive recovery. Gastrointestinal temperature, T_{sk}, individual skin temperatures, HR, blood lactate, plasma volume and subjective ratings of RPE and thermal sensation were measured throughout.

Results: Similar external work ($p = 0.70$, ES = 0.20), yet a greater T_{gi} ($p < 0.05$, ES = 2.27) and T_{sk} ($p < 0.05$, ES = 1.50) response was demonstrated by TP, compared to PA, during the ISP. At the end of the post exercise recovery, T_{gi} for TP remained elevated from rest by $1.1°C$ compared to $0.2°C$ for PA. Plasma volume ($p = 0.96$) and subjective ratings of RPE ($p = 0.52$) and thermal sensation ($p = 0.29$) were not significantly different between groups. Blood lactate ($p = 0.02$) and mean and peak HR were lower in TP than PA ($p > 0.05$).

Conclusions: Despite similar external work, a marked increase in T_{gi} in TP during exercise and post exercise recovery signifies thermoregulatory differences between the groups were predominantly due to differences in heat loss. Further increases in thermal strain were not prevented by the active and passive recovery between maximal effort bouts of the ISP as T_{gi} continually increased throughout the protocol in TP.

5.2 Introduction

Whilst Study 1 (Chapter 4) explored how evaporative heat loss and heat balance are altered as a result of an SCI at rest, taking a fundamental approach, Study 2 adopted a "real-world" sporting environment and aimed to determine the extent of the thermoregulatory impairment for athletes with an SCI during exercise. This study is the first of three exercise studies within this thesis which were designed to reflect the competitive indoor sporting scenarios that highly trained wheelchair games players would encounter.

Previous literature has stated that exercising for 60-90 minutes at 60% $\dot{V}O_{2peak}$ in 15-25°C, trained individuals with PA are likely to experience an increase in T_{core} similar to their AB counterparts (~1°C, Price 2006). Whilst individuals with TP possess a smaller area of sensate skin, a lesser amount of afferent input regarding their thermal state and a reduced efferent response compared to individuals with PA (Normell 1974, Guttmann et al. 1958). Less is known regarding the thermoregulatory responses of athletes with TP during exercise. Yet, it is thought they may experience a disproportionate increase in T_{core} and heat storage, due to the presence of little or no sweating response, leading to a greater degree of thermal strain (Price et al. 1999b). Price and Campbell (1999b) demonstrated that an athlete with TP arm cranking at 60% $\dot{V}O_{2peak}$ for 60 minutes in ~21.5°C, experienced a continuous increase in T_{core}, in contrast to a plateau experienced by the AB and athletes with PA. While the athlete with TP did not experience high thermal strain in these conditions, the continuous rise in T_{core} shows that heat balance was not achieved.

Previous research has predominantly used arm cranking protocols (Price et al. 1997, Dawson et al. 1994) to examine the thermoregulatory responses of athletes with an SCI and not their habitual mode of wheelchair exercise. Thermoregulatory differences exist between different modalities with lower physiological and thermal strain elicited during wheelchair propulsion, compared to arm cranking, due to increased convective cooling provided by the arms moving relative to the body during propulsion of the wheelchair (Price et al. 1999a). Moreover, previous studies have not matched the ambient conditions to indoor playing environments, the intermittent nature of wheelchair court sports, such as wheelchair basketball and rugby or investigated the thermoregulatory responses during initial recovery from exercise. Therefore, the purpose of this study was to compare the thermoregulatory responses of athletes with PA and TP during intermittent sprint wheelchair exercise and post exercise recovery in conditions representative of an indoor playing environment. It was hypothesised that athletes

with TP would be under a greater degree of thermal strain than athletes with PA similar to previously reported during continuous exercise.

5.3   Methods

5.3.1   Participants

Eight WCR players with TP (7 males, 1 female, 1 incomplete lesion) and eight wheelchair basketball players with PA (7 males, 1 female, 3 incomplete lesions) all competing in national teams or at an international level (Table 5.1), gave their written informed consent to participate in this experimental research study. The study was approved by Loughborough University Research Ethics Committee.

Table 5.1 Physiological and participant characteristics of athletes with tetraplegia and paraplegia (Mean ± SD).

	Tetraplegia (TP)	Paraplegia (PA)
Age (years)	27.4 ± 4.2	27.8 ± 6.2
Body mass (kg)	65.2 ± 4.4	67.7 ± 13.1
Sum of four skinfolds (mm)	52.3 ± 22.0	56.35 ± 29.7
$\dot{V}O_{2peak}$ (L·min^{-1})	1.55 ± 0.37	1.92 ± 0.47
Lesion level (range)	C4/5-C6/7	T4-S1
Time since injury (years)	8.0 ± 4.6	11.4 ± 7.7
Training (h·week^{-1})	15.0 ± 4.2	11.0 ± 6.4

5.3.2   Preliminary tests

On arrival at the laboratory, skinfold measurements were taken from the following sites while the individual was in a seated position; biceps, triceps, subscapular and superilliac to calculate the sum of four skinfolds (Harpenden Skinfold Callipers, Baty International, West

Sussex, UK.). A continuous incremental test on a motorised treadmill (HP Cosmos, Traunstein, Germany) was then conducted to determine $\dot{V}O_{2peak}$, as described in Section 3.4.1.

5.3.3 Experimental Conditions

5.3.3.1 Thermoregulatory measures

Participants ingested a telemetry pill (HQ Inc, Palmetto, Florida), for the measurement of T_{gi}, as an indicator of T_{core}. The pill was ingested ~8 h prior to the start of the test to avoid the influence of ingested food or fluid on the temperature reading, in accordance with previous recommendations (Byrne et al. 2007) and described in Section 3.1. Two hours after the preliminary test, participants were weighed to the nearest 0.1 kg using a wheelchair double-beam scale (Marsden Weighing Group Limited, Henley-on-Thames, UK), after voiding their bladder. During the ISP participants wore their usual training attire of lightweight tracksuit trousers and either a short or long sleeved fitted top. All the participants with tetraplegia wore abdominal binding. Although clothing was not standardised, this is unlikely to make a large contribution to skin temperature differences between groups, but may impact within group variation. Despite this, injury specific differences, such as injury level, are likely to make a larger contribution to any variance in regional skin temperature than the thermal properties of the clothing.

Seven thermistors (Grant Instruments, Cambridge, UK, accuracy $\pm$ 0.1°C) were attached to the skin using strips of water permeable surgical tape (3M Transpore, Loughborough). As described in Section 3.2, thermistors were placed on the forehead and right side of the body on the forearm, upper arm, upper back, chest, thigh and calf and connected to a Grant Squirrel logger (Series 2010,Grant Instruments, Cambridge, UK). The Ramanathan formula (Ramanathan 1964) was used to calculate T_{sk}, as previously described in Section 3.3.

An estimate of external work was calculated by the total distance covered (m) during the ISP multiplied by the total resistance (N) of the WERG -wheelchair system.

5.3.3.2 Intermittent sprint protocol (ISP)

Following instrumentation and transfer to their own sports wheelchair participants rested for 10 min, before completing a self-selected warm-up on a single cylinder WERG (Bromakin, Loughborough, UK). During the warm-up, participants performed a deceleration test (Mason et al. 2015), as described in Section 3.4.2. The ISP was conducted in an environmental

chamber (Weiss Gallenkamp, Loughborough) at 20.6 ± 0.1°C and 39.6 ± 0.8% relative humidity chosen to replicate a sports hall environment. All participants completed the test at a similar time in the afternoon to negate circadian variation (Winget et al. 1985) and refrained from caffeine and alcohol 24 h before the test. The ISP simulated an on-court training session, which was designed by a Great Britain wheelchair rugby coach and used previously by Leicht et al. (2012a). The ISP consisted of four exercise blocks separated by 4.5 min of passive recovery (Figure 5.1). Each block comprised of six bouts of 30 s, where athletes performed alternate three pushes forwards and backwards for the first 15 s followed by a 15 s sprint at maximum effort. Bouts were followed by 90 s of active recovery of low intensity. At the end of block four, participants rested for 15 min before all thermistors were removed and the participant was re-weighed. The whole session lasted 55.5 min with maximum intensity activity accounting for 12 min, including a total of 24 sprints. Consistent and standardised verbal encouragement was given throughout the test.
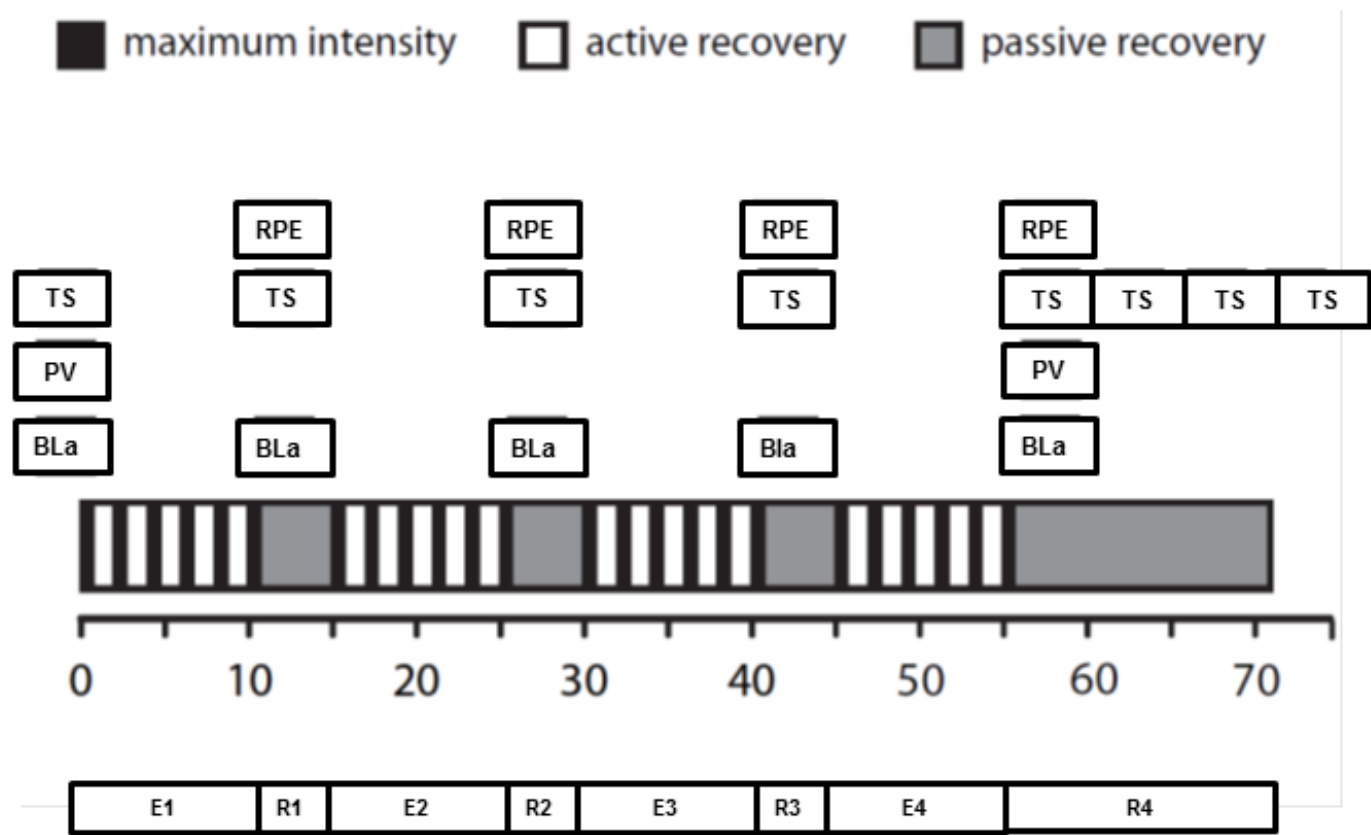
Figure 5.1 Schematic of the intermittent sprint protocol (ISP), including all measures taken throughout the four exercise blocks and post exercise recovery. The black blocks depict both the 15 s of alternate forwards and backwards pushing and the 15 s sprints. The white blocks depict the 90 s of active recovery. The grey blocks show the 4.5 min of passive recovery between each exercise block and the 15 min of recovery following the ISP. The corresponding exercise blocks and recovery periods are numbered below the time axis and Figures 2-3 will refer to these labels (E = exercise block, R = passive recovery). Warm–up is not included in the Figure. TS = thermal sensation, PV = measures to determine plasma volume (haemoglobin and haematocrit), BLa = blood lactate, RPE = rating of perceived exertion.

5.3.3.3 Heart rate and perceptual measures

Heart rate was recorded at 5 s intervals during the ISP (Polar PE 4000, Kempele Finland). Whole body ratings of RPE (Borg 1970) and thermal sensation (Toner et al. 1986) were recorded at the end of each exercise block. Prior to the start of the ISP and during post exercise recovery thermal sensation was also recorded. The thermal sensation scale, comprised of categories ranging from 0 ("unbearably cold") to 8 ("unbearably hot").

5.3.3.4 Blood lactate, plasma volume and fluid balance

After the warm-up and upon completion of exercise, capillary blood samples from the earlobe were taken using a safety lancet and heparinized capillary tube. These samples were analysed for haematocrit (Haemtospin 1300, Hawksley, Lancing, UK) and haemoglobin (B-Hemoglobin, Hemocue Limited, Dronfield, UK) to determine plasma volume using the method proposed by Dill (Dill et al. 1974). Capillary blood samples were taken at the end of each block for analysis of blood lactate (BLa) concentration (YSI SPORT, YSI Incorporated, Ohio, USA). Participants were allowed to drink *ad libitum* during the passive recovery between blocks and the volume of fluid was recorded. In addition to the absolute change in body mass ($Mass_{pre}$ - $Mass_{post}$), the change in body mass relative to fluid consumed (total mass loss) was also calculated (($Mass_{pre}$ - $Mass_{post}$) + fluid consumed).

5.3.4 Statistical Analysis

All data was checked for normality, using the Shapiro–Wilk test. Delta T_{gi} and T_{sk} were calculated from the change in temperature from the start of the ISP. Independent t-tests were used to analyse any between group differences in participant characteristics, total distance, total resistance, external work, fluid balance and start and end T_{gi} and T_{sk}. Sprint speed and power output across the 24 sprints, physiological and thermoregulatory responses were analysed using a two way (group x time) analysis of variance (ANOVA). Where significance was obtained post-hoc pairwise comparisons with a Bonferroni correction were conducted. For individual skin temperatures and T_{sk} during post exercise recovery data from seven TP were used, as data from the last three minutes of recovery were missing for one participant. For all comparisons where the assumption of sphericity was violated, a Greenhouse–Geisser correction was applied. Pearson's product-moment correlation test was used as appropriate. Effect sizes (ES) were used to supplement important findings and were estimated by Cohen's

d, where 0.2 represented a small effect size, 0.5 a medium effect size, and 0.8 a large effect size (Cohen 1988). All data were analysed using SPSS version 19.0 and significance was accepted at the $p \leq 0.05$ level. An *a priori* power analysis, conducted in G*Power 3.1, revealed a minimum sample size of 8 participants was required per group, with 90% power and an α of 5%, based on findings from previous research (Price et al. 2003).

5.4 Results

5.4.1 Participant characteristics

There were no differences between TP and PA for the physiological and participant characteristics ($p > 0.05$, Table 5.1). Yet, large effect sizes were apparent for $\dot{V}O_{2peak}$ (ES = 0.9) and training hours per week (ES = 0.7).

5.4.2 Sprint performance

There were no differences between groups or across the 24 sprints for either sprint speed or peak power output (all $p > 0.05$, Table 5.2). Total resistance of the WERG -wheelchair system was greater in TP ($p = 0.01$, ES = 1.6) whilst total distance covered during the ISP was greater for PA ($p < 0.001$, ES = 1.9). External work was not statistically different between groups ($p = 0.70$, ES = 0.2).

Table 5.2 Sprint performance for athletes with tetraplegia and paraplegia (Mean $\pm$ S.D.)

	Tetraplegia (TP)	Paraplegia (PA)
Sprint speed (m·s^{-1})[a]	3.14 $\pm$ 0.59	3.51 $\pm$ 0.44
Peak power output (W)[a]	67 $\pm$ 14	59 $\pm$ 14
Total resistance (N)	21 $\pm$ 3*	17 $\pm$ 3
Total distance (m)	2316 $\pm$ 258*	3042 $\pm$ 468
External Work (kJ)	49 $\pm$ 5	51 $\pm$ 9

[a] Sprint speed and power output across the 24 sprints of the four quarters. *significantly different from PA ($p < 0.05$).

5.4.3 Physiological responses

Mean and peak HR for each block of the ISP were greater for PA than TP ($p < 0.05$, Table 5.3). Mean HR for both groups increased from block 1 to 2 then remained stable throughout exercise. For both groups peak HR was similar over time ($p = 0.43$). Throughout exercise BLa was similar over time ($p = 0.09$) but lower in TP than PA (8.08 ± 3.04 and 8.73 ± 2.17 mmol·l^{-1} for TP and PA, respectively, $p = 0.02$).

Table 5.3 Mean and peak heart rate (HR) and blood lactate during the intermittent sprint protocol (ISP) for athletes with tetraplegia and paraplegia (Mean ± S.D.)

	Tetraplegia (TP)	Paraplegia (PA)
Mean heart rate (b.min^{-1})	107 ± 6*	132 ± 15
Peak heart rate (b.min^{-1})	133 ± 6*	161 ± 8
Blood lactate (b.min^{-1})	8.08 ± 3.04*	8.73 ± 2.16

*significantly different from PA ($p < 0.05$).

5.4.4 Gastrointestinal temperature

Gastrointestinal temperature was similar between groups at the start of exercise ($37.0 \pm 0.6°C$ and $37.1 \pm 0.3°C$ for TP and PA, respectively, $p = 0.75$). At the end of exercise TP demonstrated a greater T_{gi} than PA ($38.2 \pm 0.5°C$ and $37.6 \pm 0.4°C$ for TP and PA, respectively, $p = 0.02$, ES = 1.3). During both exercise and post exercise recovery, TP experienced a greater increase in T_{gi} from resting values than PA (both $p < 0.001$, ES = 0.8 and ES = 2.3 for exercise and recovery, respectively, Figure 5.2). At the end of post exercise recovery, T_{gi} for TP remained elevated from rest by $1.1°C$ compared to $0.2°C$ for PA ($38.1 \pm 0.5°C$ and $37.3 \pm 0.3°C$ for TP and PA, respectively, $p < 0.001$, ES = 1.8). Gastrointestinal temperature decreased by $0.3 \pm 0.3°C$ and $0.1°C \pm 0.2°C$ during the post exercise recovery for PA and TP, respectively.

5.4.5 Skin temperature

Mean skin temperature was similar between groups at the start ($29.5 \pm 1.6°C$ and $30.6 \pm 0.6°C$ for TP and PA, respectively, $p = 0.09$, ES = 0.9) and end of exercise ($30.2 \pm 1.5°C$ and $30.0 \pm 1.6°C$ for TP and PA, respectively, $p = 0.75$, ES = 0.2) and end of post exercise recovery ($30.0 \pm 1.4°C$ and $29.7 \pm 1.8°C$ for TP and PA, respectively, $p = 0.76$, ES = 0.2).

During exercise and post exercise recovery the change in T_{sk} from resting values was different for TP and PA ($p < 0.001$, ES = 1.5 and $p = 0.02$, ES = 1.4 for exercise and recovery, respectively). For the PA group, T_{sk} decreased during exercise whilst athletes with TP experienced an increase in T_{sk} (Figure 5.2). Individual skin temperatures (Figure 5.3) were similar between groups at the start and end of exercise ($p > 0.05$). During exercise, back skin temperature was the only site that demonstrated a difference between groups with an increase from resting values in TP (0.9 ± 0.6°C) and a decrease in PA (-0.4 ± 0.9°C, $p < 0.001$). During post exercise recovery, chest, back, forearm and forehead skin temperature remained elevated from the start of recovery to a greater extent in TP than PA ($p < 0.05$).
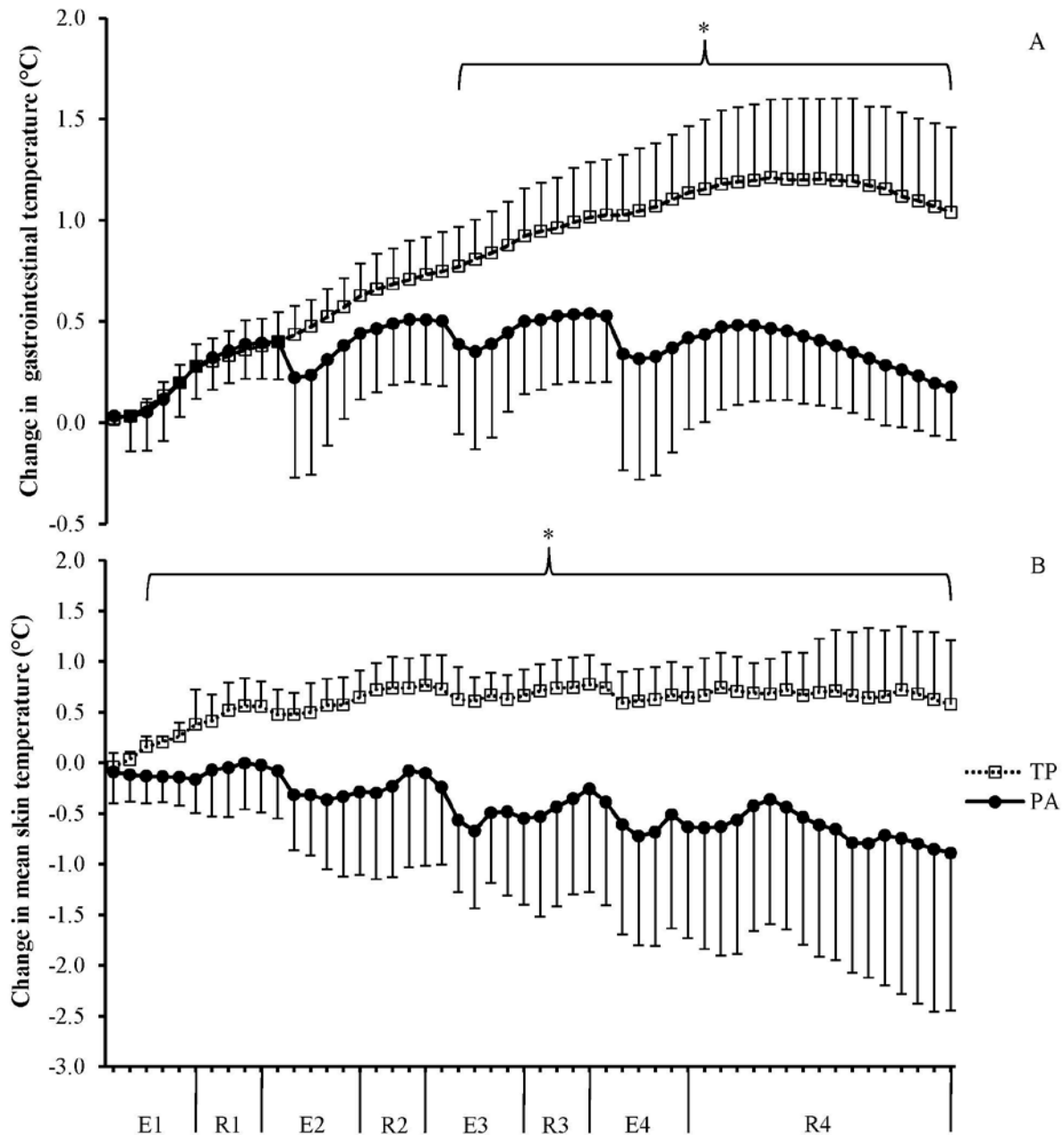
Figure 5.2 Change in A) gastrointestinal temperature B) mean skin temperature from resting values for athletes with tetraplegia (TP) and athletes with paraplegia (PA) during each exercise block and post exercise recovery (E = exercise block, R = passive recovery). *significantly different from PA (p < 0.05).
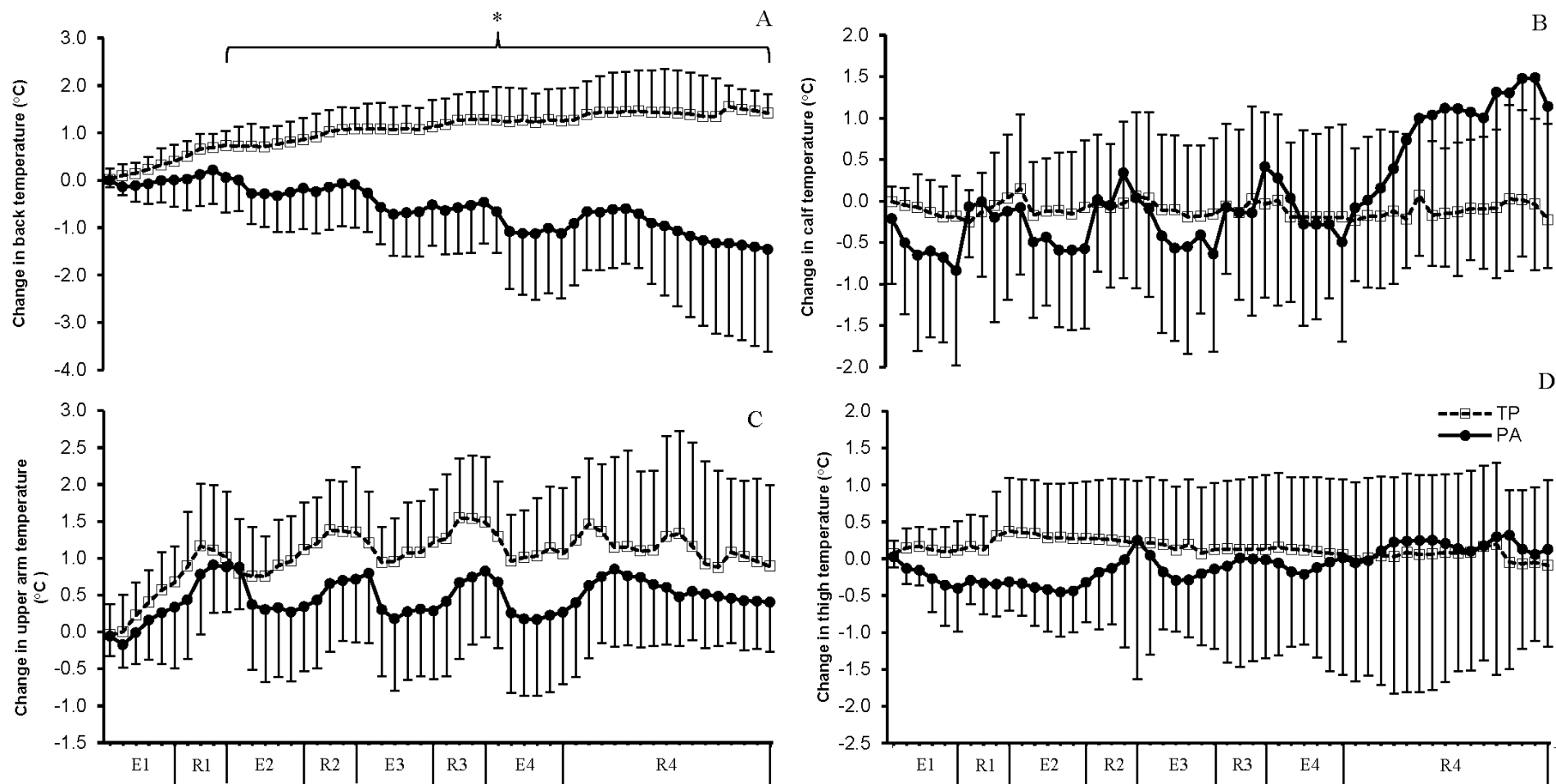
Figure 5.3 Individual skin temperatures (A-back, B-calf, C-upper arm, D-thigh) for athletes with tetraplegia (TP) and athletes with paraplegia (PA) during each exercise block and post exercise recovery (E = exercise block, R = passive recovery). *significantly different from PA (p < 0.05).

5.4.6 Perceptual measures

During exercise RPE was similar between groups (p = 0.52) with an increase over time (14 ± 1 and 16 ± 2 for the end of block 1 and 4, respectively, Figure 5.4). Thermal sensation was similar between groups during exercise, (4 ± 1 and 6 ± 1 at rest and end of block 4, respectively, p = 0.29, Figure 5.4) and post exercise recovery (6 ± 1 and 3 ± 1 at the start and end of recovery, respectively, p = 0.69). In TP and PA, T_{sk} was not significantly correlated with thermal sensation (r = -0.27, p = 0.66 and r = -0.71, p = 0.18 for TP and PA, respectively). In PA, T_{gi} was not significantly correlated with thermal sensation (r = -0.12, p = 0.84) but a significant correlation was apparent in TP (r = 0.90, p = 0.04).

5.4.7 Fluid balance

Both groups drank similar amounts during the ISP and post exercise recovery (540 ± 112 ml and 469 ± 233 ml for TP and PA, respectively, p = 0.45). The absolute change in body mass (0.4 ± 0.4 kg and 0.1 ± 0.3 kg for TP and PA, respectively, p = 0.11) and total mass loss were similar between groups (0.2 ± 0.4 kg and 0.4 ± 0.3 kg for TP and PA, respectively, p = 0.15). Plasma volume changes were similar between groups (4.0 ± 13.7% and 4.3 ± 9.5% for TP and PA, respectively, p = 0.96).
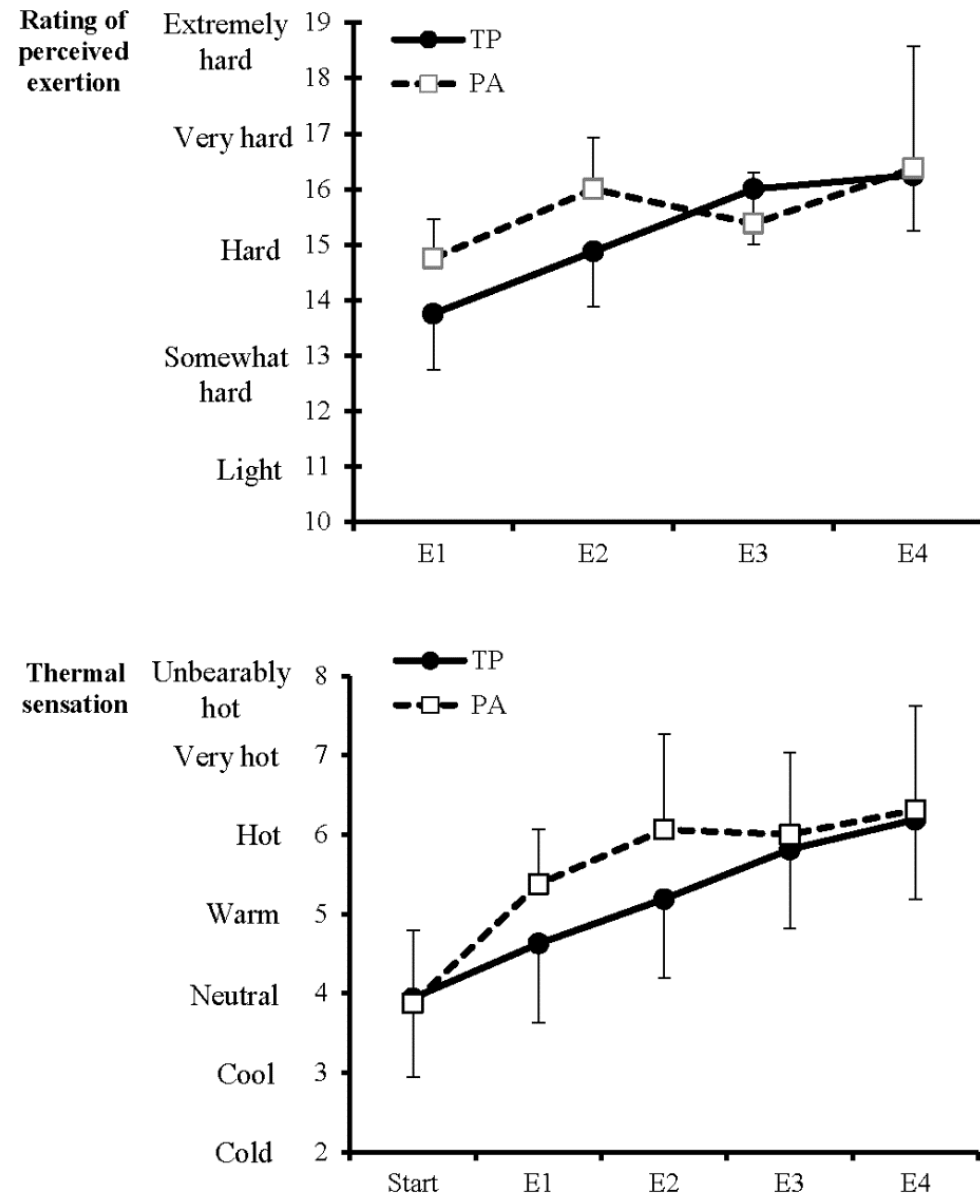
Figure 5.4. Rating of perceived exertion and thermal sensation for athletes with tetraplegia (TP) and athletes with paraplegia (PA) during each exercise block (E = exercise block).

5.5 Discussion

The main findings of the present study indicate that despite external work being similar between groups, T_{gi} increased at a greater magnitude in TP compared to PA during intermittent sprint wheelchair exercise in conditions representative of an indoor sporting environment, accepting the hypothesis. The greater increase in T_{gi} for TP compared to PA signifies that thermoregulatory differences between the groups were predominantly due to a lower capacity for heat loss in TP. Even during post exercise recovery T_{gi} remained elevated in TP signifying an inability to dissipate the heat produced during exercise, resulting in the retention of heat post exercise.

Further increases in thermal strain in TP were not prevented by the active and passive recovery between the maximum effort bouts as T_{gi} were found to continually increase throughout the protocol. The T_{gi} responses for both groups are therefore comparable to previous studies during continuous wheelchair exercise, with increases of 0.2 - 0.7°C (Gass et al. 1988, Dawson et al. 1994) and 0.9°C (Price et al. 1999b) observed for PA and TP, respectively. In contrast to Study 1 (Chapter 4), T_{sk} was greater than ambient temperature in the present study, thus heat loss could occur by both dry and wet heat exchange. Thus, PA were able to attain heat balance, shown by the stable T_{gi} and reductions in T_{gi} between exercise blocks. In TP, despite T_{sk} being above ambient temperature, due to their loss/minimal sweating capacity and vasomotor control, both in the present study and at rest in Study 1 they were unable to attain heat balance.

The T_{sk} response of the two groups likely reflects the athletes' sweating capacity, being proportional to lesion level. For instance, the greater reduction in sweating capacity in TP resulted in an increase in T_{sk} during exercise. In PA, T_{sk} decreased during exercise, likely due to the larger body surface area available for sweating and therefore greater evaporative cooling of the skin. It should be noted that although T_{sk} was not significantly different at the onset of exercise, a large ES demonstrates PA may have had a substantially warmer starting T_{sk} than TP. Yet, T_{sk} data should be interpreted with caution in individuals with an SCI as it may mask regional skin temperature responses, especially as specific formula for individuals with an SCI have not been developed (Price 2006).

During exercise, differing responses in back skin temperature were apparent, increasing in TP and decreasing in PA, due to the majority of the upper body skin of TP being insensate compared to sensate in PA. Yet a similar finding was not found for chest skin temperature. Sweat rates vary with body region in AB individuals, with a greater sweat rate apparent at the upper back than the chest (Smith et al. 2011). Thus, at the chest, a lower evaporative cooling effect of sweat may have been apparent in PA, resulting in a chest skin temperature similar to that seen in TP. In both groups, upper arm skin temperature demonstrated a decrease during exercise shown previously, yet more pronounced, during continuous wheelchair propulsion (Price et al. 1999a). The decrease in upper arm skin temperature is thought to be caused by the arm moving relative to the body in wheelchair propulsion causing convective cooling to the upper arm (Price et al. 1999a).

Neither group experienced a change in thigh skin temperature during exercise or post exercise recovery likely due to the disrupted blood flow and vascular atrophy below the level of the lesion (Hopman 1994). Although small, there was a significant increase from rest in calf skin temperature over time, possibly due to the variable response of calf skin temperature in PA (Price et al. 1997). The degree of sweating and blood flow redistribution in the lower limb may be dependent on the lowest intact part of the sympathetic chain, with the pathway for vasodilation in the lower limb located at or below T10 (Gass et al. 1988). In individuals with lesions at T12, calf skin temperature has been shown to increase during exercise with little or no change for individuals with lesions at T10/T11 (Gass et al. 1988). However, in the present study, similar trends in calf skin temperature were apparent for individuals with lesions above (n = 5) and below T10 (n = 3) in the PA group. To fully understand the underlying mechanisms of vasomotor control of the lower body during upper body exercise further study is required.

More pronounced differences between skin temperature sites may have been masked by the large inter-individual variations in skin temperatures, a noticeable response in individuals with an SCI (Price et al. 2002, Gass et al. 1992). These variations may have been heightened by the large range of lesion levels in PA (T4-S1) and completeness of the lesion, resulting in differences in sympathetic and somatosensory pathways, in arrangements of sympathetic outflow and the type and degree of reinnervation (Hopman 1994, Price et al. 1997).

From a perceptual perspective, even though TP were exercising at a greater T_{gi} than PA, similar thermal sensation scores throughout exercise indicate they did not perceive to be

warmer. In the AB, thermal sensation is largely dictated by T_{sk} independent of T_{core} (Schlader et al. 2011), however in the current study thermal sensation did not correlate with T_{sk} in either TP or PA. Only a small portion of an individual with an SCI's body (head, anterior of arms and shoulders) is sensate, therefore the role of skin temperature for thermal perceptions may be limited to a small surface area (Attia et al. 1983). Gastrointestinal temperature did significantly correlate with thermal sensation in TP, suggesting they were able to perceive their increasing T_{gi}. However, this relationship may be due to the concomitant and continuous increase in T_{gi} and thermal sensation during the ISP and may not represent a causal relation. During higher intensity exercise and in warmer ambient conditions this may be of more concern, especially as these athletes could potentially override perceived signs of thermal strain, putting them at risk of heat injury (Webborn et al. 2010).

A large ES in training hours (ES = 0.7) signifies TP were more highly trained than PA, which may have led to a greater development of their remaining musculature (Abel et al. 2008). Potentially, this may have enabled TP to produce similar power outputs and external work to PA. The larger total resistance of the WERG -wheelchair system for TP was, however, likely caused by the differences in the mass of the wheelchairs used in wheelchair basketball and rugby, with heavier wheelchairs used in the latter (~11-13 kg vs. 15-19 kg). The lower mean and peak HR in TP, due to the reduced sympathetic innervation of the heart resulting in reductions in maximal HR, is consistent with previous studies (Theisen 2012). Although there was no significant difference in $\dot{V}O_{2peak}$, a large ES signifies a meaningful difference between the groups was apparent, with previous research indicating an inverse relationship exists between lesion level and $\dot{V}O_{2peak}$ (Theisen 2012). The extent to which the athlete's aerobic fitness would have affected the results is unclear, yet, future work matching the groups for training status may accentuate the differences in thermoregulatory responses due to the level of spinal lesion.

A limitation of the study may be the inclusion of four individuals with an incomplete SCI (one TP and three PA) in the mean group values. The degree of autonomic dysfunction may be dependent on the completeness of the injury (Theisen 2012), with incomplete lesions resulting in a greater amount of sensory information regarding their thermal state and a greater capacity to sweat (Webborn et al. 2010). Yet, studies investigating the effects of the completeness of a lesion are scarce (Song et al. 2015). In Study 1 (Chapter 4), both individuals with incomplete and complete TP and incomplete PA had a similar T_{sk} response,

whilst an attenuated response was apparent in individuals with complete PA. If the degree of autonomic dysfunction is dependent on the completeness of the injury, one would expect complete PA to have a greater T_{sk} response than incomplete PA. These results depict that further work is greater needed to determine whether physiological responses differ between athletes with complete and incomplete injuries. Nevertheless, in the present study the inclusion of individuals with incomplete lesions was justified as their T_{gi} and T_{sk} responses were within one standard deviation of the mean response of each group. Furthermore, one female in both PA and TP was included in the mean group responses. Similarly their T_{gi} and T_{sk} responses were within 1 standard deviation of the mean response of each group, justifying their inclusion.

5.6 Practical Applications

Although neither group were under considerable thermal strain, the present study highlights that TP experience a greater increase in T_{gi} for the same external work load of intermittent sprint wheelchair exercise compared to PA. Thus despite the short periods of recovery during each exercise block and between blocks, T_{gi} continued to rise similarly to during steady state continuous exercise (Price et al. 2003). Even during the 15 min post- exercise recovery period T_{gi} continued to rise in TP and at the end of recovery was still 1.1°C warmer than at the start of the protocol. This signifies that support staff should be aware that if multiple matches are played in one day, TP may be starting the second match at a heightened T_{gi} than the first match.

Even though the protocol had greater ecological validity than previous studies due to the intermittent nature and use of wheelchair propulsion, the ISP may not have been wholly reflective of a WCR or basketball match. Total distances covered were considerably shorter (2316 ± 258 m) than the activity profiles of WCR players during a match (4316 ± 626 m, Rhodes et al. 2015). If the ISP was of a similar magnitude to match play, i.e. greater metabolic work, the athletes may have experienced a greater thermal response, especially TP.

5.7 Conclusions

Similarly to continuous arm cranking and wheelchair exercise, TP have a greater inability to dissipate heat than PA during intermittent sprint wheelchair exercise in conditions representative of an indoor sporting environment. Despite the two groups producing similar amounts of external work, TP had a marked increase in T_{gi} during exercise and post exercise

recovery, signifying that differences between the groups were predominantly due to differences in heat loss. Neither group were under high levels of thermal strain, yet the present study highlights the heightened thermal response of TP to intermittent sprint wheelchair exercise, with caution that a greater T_{gi} response may be apparent during actual match play.

Chapter 6

Study 3: Thermoregulatory Responses during Competitive Wheelchair Rugby Match Play

A modified version of this chapter has been accepted for publication in the *International Journal of Sports Medicine.*

Study 2 identified that athletes with TP have a greater inability to dissipate heat than athletes with PA during intermittent sprint wheelchair exercise in conditions representative of an indoor sporting environment. Study 3 extends the findings from Study 2 to competitive sports specific on-court match play. This study aims to highlight whether a player's physical impairment, activity profile or physical attributes predisposes them to a greater amount of thermal strain during match play.

6.1 Abstract

Purpose: Wheelchair rugby was originally developed for individuals with TP, but recent changes to the classification system have meant that individuals with other physical impairments are now eligible to compete. Based on physical impairment, WCR players are classified into 1 of 8 classification groups. Yet, players with TP within the same classification group as players with a non-spinal related physical impairment may be at a thermoregulatory disadvantage during WCR match play. The purpose of this study was to determine whether a player's physical impairment or activity profile was related to the amount of thermal strain experienced during competitive WCR match play.

Methods: Seventeen (16 male and 1 female) elite WCR players played a competitive WCR match, whilst activity profiles were determined using an indoor tracking system. Measures of T_{gi}, skin temperature, HR, RPE and thermal sensation were recorded during the match. For analysis, players were divided into two groups depending on their physical impairment; players with TP (n = 10) or non-spinal related physical impairment (NON-SCI, n = 7).

Results: Total distance was lower (4842 ± 324 m vs. 5541 ± 316 m, $p < 0.01$, ES = 2.2) and mean speed slower (1.13 ± 0.11 m·s^{-1} vs 1.27 ± 0.11 m·s^{-1}, $p < 0.03$, ES = 1.3) in TP than NON-SCI during match play. Yet, the change in T_{gi} was significantly greater in TP ($1.6 \pm 0.4°$C) than NON-SCI ($0.7 \pm 0.3°$C, $p < 0.01$, ES = 2.5). Mean skin temperature was not significantly different between groups ($p > 0.05$, ES = 0.2), yet T_{sk} increased at the end of quarter 2 in TP whilst decreased in NON-SCI at the same time point. RPE and thermal sensation were not significantly different between groups ($p > 0.05$).

Conclusions: Players with TP covered less distance and had slower mean speeds during WCR match play, thus were producing a smaller amount of heat than NON-SCI. Yet, these players were under greater thermal strain, depicted by the greater T_{gi} and T_{sk}, due to a reduction in heat loss capacity as a result of their SCI.

6.2 Introduction

The distances covered in Study 2 (Chapter 5) were considerably less than the distances covered by WCR players during a match (Rhodes et al. 2015). Despite this, results revealed that even though similar amounts of external work were produced during intermittent sprint wheelchair exercise, athletes with TP have a greater inability to dissipate heat than athletes with PA. Whether athletes with TP are under greater thermal strain compared to teammates with non-spinal related physical impairments (NON-SCI) during competitive WCR match play, taking into account their activity profiles and roles on court, is currently unknown.

Wheelchair rugby was originally developed for individuals with TP. However, recent changes to the International Wheelchair Rugby Federation (IWRF) classification system have meant that individuals with other physical impairments, such as cerebral palsy, multiple amputations and neuromuscular disease, are now eligible to compete. Based on physical impairment, male and female WCR players whom compete together are classified into 1 of 8 classification groups from 0.5 (most impaired) to 3.5 (least impaired, International Wheelchair Rugby Federation 2015). In individuals with TP, in addition to the lack of voluntary control of their torso and upper limb dysfunction, they are also thermoregulatory impaired (Guttmann et al. 1958). Hence, players with TP within the same classification group as players with a NON-SCI may be at a thermoregulatory disadvantage during WCR match play.

Studies have shown IWRF classification to be closely related to the volume of activity elicited over a typical WCR quarter (Rhodes et al. 2015, Sarro et al. 2010, Sporner et al. 2009). For example, high point players (2.0-3.5 points) are capable of greater peak speeds and spend less time within low speed zones compared to low point players (0.5-1.5 points, Rhodes et al. 2015). Furthermore, high point players are shown to have better ball-handling skills, such as interceptions and passes made and caught (Morgulec-Adamowicz et al. 2010, Molik et al. 2008), most likely attributed to these players occupying offensive rather than defensive roles (Rhodes et al. 2015). Interestingly, despite the noted thermoregulatory impairment of individuals with TP, no study to date has examined the combination of thermal strain of WCR players during match play and the associated activity profiles. Individual thermoregulatory outcomes during exercise may be influenced by independent factors, such as the physical attributes of body mass and body composition (Havenith et al. 2015). Although it has also been suggested that a smaller percentage of individual variability in

thermoregulatory responses is explained by body composition in the AB (Cramer et al. 2015), due to the atrophy of skeletal muscle in the lower limbs, whether the same variability exists for individuals with an SCI is currently unknown.

Whether a player's physical impairment, activity profile or physical attributes predisposes them to a greater amount of thermal strain during match play has both a practical and clinical importance. For instance, identifying players under greater thermal strain could enable both the implementation of targeted cooling strategies and a reduction in performance decrements due to a high T_{core}. Furthermore, by investigating players during actual match play a physical challenge and psychological stress is attained that is difficult to replicate in a laboratory. Thus the purpose of this study was twofold 1) to compare the thermoregulatory responses and activity profiles of players with TP to those players with a NON-SCI during competitive WCR and 2) in TP determine whether their classification, activity profile and/or physical attributes were related to the thermal strain experienced during competitive WCR. It was hypothesised that 1) TP would be under a greater amount of thermal strain than players with a NON-SCI during competitive WCR and 2) due to the greater volume of activity of high point players, reported previously (Rhodes et al. 2015), high point players with TP would experience a heightened thermal response.

6.3 Methods

6.3.1 Participants

Sixteen male and one female highly trained WCR players from the BT Great Britain Wheelchair Rugby (GBWR) squad gave their written informed consent to participate in this study. The study was approved by the Loughborough University Research Ethics Committee. Participants were divided into two groups, TP (n = 10) or NON-SCI (n = 7, Table 6.1).

Table 6.1 Physical attributes and participant characteristics of the two groups of wheelchair rugby players; players with tetraplegia (TP) and non-spinal related physical impairment (NON-SCI).

	Tetraplegia	Non-spinal related physical impairment
Impairment/ level of SCI	C5/6 - C7 (2 incomplete)	Including Cerebral Palsy (n=2), lower limb deficiency (n=4) and leg amputation (n=1).
Age (years)	30 ± 5*	23 ± 5
Body mass (kg)	68.4 ± 10.5	65.3 ± 14.8
Sum of four skinfolds (mm)	57.3 ± 30.6	51.0 ± 13.6
$\dot{V}O_{2peak}$ (L·min^{-1})	1.4 ± 0.3*	2.4 ± 0.7
Training (h·week^{-1})	14 ± 4	10 ± 4
Classification	0.5-2.5	1.5-3.5

*significantly different to NON-SCI, $p \leq 0.05$.

6.3.2 Experimental design

All participants completed an incremental exercise test to exhaustion on a treadmill for determination of $\dot{V}O_{2peak}$. On separate occasions participants played in a WCR game at the squad's usual training venue and in TP, seven participants had a dual-energy X-ray

absorptiometry (DXA) scan. Three TP participants had a history of high levels of ionising radiation in the previous 12 months and were excluded from having a DXA scan.

6.3.3   Preliminary testing

6.3.3.1   Peak oxygen uptake ($\dot{V}O_{2peak}$)

The incremental exercise test was completed on a motorised treadmill (HP Cosmos, Traunstein, Germany) as described in Section 3.1.

6.3.3.2   Body composition

Skinfold measurements (Harpenden Skinfold Callipers, Baty International, West Sussex, UK) were taken for all participants (n = 17) in a seated position from the biceps, triceps, subscapular and suprailliac to calculate the sum of skinfolds (mm). However to get a true reflection of body composition for individuals with an SCI, according to recent studies (Goosey-Tolfrey et al. 2016), a DXA scan was performed for seven of SCI using a Lunar Prodigy Advance DXA scanner (GE Lunar, Madison, WI, USA), following procedures previously described in Keil et al. (2016). Each individual was aligned supine on the examination bed and positioned as closely as possible to the standard protocols. Positions that may have produced spasms or any discomfort were minimised and time was allowed for any spasm generated to subside before scanning. On the same day, two whole body scans were performed on each participant. The compartments measured were total body fat and lean tissue mass. Total body fat and lean tissue mass percentage was obtained from the total body fat mass and lean tissue mass, respectively, divided by the total body mass. Body surface area (m^2) was estimated by the Dubois formula (Dubois et al. 1916).

6.3.4   Field testing

6.3.4.1   Match play

Participants were separated into teams in consultation with the GBWR coach which consisted of four participants (classification points totalling 8.0), with games refereed by an official following IWRF regulations (International Wheelchair Rugby Federation 2015). The match was played on a standard indoor basketball court and consisted of four 8 minute quarters with the game clock stopped during any stoppages or when the ball was out of play, in accordance with IWRF regulations (International Wheelchair Rugby Federation 2015).

To obtain a continuous trace of T_{gi} data, Cortemp data recorders (HQ Inc, Palmetto, Florida) were attached in a secure position to the wheelchairs of up to three participants per match, due to the availability of Cortemp data recorders. Due to a disruption in connection between the pill and recorder the authors were not able to obtain continuous data sets for all players, thus T_{gi} values for the end of each quarter were analysed. Therefore a total of seven matches were monitored. The range of environmental conditions of the seven matches was 18.4 - 20.9°C and 31.1 – 45.1% relative humidity. Participants were required to play the full duration of the match and were not permitted to use any form of cooling strategy.

6.3.4.2 Activity profiles

A radio-frequency based indoor tracking system (Ubisense, Cambridge, UK) was used to provide real-time analysis of WCR activity profiles (Perrat et al. 2015, Rhodes et al. 2014). The indoor tracking system is a radio frequency based real-time location system with an overall bandwidth of 137 Hz. Each participant was equipped with a small, lightweight tag (25g) fitted into the back of a global positioning system vest that communicated with six sensors through ultra-wideband signals (Figure 6.1). Each sensor was mounted on an extendable tripod, elevated to approximately 4 m in height. The sensors detect ultra-wideband signals from the tags, measuring both the angle of arrival and the time difference of arrival to generate an accurate position of each tag. This provides raw, unfiltered data on the positional coordinates in three dimensions (x, y, & z). A calibration procedure outlined by Rhodes et al. (2014) was conducted prior to the start of each match. Data collection commenced at the beginning and terminated at the end of each quarter and was paused during periods of extended stoppages (e.g. time-outs, equipment breaks), resulting in a mean collection time of 17.5 ± 1.5 min/quarter.

Total distance travelled (m), distance travelled relative to time spent on court ($m \cdot min^{-1}$) and mean and peak speed were determined for each participant. Using the mean peak speed (V_{max}) from the match, five arbitrary speed zones were individualised for each participant, as previously used by Rhodes et al. (2015); very low ($\leq 20\%$ V_{max}), low (21-50% V_{max}), moderate (51-80% V_{max}), high (81-95% V_{max}) and very high ($\geq 95\%$ V_{max}). The percentage of total match time spent in each speed zone was determined for each individual. High intensity activities (HI, high and very high speed zones) were extended to include the total number and distance covered during these activities.
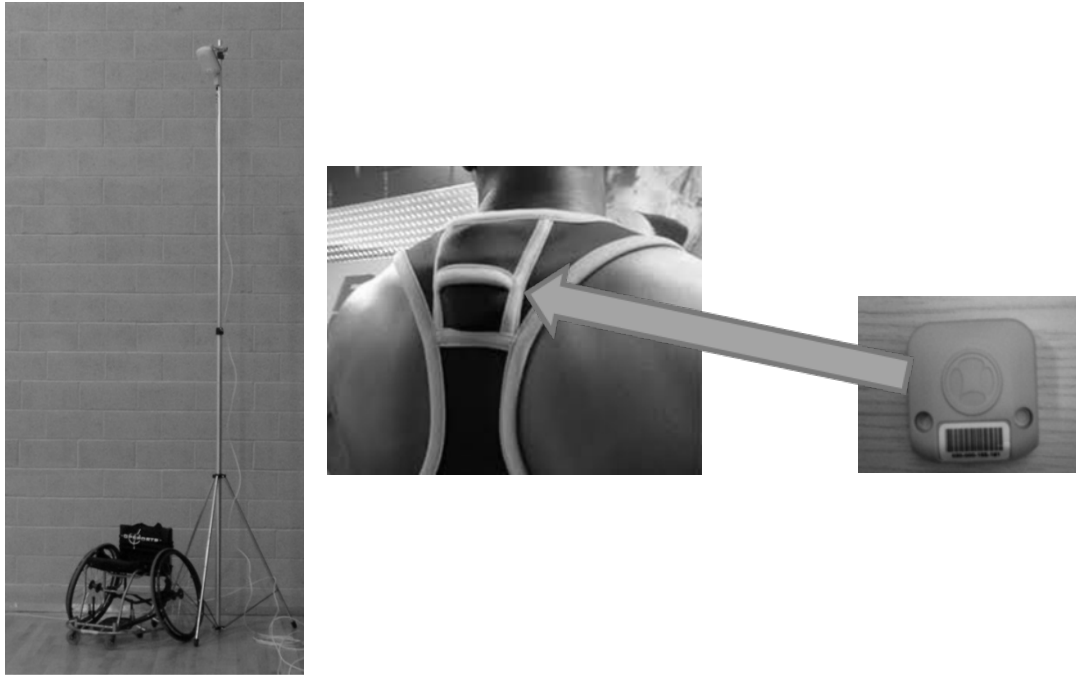
Figure 6.1 Indoor tracking system sensor mounted on a tripod and lightweight tag housed on the back of a global positioning system vest.

6.3.5 Thermoregulatory measures

Participants ingested a telemetry pill (HQ Inc, Palmetto, Florida) for the measurement of T_{gi}, as an indicator of T_{core}, ~6-8 h prior to the start of the match, to avoid the influence of ingested food or fluid on the temperature reading in accordance with previous recommendations (Byrne et al. 2007), as described in Section 3.1. All matches were played at a similar time in the afternoon to negate circadian variation (Winget et al. 1985). Participants were weighed before and after the match to the nearest 0.1 kg (Detecto, Cardinal Scale Manufacturing Co., Webb City, Missouri, USA). Participants were allowed to drink *ad libitum* during breaks between quarters and the volume of fluid was recorded. In addition to the absolute change in body mass ($Mass_{pre}$ - $Mass_{post}$), the change in body mass relative to fluid consumed (total mass loss) was also calculated (($Mass_{pre}$ - $Mass_{post}$) + fluid consumed). Participant wore their usual competition attire, which consisted of playing vest and lightweight trousers. Some participants also wore abdominal binding and/or wore arm bands over the middle of their arm to protect their skin from grazes when abruptly stopping their wheelchair with their arms. Therefore clothing may have varied slightly between participants

but was representative of the clothing participants wear during competition, further increasing ecological validity of the study.

Gastrointestinal temperature was measured by Cortemp data recorders at the end of each quarter, by averaging three values taken over a 1 min period. Seven iButtons (DS1922T, Maxim Integrated Products, Inc., Sunnyvale, CA, USA) were applied to the forehead and on the right side of the body at the forearm, upper arm, upper back, chest, thigh and calf, as described in Section 3.2, prior to the 30 min warm-up led by the coach.

In addition to individual skin temperatures, T_{sk} was calculated in accordance with the formula by Ramanathan (Ramanathan 1964), as previously described in Section 3.3. Convective (h_c) and evaporative (h_e) heat transfer coefficients were calculated using the following equations for a seated person (Mitchell 1974):

$$h_c (Wm^{-2} \cdot C^{-1}) = 8.3 \, (v)^{0.6} \tag{1}$$

$$h_e \, (Wm^{-2} \cdot C^{-1}) = 16.5 h_c \tag{2}$$

Where: v is the estimated player mean speed in m·s^{-1} from the ITS.

6.3.6 Heart rate and perceptual measures

Heart rate was continually recorded at 5 s intervals (Polar PE 4000, Kempele Finland). Thermal sensation (Toner et al. 1986) was recorded at the start of the match (categories ranged from 0.0 ["unbearably cold"] to 8.0 ["unbearably hot"] in 0.5 increments) and at the end of each quarter in addition to RPE (Borg 1970).

6.3.7 Metabolic energy expenditure

Metabolic energy expenditure (M) during the match was estimated using the minute-average values for oxygen consumption ($\dot{V}O_2$) in litres per minute and the respiratory exchange ratio (RER) during the $\dot{V}O_{2peak}$ test. The metabolic cost of pushing at the mean speed during each quarter was calculated from the plot of oxygen consumption vs. mean speed using these data. Metabolic energy expenditure was calculated using the equation below:

$$M \, (W) = V\dot{O}_2 \, \frac{\left(\frac{RER - 0.7 \cdot e_c}{0.3}\right) + \left(\frac{1 - RER \cdot e_f}{0.3}\right)}{60} \cdot 1000 \tag{3}$$

Where: e_c is the caloric equivalent per litre of oxygen for the oxidation of carbohydrates (21.13 kJ), and e_f is the caloric equivalent per litre of oxygen for the oxidation of fat (19.62 kJ).

6.3.8 Statistical analysis

Data analysis was performed using the Statistical Package for the Social Sciences (SPSS version 22, Chicago, IL) and all data are presented as mean ± SD. Delta T_{gi} and T_{sk} were calculated as the change from the start of the match. The rate of change in T_{gi} was calculated by the change in T_{gi} over a quarter divided by the total time of the quarter. Normality and homogeneity of variance were confirmed by Shapiro–Wilk and Levene's test, respectively. One participant from the TP group was stopped during the match due to reaching the safety limit of a high T_{gi} (39.5°C). Thus data analysis for TP used nine participants, except for the correlations between activity profiles, physical attributes and end of match T_{gi} where analysis was based on all ten participants. Independent t-tests were used to analyse differences between TP and NON-SCI in participant characteristics, activity profiles, heat transfer coefficients and fluid balance. Speed zones, HR, change in T_{gi}, T_{sk} and individual skin temperatures, and perceptual responses were analysed using a mixed method ANOVA. For all comparisons where the assumption of sphericity was violated, a Greenhouse–Geisser correction was applied. Where significance was obtained post-hoc pairwise comparisons with a Bonferroni correction were conducted. Main effects and interactions were accepted as statistically significant when $p \leq 0.05$. Confidence intervals (95% CI) for differences are presented, alongside effect sizes (ES) to supplement important findings. Effect sizes were calculated as the ratio of the mean difference to the pooled standard deviation of the difference. The magnitude of the ES was classed as trivial (<0.2), small (0.2–0.6), moderate (0.6–1.2), large (1.2–2.0) and very large ($\geq$2.0) based on previous guidelines (Batterham et al. 2006). Pearson's product-moment correlation test was used as appropriate. An *a priori* power analysis, conducted in G*Power 3.1, revealed a minimum sample size of 14 participants was required, with 90% power and an α of 5%, based on findings from Study 2 (Chapter 5). Given the heterogeneity of the population, an additional three participants were recruited to increase statistical power.

6.4 Results

6.4.1 Participant characteristics

The two groups were similar in terms of body mass (p = 0.63) and sum of skinfolds (p = 0.39). Yet TP were older (p = 0.04), demonstrated a lower $\dot{V}O_{2peak}$ (p = 0.01) and functional class than NON-SCI (p = 0.01, Table 6.1).

6.4.2 Activity profiles

Total (p < 0.01, 95% CI = - 1045.5 to -352.5, ES = 2.2,) and relative distances (p = 0.03, 95% CI = -15.5 to -0.9, ES = 1.2) travelled and mean speed (p = 0.03, 95% CI = -0.3 to -0.1, ES = 1.3) revealed large ES and were significantly lower in TP compared to NON-SCI. Peak speed (p = 0.10, ES = 0.8), number of HI activities (p = 0.57, ES = 0.4) and total distance of the HI activities (p = 0.24, ES = 0.7) were not statistically different between groups (Table 6.2).

The two groups did not differ in the percentage of total quarter time spent in each speed zone (p > 0.05, Figure 6.2). There was no difference across all 4 quarters in the percentage of time spent in each speed zone, except TP spent a significantly smaller percentage of time in the high speed zone in the first quarter than NON-SCI ($0.8 \pm 0.4\%$ vs. $1.8 \pm 0.7\%$; p < 0.001).

Table 6.2 Match play activity profiles during the wheelchair rugby match for players with tetraplegia (TP) and non-spinal related physical impairments (NON-SCI).

	TP	NON-SCI
Total distance (m)	$4842 \pm 324^*$	5541 ± 316
Relative distance (m·min^{-1})	$68.1 \pm 7.0^*$	76.3 ± 6.4
Mean speed (m·s^{-1})	$1.13 \pm 0.11^*$	1.27 ± 0.11
Peak speed (m·s^{-1})	3.42 ± 0.50	3.76 ± 0.18
Number of HI activities	22 ± 10	26 ± 13
Total distance of HI activities (m)	134 ± 45	188 ± 105

HI = high intensity activities, combination of high (81-95%V_{max}) and very high ($\geq$95%V_{max}) speed zones. *significantly different to NON-SCI, p ≤ 0.05.
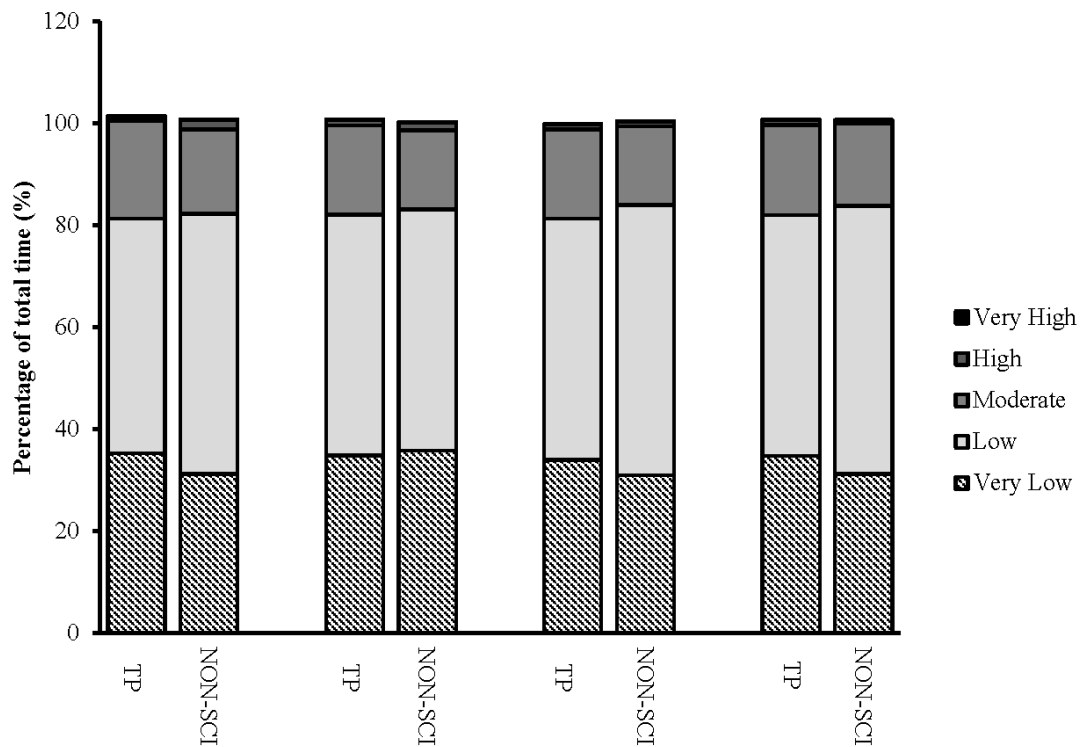
Figure 6.2 Percentage of total quarter time spent in each speed zone. TP = tetraplegia, NON-SCI = non-spinal related physical impairment (NON-SCI), Q = quarter.

6.4.3 Thermoregulatory measures

The absolute change in body mass was significantly greater in TP than NON-SCI (p = 0.05, ES = 1.1), whilst there was no difference between groups for the amount of fluid ingested (p = 0.75, ES = 0.1). Total mass loss was significantly lower in TP than NON-SCI (p = 0.04, ES = 1.1).

Prior to the warm-up (37.0 ± 0.4°C vs. 37.4 ± 0.5°C, p = 0.01, ES = 0.90) and start of the match (37.6 ± 0.4°C vs. 38.1 ± 0.3°C prior to start of the match; p < 0.001, ES = 1.4), absolute T_{gi} was cooler in TP compared to NON-SCI. During the match the change in T_{gi} was greater in TP (1.6 ± 0.4°C) than NON-SCI (0.7 ± 0.3°C, p < 0.001, 95% CI = 0.5 to 1.3, ES = 2.5, Figure 6.3). A large ES for final T_{gi} revealed warmer end T_{gi} in TP (39.3 ± 0.5°C) than in NON-SCI (38.8 ± 0.3°C; p = 0.06, 95% CI = 0.1 to 1.0, ES = 1.7). The rate of change in T_{gi} was greater in TP than NON-SCI over each quarter (p < 0.001). To emphasise the

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differences between groups, Figure 6.4 shows accumulated distance and the change in T_{gi} for one player in each group during one quarter.
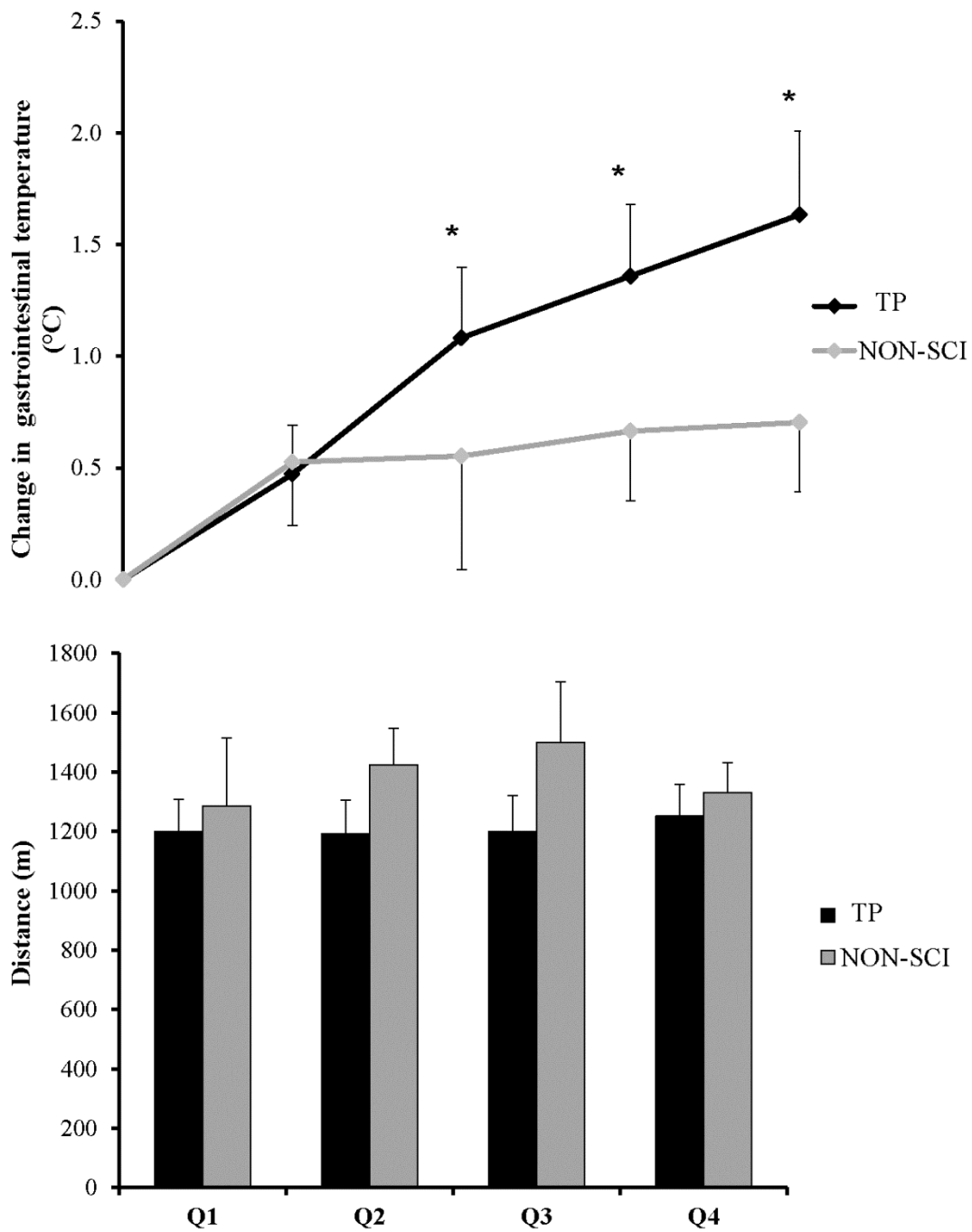
Figure 6.3 Distance travelled and change in gastrointestinal temperature over duration of the match for players with tetraplegia (TP) and non-spinal related physical impairments (NON-SCI). Q = quarter. * significantly different to NON-SCI, $p \leq 0.05$.
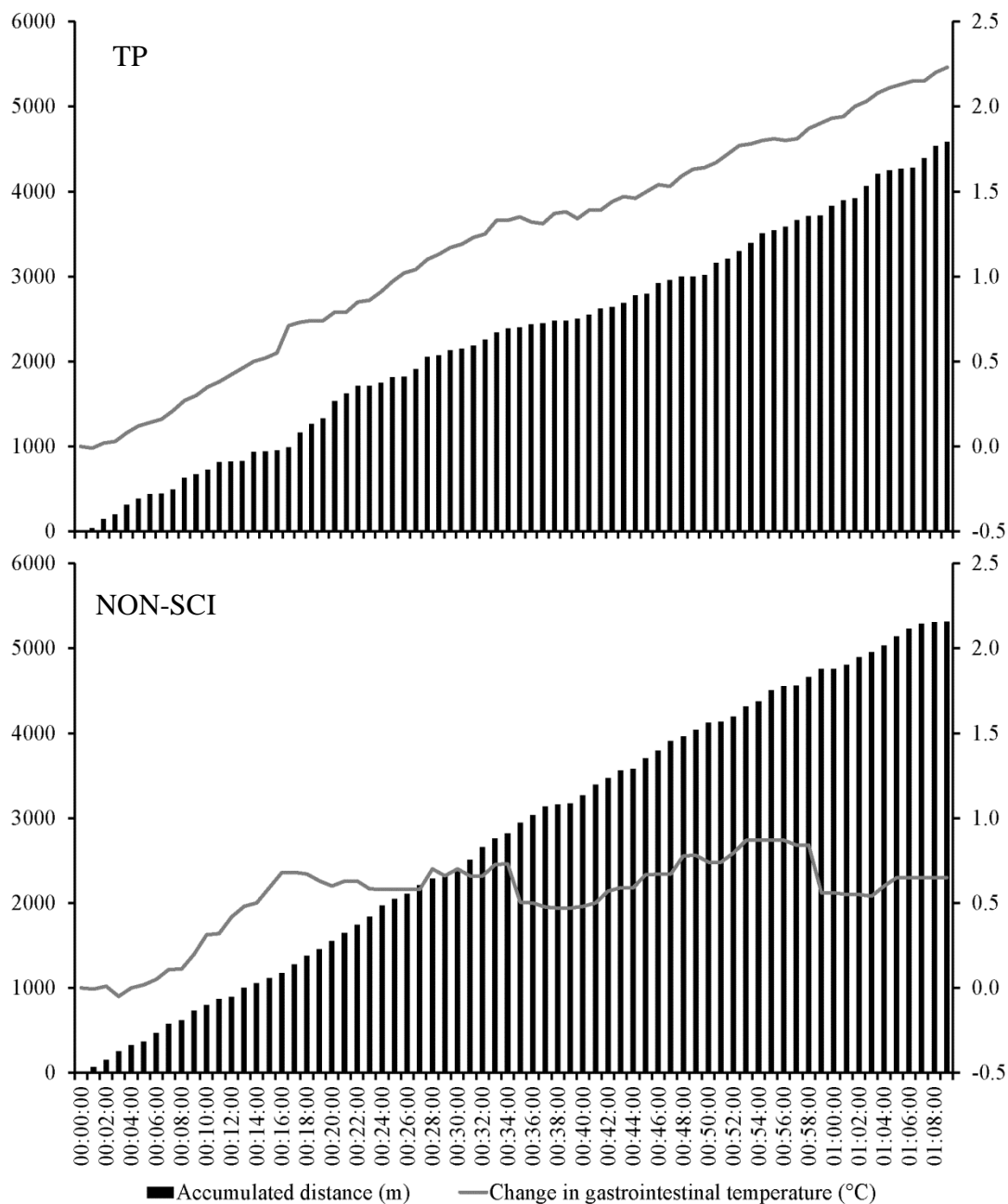
Figure 6.4 Accumulated distance and change in gastrointestinal temperature over a course of a match for a player with tetraplegia (TP) and a player with a non-spinal related physical impairment (NON-SCI).

vs. $32.59 \pm 1.15°C$ for TP and NON-SCI respectively, $p = 0.68$, $ES = 1.9$). The change in T_{sk} was not different between groups or over time during the match (Figure 6.5, $ES = 0.2$, $p > 0.05$). In TP, Figure 6.5 shows T_{sk} increased at the end of quarter 2, whilst after an initial increase T_{sk} started to decrease at the end of quarter 2 in NON-SCI. Changes in forearm,

upper arm, chest, back, thigh and calf skin temperatures during the match were similar between groups (all p > 0.05), yet a main effect of time was only revealed for the forearm, upper arm and back (all p < 0.05). The convective and evaporative heat transfer coefficients were significantly lower for TP than NON-SCI (p = 0.03).
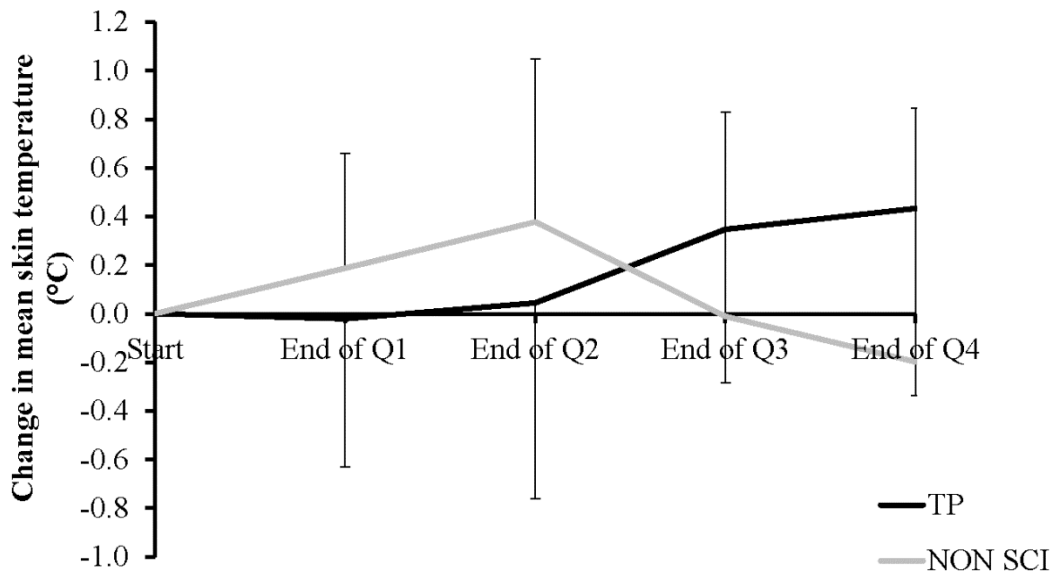
Figure 6.5 Change in mean skin temperature over the duration of the match for players with tetraplegia (TP) and non-spinal related physical impairments (NON-SCI). Q = quarter. *significantly different to NON-SCI, p ≤ 0.05.

6.4.4 Heart rate and perceptual measures

Heart rate was significantly lower in TP than NON-SCI (100 ± 20 b.min^{-1} vs. 143 ± 27 b.min^{-1}; p < 0.001), yet there was no main effect of group or time for RPE (p > 0.05) or thermal sensation (p > 0.05). During the match, RPE increased from 13 to 16 and 12 to 16 whilst thermal sensation increased from 4 to 6 and 4 to 7 in TP and NON-SCI, respectively (Figure 6.6). Significant relationships were only apparent between the change in T_{gi} with both thermal sensation (r = 0.37, p = 0.02) and RPE (r = 0.82, p < 0.001) for TP. Thermal sensation was significantly negatively correlated with the change in T_{sk} for TP (r = -0.47, p < 0.001).
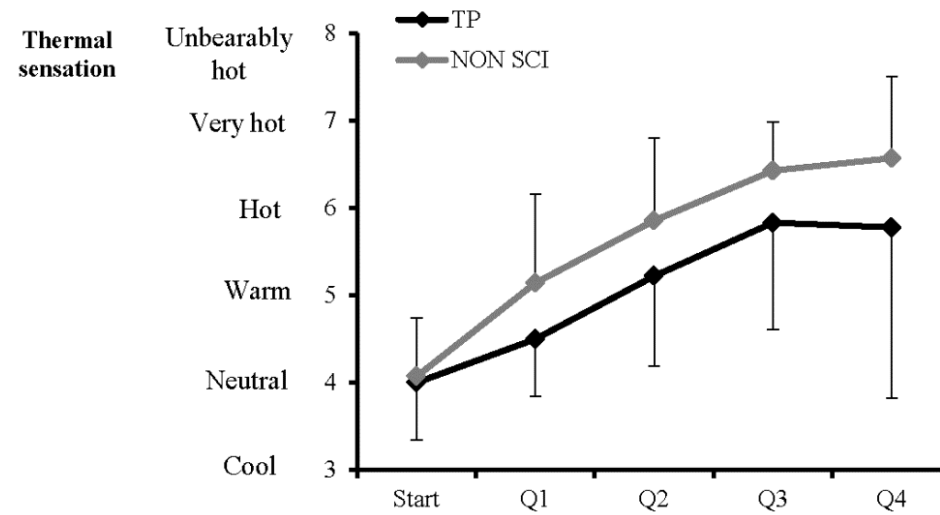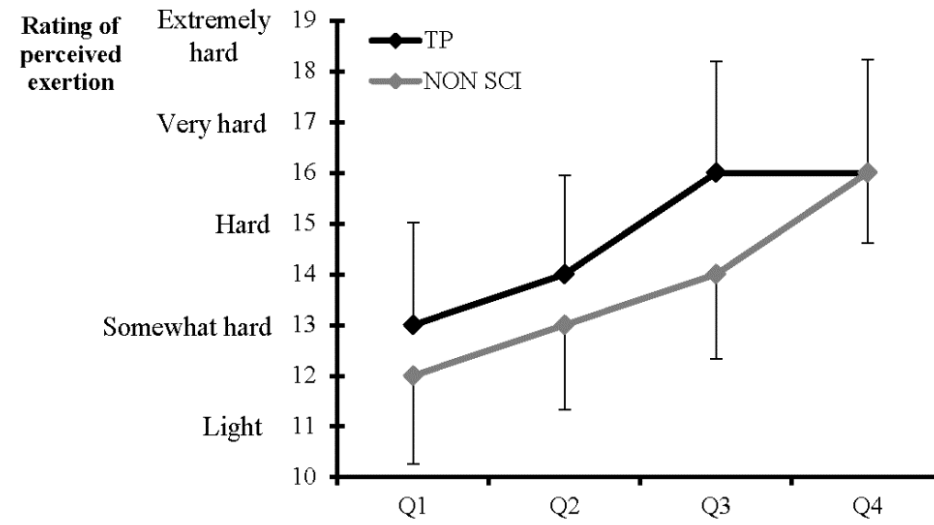
Figure 6.6 Rating of perceived exertion and thermal sensation for athletes with tetraplegia (TP) and athletes with a non-spinal related physical impairment (NON-SCI) over the duration of the match. Q = quarter.

6.4.5 Metabolic energy expenditure

Differences between groups in metabolic energy expenditure did not reach significance, but revealed a moderate ES (158 ± 44 W and 200 ± 74 W for TP and NON-SCI, respectively, p = 0.21, ES = 0.7).

6.4.6 Identifying WCR players under greatest thermal strain

For the seven TP participants that underwent the DXA procedures, body mass was 65.8 ± 4.2 kg, body surface area was 1.85 ± 0.11 m^2, lean tissue mass was 46.2 ± 6.6 kg and 70.2 ± 9.0% and fat mass was 16.3 ± 5.3 kg and 26.2 ± 8.9%. Relationships between key variables are shown in Figure 6.7. Thermal sensation and RPE were not correlated with any of the activity profile measures, end T_{gi} or physical attributes.
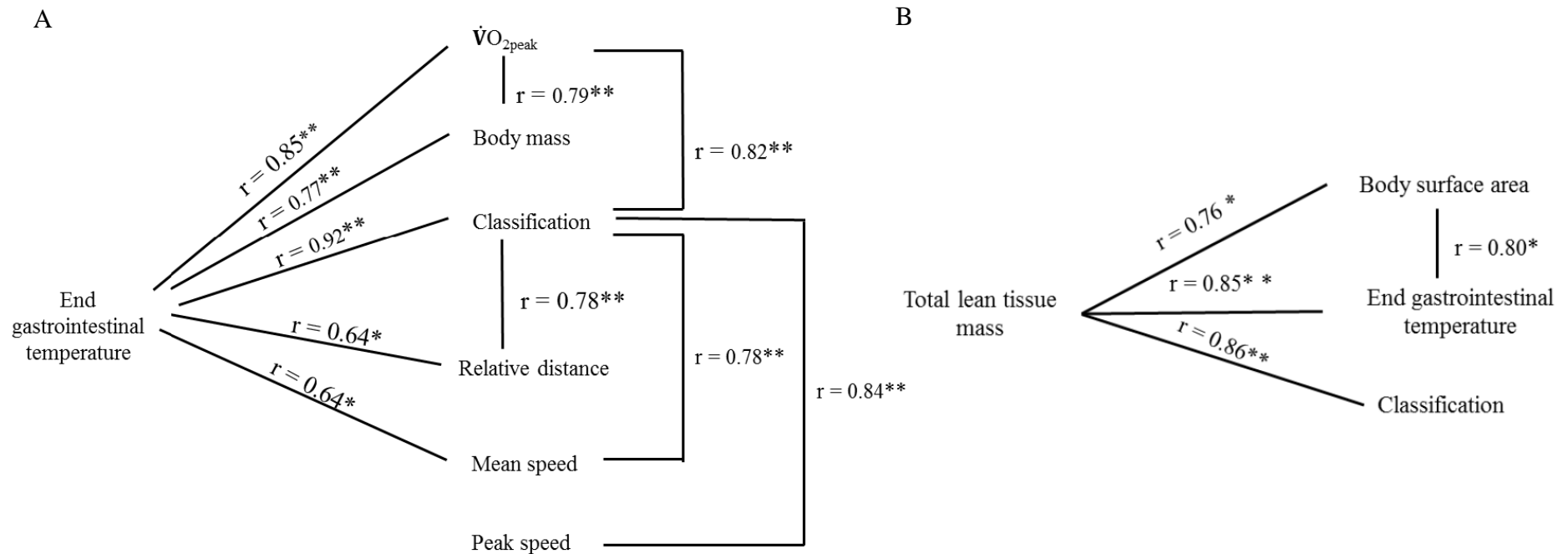
Figure 6.7 A) Relationship for players with tetraplegia (n=10) between participant characteristics, physical attributes, activity profiles and thermal measures. B) Relationship for players with tetraplegia (n=7) between dual-energy X-ray absorptiometry measures, participant characteristics and thermal measures. $\dot{V}O_{2peak}$ = peak oxygen uptake, *= significantly different at p ≤ 0.05, ** = significantly different at p ≤ 0.01.

6.5 Discussion

This study, to our knowledge, is the first comparison of both the physiological responses and activity profiles of players with TP and a NON-SCI during competitive WCR. Using this novel approach, findings revealed that players with TP experienced greater thermal strain than NON-SCI players despite covering ~17% less distance and pushing on average ~10% slower. Therefore, confirming our primary hypothesis, players with TP were under a greater amount of thermal strain compared to their NON-SCI teammates mainly due to the reduction in heat loss capacity as a result of their impairment and not by the amount of work performed.

In line with previous data, players in the current study spent ~80% of total quarter time in the very low/low speed zones (Rhodes et al. 2015), with both groups spending a similar percentage of total quarter time in each speed zone (Figure 6.2). Nevertheless, the lower mean speed of TP and thus lower self-generated air flow, would have caused significantly lower dissipation of heat by convection and evaporation, depicted by the lower heat transfer coefficients. Furthermore, evaporative heat loss would be minimal for TP (Normell 1974, Gass et al. 1992), given the large body surface area of insensate skin. In relation to heat generation, although metabolic energy expenditure was not significantly different, the observed moderate ES (ES = 0.7) implies that metabolic energy expenditure tended to be lower in TP than NON-SCI during the match. Thus, this suggests that heat production would also likely be lower. Field-based testing has the benefit of testing players in their natural environment making the results more relevant than laboratory testing. However, to ensure minimal disturbance to the players, energy expenditure could not be measured during the match and thus estimations of energy expenditure were taken from $\dot{V}O_{2peak}$ laboratory data. Nevertheless, combining the effects of both a loss of sweating capacity and lower mean speed suggests players with TP are predisposed to a greater increase in T_{gi} than NON-SCI, despite NON-SCI expending more energy and potentially producing more heat during match play.

For NON-SCI, the production and evaporation of sweat triggered by the rising T_{gi} would have caused a dissipation of heat lowering T_{sk} (Figure 6.5), with the increasing heat loss leading to the stabilisation of T_{gi} by half-time (Webb 1995, Figure 5.3). Therefore, effective heat loss occurred in NON-SCI, whilst the opposite was the case for TP. Due to the inactivation of the leg muscle pump, loss of sweating capacity and vasomotor control below the lesion level (Normell 1974, Hopman 1994, Freund et al. 1984), players with TP are unable to dissipate the majority of heat produced through exercise leading to a continual

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increase in T_{gi} and T_{sk} (Griggs et al. 2015, Price et al. 2003, Price et al. 1999b, Webb 1995). Thus the results depict that in TP convective heat loss through muscle and skin blood flow, in addition to evaporative heat loss through sweating below the lesion is limited, leading to a continual increase in T_{gi} and T_{sk}.

The warmer T_{gi} at the end of the match (39.3 ± 0.5°C), coupled with the larger rate of rise of T_{gi} for TP during WCR match play highlights the greater thermal strain. Figure 6.4 gives an insight into the activity profile of a player in each group and the contrasting effects on T_{gi}. For instance for the TP player, T_{gi} continually increased despite a lower accumulated distance, and hence metabolic heat production, compared to the NON-SCI player, who was able to maintain a stable T_{gi}, and hence heat balance, throughout the course of the match. Although it has been shown that AB athletes can operate at a greater T_{core} during exercise without any sign of fatigue or heat illness (Ely et al. 2009), whether a similar critical T_{core} exists for players with TP is currently unknown. For instance, anecdotally the player that was stopped at 39.5°C displayed noticeable difficulties with decision-making during play. Of practical importance, T_{gi} in athletes with TP continues to increase following exercise (Griggs et al. 2015), as shown in Study 2 (Chapter 5), therefore a T_{gi} of 39.3°C could be an additional concern if multiple matches are played in succession, thus players will be starting the second match significantly warmer than resting levels.

Despite players with TP having a greater increase in T_{gi} and T_{sk} during match play they did not perceive to be any warmer than NON-SCI. Significant relationships between the change in T_{gi} and thermal sensation and RPE were however apparent for TP. These relationships may be due to the concomitant and continuous increase in T_{gi}, thermal sensation and RPE during match play and may not represent a causal relation. In AB individuals, thermal sensation is largely dictated by skin temperature, independent of T_{core} (Schlader et al. 2011), yet a significant negative relationship was apparent between the change in T_{sk} and thermal sensation for TP. During exercise a larger change in skin temperature may be needed to induce a change in thermal sensation of similar magnitude (Gerrett et al. 2014, Ouzzahra et al. 2012) or due to only a small portion of their body (head, anterior of arms and shoulders) being sensate, the role of skin temperature for thermal perceptions may be limited to a small surface area in TP (Attia et al. 1983). Whether thermal sensation in TP would have reflected dynamic changes in T_{sk} is unknown. A better understanding of thermal perceptions in TP is greatly needed to assist coaches and medical staff to gauge when and which players should be

removed from play due to thermal strain, as the results suggest that the players themselves cannot judge their thermal strain reliably.

A limitation of the study may have been the inclusion of only one female WCR player. Despite this being reflective of the GBWR squad at the time, her change in T_{gi} and T_{sk} was on average, 0.4°C and 0.2°C different, for T_{gi} and T_{sk}, respectively, to a player of the same classification (0.5) over the course of the match. Thus, her inclusion in the study is justified, especially as large inter-individual variation in thermoregulatory responses is common for individuals with TP (Price et al. 1997, Price et al. 1999b).

6.6 Practical applications

Preliminary data from the current study aimed to determine if certain physical attributes or activity profiles were related to T_{gi} at the end of the match in TP (Figure 6.7). Multifactorial inter-individual variability makes it challenging to determine factors that predict heightened thermal strain (Girard 2015). However, the present study attempted to enable the coach and support staff to identify WCR players at the greatest thermal strain. From the correlation data for TP those with a greater $\dot{V}O_{2peak}$, larger body mass, larger lean mass and body surface area, and/or were a higher point player, showed a greater end T_{gi}. Of note in TP, an individual with a larger body mass likely indicates a larger amount of upper body mass due to muscular atrophy below the lesion. In relation to functional ability, a greater end T_{gi} was apparent for higher point players covering a greater relative distance and mean speed, i.e. generating a greater amount of metabolic heat. Therefore, within the TP group, it is the players with a greater amount of functional ability, typically linked to roles on court that elicit greater distances and speeds that are under the greatest thermal strain. In fact the player that was stopped due to a high T_{gi} (>39.5°C) was a high point player and had the greatest body mass and $\dot{V}O_{2peak}$ in the SCI group. Although the low number of participants used to identify WCR players under the greatest thermal strain does make drawing firm conclusions difficult, as a preliminary data set it does provide insight for coaches and support staff on which players may need greater attention in regards to cooling strategies or breaks in play.

The present study highlights that despite players in WCR being classified according to their physical impairment, physiological responses greatly differ between players affecting their activity profile during a match. Thus, two players of the same classification have similar functional ability but physiologically behave very differently as a result of their impairment.

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As more Paralympic sports develop and open up their classification systems to include a greater range of impairments, disparity in physiological function is likely to occur. Despite this, classifying individuals by physical and physiological function would be extremely difficult and detrimental to the development of the sport, but is an issue that sporting organisations should be aware of.

6.7 Conclusions

In line with the previous study, the current study also revealed that WCR players with TP are under a greater amount of thermal strain compared to NON-SCI players during competitive match play. Players with TP covered less distance and had slower mean speeds, thus generating a smaller amount of heat than NON-SCI. Yet, these players were under greater thermal strain, due to a reduction in heat loss capacity as a result of their SCI. Preliminary data revealed players with TP with greater functional ability (high point players) tend to produce more heat during play and be predisposed to a greater T_{gi} response than low point players. Practically, coaches and support staff should be aware of the greater thermal strain experienced by these players and implement appropriate cooling strategies and playing tactics.

Chapter 7

Study 4: Effects of cooling before and during simulated match play on thermoregulatory responses of athletes with tetraplegia

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Both Studies 2 and 3 highlighted that athletes with TP were under greater thermal strain than athletes with PA and WCR players with non-spinal related physical impairments. Study 4 aimed to establish the effectiveness of current cooling practices employed by athletes with TP, with the aim to reduce the thermal strain depicted in both Studies 2 and 3.

7.1 Abstract

Purpose: Athletes with TP are under greater thermal strain during exercise than athletes with PA and WCR players with non-spinal related physical impairments. Two cooling methods currently used by athletes with TP are ice vests and water sprays, yet the effectiveness of these two methods using a "real-world" sporting environment has not been investigated for this population group. Thus the purpose of this study was to investigate the effectiveness of pre-cooling using an ice vest and the combination of pre-cooling and cooling during play using water sprays in athletes with TP.

Methods: Eight WCR players with TP completed a 60 min ISP on a WERG in 20.2 °C $\pm$ 0.2 °C and 33.0 % $\pm$ 3.1 % relative humidity. The ISP was conducted on three occasions; no cooling (NC), pre-cooling with an ice vest (P) and pre-cooling with an ice vest and water sprays between quarters (PW). Gastrointestinal temperature, T_{sk}, perceptual responses and performance measures were recorded throughout.

Results: At the end of the pre-cooling period, the change in T_{gi} was not significantly different between conditions but the change in T_{sk} was significantly greater in P ($p < 0.001$, ES = 0.4) and PW ($p < 0.001$, ES = 0.6) compared to NC. The change in T_{gi} over the ISP was significantly lower in P and PW compared to NC ($p < 0.01$), whilst the change in T_{sk} was lower in PW compared to P and NC ($p < 0.05$). Cooling had no effect on any performance measure or perceptual responses ($p > 0.05$).

Conclusions: Pre-cooling using an ice vest combined with water spraying between quarters lowers thermal strain to a greater degree than pre-cooling only in athletes with TP. Although the attenuation in T_{sk} was not long lasting in P, T_{gi} was still lower compared to NC throughout the ISP. Despite this, neither cooling condition had an effect on simulated WCR performance or perceptual responses.

7.2 Introduction

As depicted by Study 2 and 3 (Chapters 5 and 6), athletes with TP experience a heightened thermal response during intermittent wheelchair exercise compared to athletes with PA or athletes with a non-spinal related physical impairment. To reduce thermal strain cooling methods have received considerable interest in the AB athletic population (Tyler et al. 2015), especially when applied as a pre-cooling strategy, delaying the onset of thermally induced fatigue (Quod et al. 2006). It is generally accepted that pre-cooling elicits a performance improvement for endurance or intermittent exercise (Tyler et al. 2015, Ross et al. 2013, Wegmann et al. 2012), yet similar benefits are not found for sprint exercise (Wegmann et al. 2012). Alternatively, cooling during exercise/rest periods, to increase the dissipation of heat gained from environmental or metabolic sources, or a combination of strategies (e.g. pre-cooling and during exercise) may be just as effective as pre-cooling in improving performance (Bongers et al. 2014).

To date ten studies (Pritchett et al. 2010, Webborn et al. 2010, Webborn et al. 2005, Diaper et al. 2009, Goosey-Tolfrey et al. 2008a, Goosey-Tolfrey et al. 2008b, Hagobian et al. 2004, Bongers et al. 2015, Trbovich et al. 2014, Armstrong et al. 1995) have addressed the application of cooling methods in the SCI population (Griggs et al. 2014). Webborn et al. (2005, 2010) investigated the use of ice vests prior to and during an intermittent arm cranking protocol resulting in a lowered T_{core} and increased time to exhaustion compared to no cooling, as previously discussed in Section 2.12.2. Yet, the protocol's sports specificity to wheelchair court sports could be questioned, as thermoregulatory differences have been shown to exist between arm cranking and wheelchair propulsion (Price et al. 1999a). Furthermore, wearing an ice vest during exercise may be considered impractical due to the adverse effect of size, weight and coverage of a garment. Athletes with TP, for instance those eligible to play WCR, use water sprays during matches to cool themselves in an attempt to mimic the sweat response of an AB individual. Only one study, previously discussed in Section 2.12.1, has investigated the effectiveness of this cooling method in wheelchair basketball players with PA (Pritchett et al. 2010). The authors concluded that water spraying was ineffective in attenuating thermal and cardiovascular strain due to a lack of differences in T_{core}, T_{sk}, HR and perceptual responses between the no cooling and water spray trial. However, these findings may be partly due to the lack of ecological validity of the incremental arm cranking protocol used.

Given the limitations in existing research, the purpose of this study was to investigate pre-cooling and the combination of pre-cooling and cooling during breaks in play, on simulated WCR match play in athletes with TP. An ice vest was used as a pre-cooling strategy and water sprays were used during breaks in play, both of which are currently used by wheelchair athletes with TP. It was hypothesised that pre-cooling alone would reduce T_{gi} and T_{sk} compared to no cooling at the beginning of the exercise protocol, though the effect would not be long lasting. Whilst the combination of methods would lower T_{sk} compared to no cooling, with no further reductions in T_{gi} compared to pre-cooling only.

7.3   Methods

7.3.1   Participants

Eight highly trained WCR players with TP (7 male, 1 female) from the BT GBWR squad participated in this study (Table 7.1). Participants gave their written informed consent to participate, which was approved by Loughborough University Research Ethics Committee.

Table 7.1 Participant characteristics for the eight wheelchair rugby players that participated in this study.

	Participant characteristics
Age (years)	32 ± 7
Body mass (kg)	64.0 ± 6.8
Sum of four skinfolds (mm)	52.4 ± 24.3
$\dot{V}O_{2peak}$ (L·min^{-1})	1.35 ± 0.27
Lesion level (range)	C5/6-C7
	(1 incomplete)

7.3.2 Preliminary tests

On the first visit to the laboratory, skinfold measurements (Harpenden Skinfold Callipers, Baty International, West Sussex, UK) were taken from the biceps, triceps, subscapular and suprailliac to calculate the sum of skinfolds (mm). Following this, a wheelchair incremental test to determine $\dot{V}O_{2peak}$ was completed on a motorised treadmill (HP Cosmos, Traunstein, Germany), described previously in Section 3.1.

7.3.3 Experimental conditions

The remaining three visits; two cooling conditions and a no cooling condition, were conducted, at least 24 h apart, and involved an ISP in 20.2 ± 0.2ºC and $33.0 \pm 3.1\%$ relative humidity. The ISP was preceded by a 15 min rest period and a 20 min warm-up. Conditions were completed in a balanced, cross-over design and each participant served as their own control. Participants were instructed to refrain from alcohol, caffeine and strenuous exercise 24 h prior to each condition. All conditions for each participant were completed at a similar time in the afternoon to negate circadian variation (Winget et al. 1985).

7.3.3.1 Thermoregulatory measures

Participants ingested a telemetry pill (HQ Inc, Palmetto, Florida) for the measurement of T_{gi}, ~6-8 h prior to each condition, described previously in Section 3.1. Upon arrival, participants were weighed to the nearest 0.1kg (Detecto, Cardinal Scale Manufacturing Co., Webb City, Missouri, USA) after voiding their bladder. Participants were allowed to drink *ad libitum* during breaks between quarters and the volume of fluid was recorded. Participants were re-weighed at the end of the ISP. In addition to the absolute change in body mass ($Mass_{pre}$ - $Mass_{post}$), the change in body mass in relation to fluid consumed (($Mass_{pre}$ - $Mass_{post}$) + fluid consumed) was also calculated (total mass loss).

Seven iButtons (DS1922T, Maxim Integrated Products, Inc., Sunnyvale, CA, USA) were placed on the forehead and right side of the body on the forearm, upper arm, upper back, chest, abdomen, thigh and calf, described previously in Section 3.2. In addition to individual skin temperatures, T_{sk} was estimated using the formula by Ramanathan (Ramanathan 1964), as previously described in Section 3.3.

7.3.3.2 Heart rate and perceptual measures

Heart rate (HR, Polar PE 4000, Kempele Finland) was recorded throughout the ISP. Thermal comfort and thermal sensation were recorded at the start and end of the 15 min rest, warm-up and each quarter. The thermal sensation scale, comprised of categories ranging from 0 ("unbearably cold") to 8 ("unbearably hot") in 0.5 increments (Toner et al. 1986). The thermal comfort scale ranged from 1 ("comfortable") to 4 ("very uncomfortable") in 1.0 increments (Gagge et al. 1969).

7.3.3.3 Intermittent sprint protocol

Following instrumentation, participants transferred into their sports wheelchair and rested for 15 min before completing a 20 min warm-up on the WERG (VP Handisoft-25, Medical Developpment Hef Groupe, Andreziuex Boutheon, France), described previously in Section 3.4.2. The warm-up consisted of 3 min of self-selected low intensity pushing and stretching, followed by two 5 min structured exercise blocks interspersed with 2 min of active recovery and stretching. These structured exercise blocks consisted of 6 cycles of activity, during each cycle the player performed forwards and backwards pushing for 15 s, a 10 s sprint, followed by 30 s of active recovery. Following the second 2 min of active recovery, three maximum effort 15 s sprints interspersed with 45 s of active recovery were conducted. The highest maximum speed achieved in these 15 s sprints was used to determine the speed zones (20%, 50%, 60% and 75% of maximum speed) of the subsequent ISP.

The ISP aimed to represent a WCR match based on data previously collected by the indoor tracking system in Study 3 (Chapter 6). The ISP consisted of four quarters of 15 min, interspersed with 2 min passive rest after the first and third quarter and 5 min after the second (Figure 7.1). A game of wheelchair rugby consists of four 8 minute quarters (with the same rest periods as stated above) with the game clock stopped during any stoppages or when the ball is out of play, as described in section 2.5.3. Typically quarters last a total of 15-17 min in duration, according to data from Study 3 (Chapter 6) and Rhodes et al. (2015), respectively, with players remaining active during stoppages (Rhodes et al. 2015, Sarro et al. 2010). Due to Rhodes et al. (2015) being based on a larger data set than Study 3 (Chapter 6), quarters of 15 min duration were chosen for the present study.

Each quarter consisted of alternation between 20%, 50%, 60% and 75% of maximum speed separated with 10 s maximum effort sprints (9 x 10 s sprints per quarter), with 80% of the ISP

conducted at ≤60% of maximum speed. During the last 2 min of each quarter, 4 x 15 s maximum effort sprints were performed, interspersed with 15 s passive rest. Percentage change in peak speed from the first to the last sprint of the 4 x 15 s maximum effort sprints was calculated ((last sprint speed- first sprint speed) / first speed *100)) to compare sprinting ability between quarters and across conditions. The protocol was terminated if participants reached the safety limit of high T_{gi} (39.5ºC).
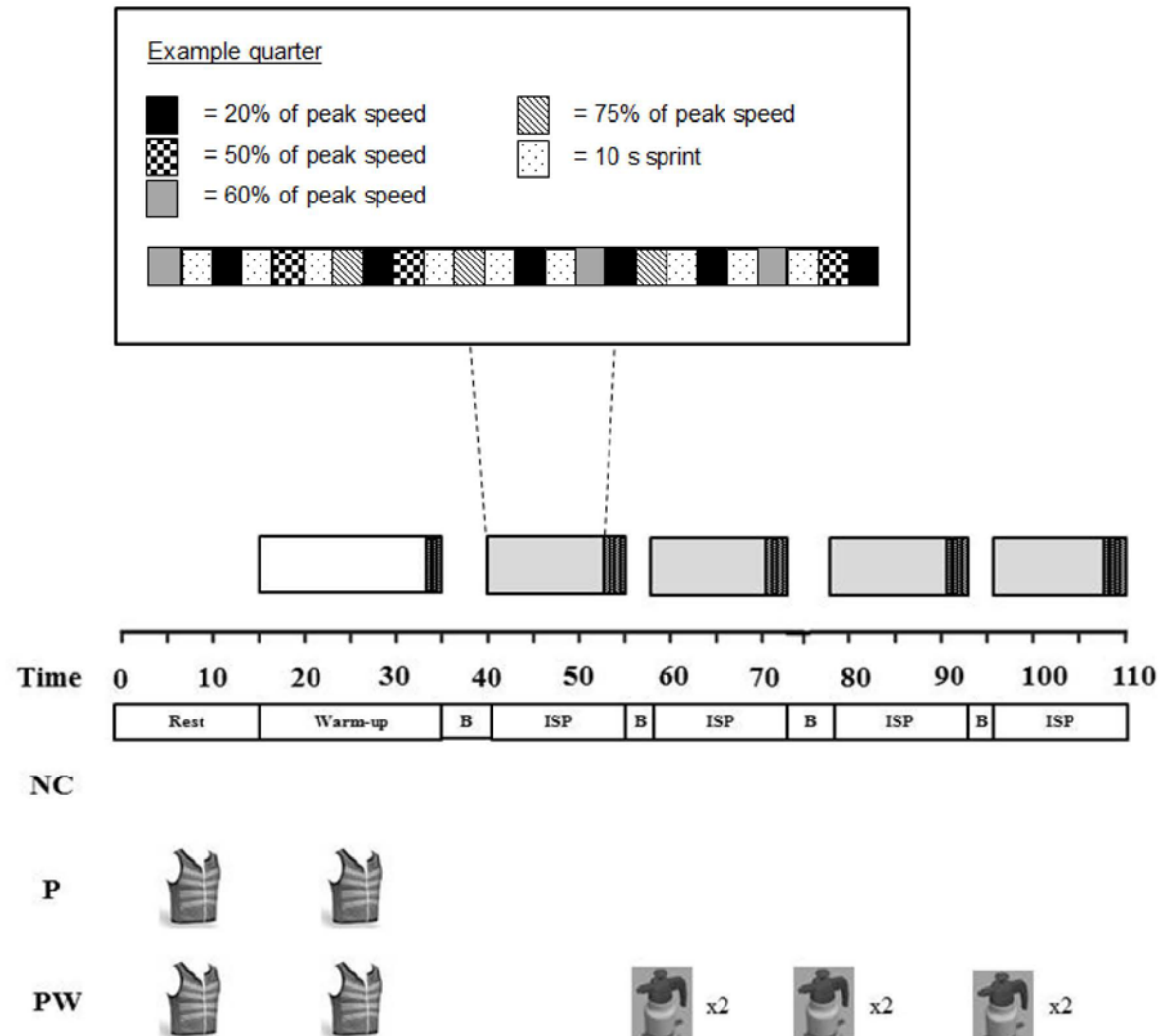
Figure 7.1 Schematic of protocol, including when cooling was applied in each condition, depicted by the ice vest and water spray images. The white box depicts the warm-up, the grey boxes the intermittent sprint protocol (ISP) and the dark grey boxes the 15 s sprints. ISP = intermittent sprint protocol, B= break, NC = no cooling, P = pre-cooling using an ice vest, PW = pre-cooling using an ice vest and water sprays during breaks.

7.3.3.4 Cooling procedures

The three conditions consisted of no cooling (NC), pre-cooling using an ice vest (P, Artic Heat Products, Burleigh Heads, Queensland, Australia, Figure 7.2) or the combination of pre-cooling and water spraying during the passive rest between quarters (PW). Pre-cooling was provided during the 15 min rest and 20 min warm-up. During the warm-up and the ISP, a fan positioned 1 m away from the participant was set at ~1.4 $m \cdot s^{-1}$ to mimic movement induced air flow during on-court match play.

During the ISP participants wore their usual competition attire of lightweight tracksuit trousers and a playing vest. All participants wore abdominal binding (over the bottom of the ice vest), whilst some participants also wore arm bands over the middle of their arms to protect their skin from grazes when abruptly stopping their wheelchair with their arms. The abdominal binding did not cover the ice strips on the vest. Clothing may have varied slightly between participants but was representative of the clothing participants wear during competition, further increasing ecological validity of the study. Participants wore the same clothing for each condition, thus as participants were their own control, this should not have influenced their thermoregulatory responses.

For the pre-cooling conditions, the ice vest was frozen overnight at -20°C, weighed ~ 800g when activated and was worn over the top of the playing vest. The ice vest was made of SportWoolTM, Microfiber and pockets of viscose gel that absorb water. The cooling power of the ice vest was calculated on a thermal manikin (NEWTON, MTNW, Seattle, WA) in ambient conditions of 20.5°C and 50% relative humidity. A manikin skin surface temperature of 34°C to mimic typical skin temperature for an AB individual was used. The total energy required to maintain a 34°C surface temperature was recorded and the average power calculated over a 35 minute period for each condition; frozen ice vest and no ice vest. By subtracting the power required to maintain the whole torso of the manikin at 34°C whilst wearing no ice vest (86 $W \cdot m^2$) compared to a frozen ice vest (123 $W \cdot m^2$), a resultant cooling power of 37 $W \cdot m^2$ was recorded. In PW, participants were also sprayed on the face, fronts of both arms and torso for a total of 20 s with a water spray (~50 ml per 20 s spray at 17°C, Figure 7.2), administered by the same researcher.

Figure 7.2 Artic Heat Ice vest (deactivated) and water spray bottle used for the cooling procedures

7.3.3.5 Infra-red imaging

Whole-body T_{sk} was recorded for three of the participants using an infrared camera at the start and end of 15 min rest (Therma- cam B2, FLIR Systems Ltd,West Malling, Kent, UK, spectral range 7.5–13 µm, accuracy ±2°C, thermal sensitivity ±0.1°C). The infrared images were taken to highlight the fit of the garment and to see if the seated position of the athletes in their wheelchairs altered the position of the garment in relation to the wearer's body. Two thermograms were taken (anterior and posterior) at each time point; 1) start (with no top), 2) after donning a top, frozen ice vest and abdominal strapping and 3) at the end of 15 mi3n rest period (with no top). The infrared images were analysed using the software package FLIR tools (Flir Systems Inc. Portland, USA) to determine skin temperature of the whole anterior and posterior torso.

7.3.3.6 Metabolic heat production

Metabolic energy expenditure (M) was obtained from minute-average values for oxygen consumption ($\dot{V}O_2$) in litres per minute and the respiratory exchange ratio (RER) during the $\dot{V}O_{2peak}$ test. The metabolic cost of pushing at the mean speed during each quarter was calculated from the plot of oxygen consumption vs. mean speed using these data. Metabolic energy expenditure was calculated using the equation below:

$$M \ (\text{W} \cdot m^2) = \ V\dot{O}_2 \ \frac{\left(\dfrac{RER - 0.7 \ \cdot e_c}{0.3}\right) + \left(\dfrac{1 - RER \ \cdot e_f}{0.3}\right)}{60 \cdot \text{BSA}} \cdot 1000 \tag{1}$$

Where: ec is the caloric equivalent per litre of oxygen for the oxidation of carbohydrates (21.13 kJ), and ef is the caloric equivalent per litre of oxygen for the oxidation of fat (19.62 kJ). Body surface area (BSA) was calculated using the Dubois formula (Dubois et al. 1916). External work (W) was calculated by the WERG. Heat production was calculated as the difference between M and W.

$$\text{Heat production } (W \cdot m^2) = M - W \tag{2}$$

7.3.4 Statistical analysis

All data were analysed using the Statistical Package for Social Sciences (version 19; SPSS Chicago, IL). Delta T_{gi}, T_{sk} and individual skin temperatures were calculated as the change from the start of the 15 min rest period. The rate of change in T_{gi} was calculated as the difference over a quarter divided by the time of the quarter. Data analysis was performed separately for the 15 min rest period whilst the pre-cooling period refers to the combination of the 15 min rest period and the 20 min warm-up. Normality of data was confirmed by the Shapiro–Wilk test. One participant was stopped during two of the three trials due to T_{gi} reaching the safety limit of 39.5°C. Subsequently, temperature estimations for three missing data points (out of a total of 264) for this participant were performed by substitution of the mean temperature change, enabling the thermoregulatory responses to be presented from all eight participants. The analysis for the sprint performance data was conducted with n = 7, due to missing data for one quarter. Physiological responses, thermoregulatory responses and sprint performance were analysed using a two way (condition x time) ANOVA. Where assumptions of sphericity were violated, a Greenhouse–Geisser correction was applied. Post hoc analysis was conducted using pairwise comparisons with a Bonferroni correction. Main effects and interactions were accepted as statistically significant when $p \leq 0.05$. All values are presented as mean ± SD. Confidence intervals (95% CI) for differences are presented, alongside effect sizes (ES) to supplement important findings. Effect sizes were calculated as the ratio of the mean difference to the pooled standard deviation of the difference. The magnitude of the ES was classed as trivial (<0.2), small (0.2–0.6), moderate (0.6–1.2), large (1.2–2.0) and very large ($\geq$2.0) based on previous guidelines (Batterham et al. 2006). Pearson's product-moment correlation test was used as appropriate. An *a priori* power analysis, conducted in G*Power 3.1, revealed a sample size of six participants was required, with 90% power and an α of 5%, based on findings from Webborn et al. (2010). Given the

heterogeneity of the population, an additional two participants per group were recruited to increase statistical power (n = 8).

7.4   Results

7.4.1   Thermoregulatory measures

Gastrointestinal temperature at baseline (36.8 ± 0.1°C, 36.7 ± 0.5°C and 37.1 ± 0.3°C for NC, P and PW, respectively, p = 0.06) and the change in T_{gi} during the rest and pre-cooling period were not significantly different between conditions (p > 0.05). Mean skin temperature at baseline was not significantly different between conditions (30.9 ± 0.5 °C, 31.1 ± 1.1°C and 30.8 ± 0.8°C for NC, P and PW, respectively, p = 0.58). The change in T_{sk} was significantly greater in P and PW compared to NC (p < 0.001) at the end of the rest (95% CI = -1.8 to -0.8, ES = 2.0 and 95% CI = -2.0 to -0.6, ES = 2.8 for P and PW, respectively) and pre-cooling period (95% CI = -1.5 to 0.0, ES = 1.9 and 95% CI = -1.0 to 0.1, ES = 1.1 for P and PW, respectively). For individual skin temperatures, only the changes in chest and abdomen skin temperatures were significantly greater in P and PW than NC during the pre-cooling period (p < 0.001). Pre- cooling had no effect on HR, RPE, thermal sensation or thermal comfort (p > 0.05). Despite the condition, participants reached similar peak speeds during the three maximum effort 15 s sprints at the end of the warm-up, thus, participant's speed zones for each condition were not significantly different and revealed a trivial ES (p = 0.25, ES = 0.1).

The change in T_{gi} during the ISP was significantly smaller from the end of quarter 2 to the end of quarter 4 in PW and P compared to NC (p < 0.05, Figure 7.3). At the end of quarter 4, the change in T_{gi} in PW (1.3 ± 0.9°C) was significantly smaller than both NC (1.9 ± 0.7 °C, p < 0.01, 95% CI = - 1.3 to - 0.5, ES = 0.7) and P (1.7 ± 0.8°C, p < 0.001, 95% CI = - 1.5 to - 0.3, ES = 0.5). The rate of T_{gi} increase over the ISP was smaller in PW (0.015 ± 0.007°C/min, p < 0.01) than NC (0.021 ± 0.008°C/min, p = 0.01, ES = 0.8) and P (0.020 ± 0.008°C/min, p = 0.05, ES = 0.7). At the start and end of the first quarter the change in T_{sk} was smaller in P than NC (p < 0.05). By the end of quarter 2 to the end of quarter 4, T_{sk} was smaller in PW compared to NC and P (p < 0.05, Figure 7.3). At the end of quarter 4, the change in T_{sk} revealed a large ES and was significantly smaller in PW (-2.33 ± 0.77°C) compared to NC (-0.59 ± 0.72°C, p < 0.001, 95% CI = -2.5 to -0.9, ES = 2.3) and P (-0.65 ± 0.69°C, p = 0.01, 95% CI = -2.5 to -0.9, ES = 2.3).
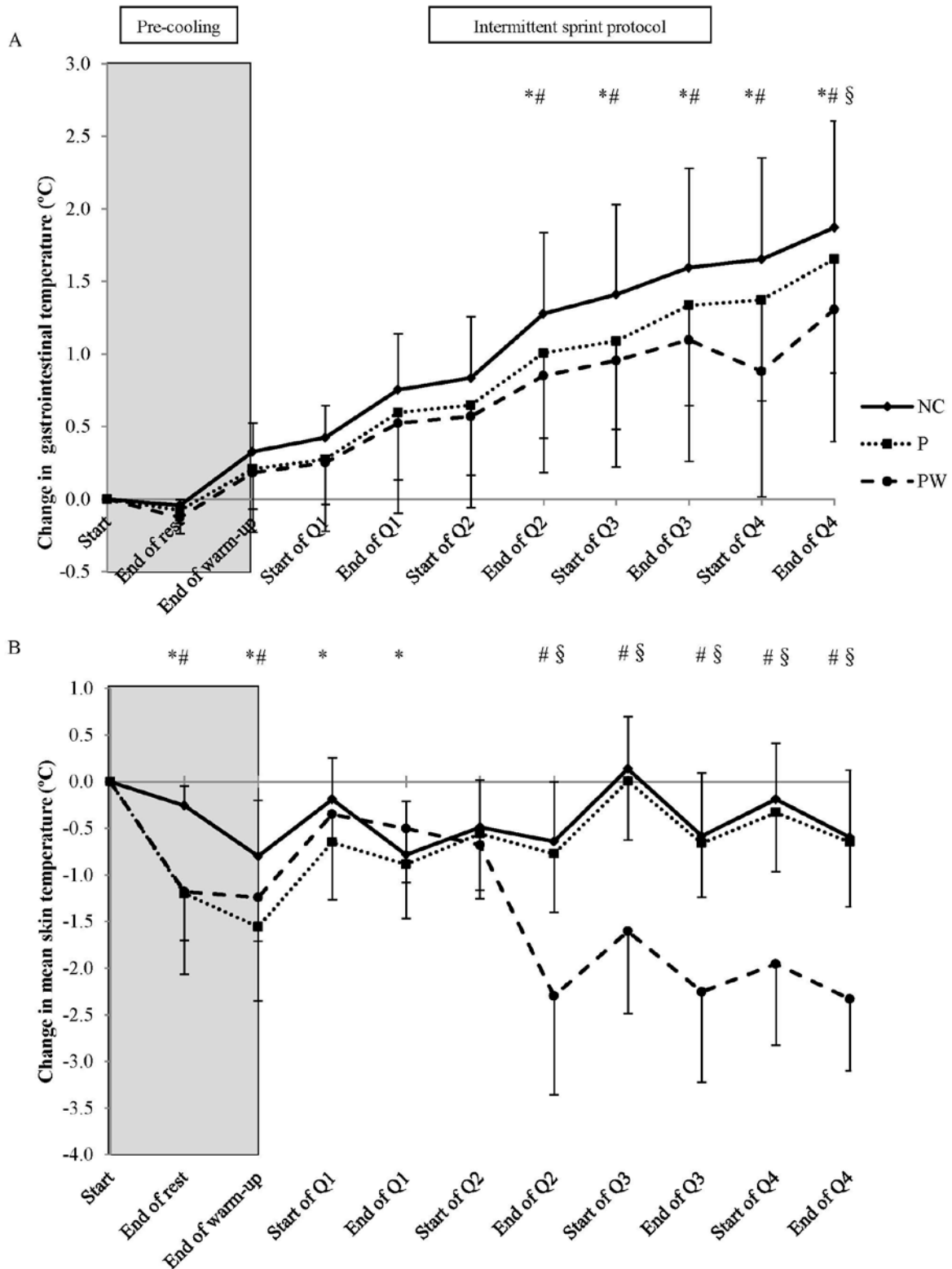
Figure 7.3. Change in gastrointestinal temperature (A) and mean skin temperature (B) over the pre-cooling period and the intermittent sprint protocol for the three conditions; no cooling (NC), pre-cooling using an ice vest (P) and pre-cooling using an ice vest and water sprays between quarters (PW). * significant difference between NC and P, $p < 0.05$. $^#$ significant difference between NC and PW, $p < 0.05$. § significant difference between P and PW, $p < 0.05$. Q = quarter.

The change in skin temperature at the upper arm (p = 0.02), chest (p < 0.01), forearm (p = 0.01), forehead (p = 0.08) and abdomen (p < 0.01) were all smaller in PW than in NC during the ISP. The chest (p = 0.01), forearm (p = 0.01), upper arm (p = 0.01) and abdomen (p < 0.01) were also smaller in PW than P from the start of quarter 2 to the end of quarter 4 (p < 0.05).

Significantly more fluid was consumed in NC than in PW (p < 0.03, ES = 0.9), whilst fluid consumption in P, was not different to the other two conditions (p = 0.12, ES = 0.3 and p = 0.49, ES = 0.5 for NC and PW, respectively). Absolute body mass changes were significantly different and revealed a large ES with greater gains in body mass noted in NC than PW (p = 0.03, ES = 1.3). There were no significant differences and small ES between conditions for total mass loss (p = 0.49, ES = 0.1 - 0.4). All fluid balance data is shown in Table 7.2.

7.4.2   Heart rate and perceptual measures

Heart rate, RPE, thermal sensation and thermal comfort were similar between conditions (p > 0.05, Table 7.2 and Figure 7.4).

Table 7.2 Mean heart rate, perceptual responses and fluid balance for each condition across all four quarters.

	NC	P	PW
Heart rate (b·min^{-1})	96 ± 21	91 ± 23	94 ± 23
Rating of perceived exertion	17 ± 2	16 ± 2	16 ± 2
Thermal sensation	5.0 ± 1.0	5.0 ± 1.0	5.0 ± 1.0
Thermal comfort	2.0 ± 1.0	2.0 ± 1.0	2.0 ± 1.0
Absolute body mass changes (kg)	-0.9 ± 0.2	-0.6 ± 0.3	-0.5 ± 0.4*
Fluid consumption (ml)	819 ± 250	674 ± 285	596 ± 250*
Total mass loss (kg)	0.0 ± 0.3	0.1 ± 0.3	0.1 ± 0.2

*significantly different to NC (p<0.05)
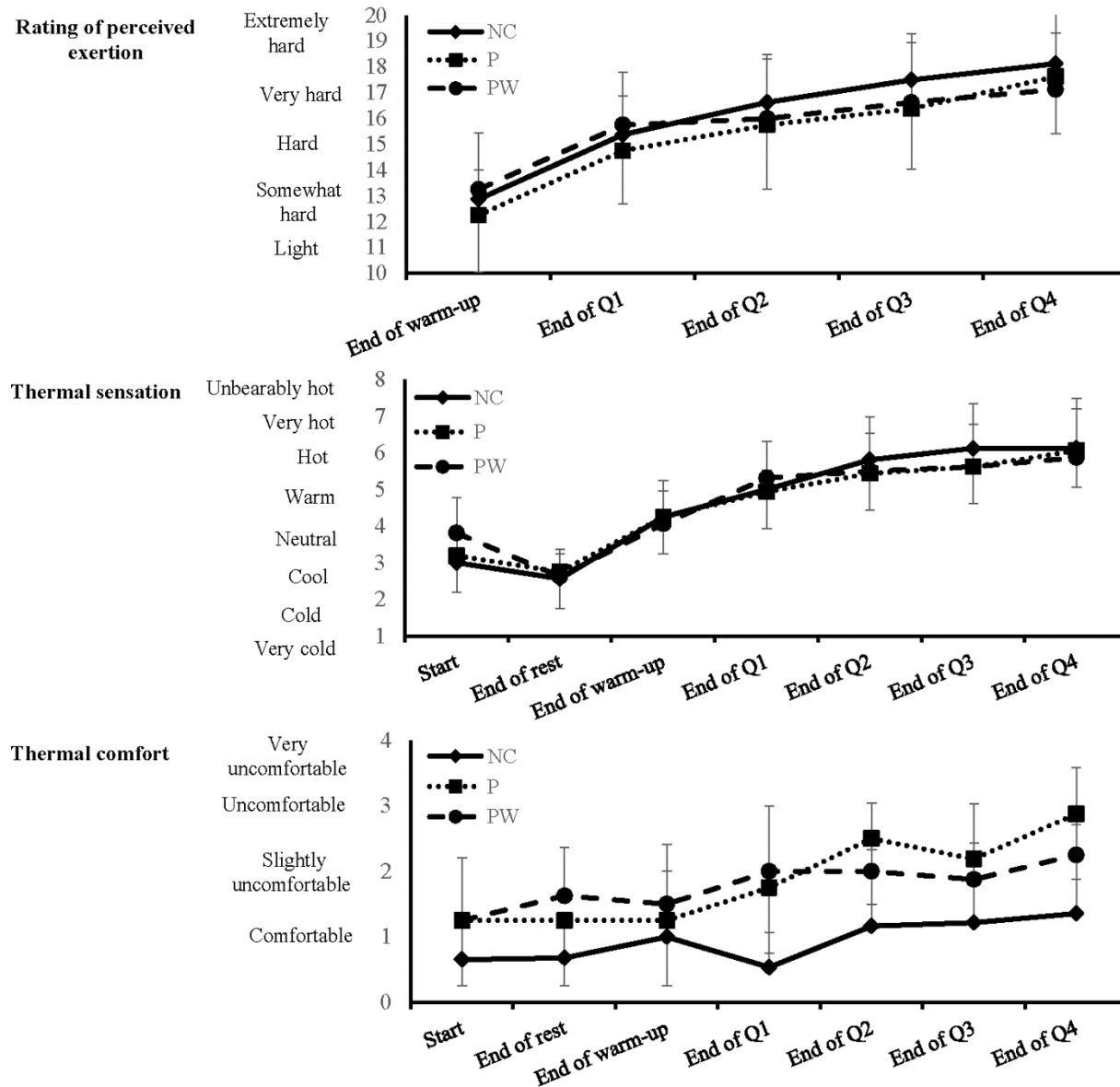
Figure 7.4. Rating of perceived exertion, thermal sensation and thermal comfort over the pre-cooling period and the intermittent sprint protocol for the three conditions; no cooling (NC), pre-cooling using an ice vest (P) and pre-cooling using an ice vest and water sprays between quarters (PW). Q = quarter.

Gastrointestinal temperature was significantly correlated with thermal sensation in NC (r = 0.84, p < 0.01) and P (r = 0.91, p < 0.01) and with RPE in all conditions (r = 0.90-0.98, p < 0.05). Gastrointestinal temperature was only significantly correlated with thermal comfort in NC (r = 0.87, p < 0.01). No significant correlations were apparent between T_{sk} and either thermal sensation or thermal comfort. Mean skin temperature was significantly correlated with RPE in both NC (r = 0.96, p < 0.01) and P (r = 0.94, p < 0.05) but not PW (r = -0.45).

7.4.3 Intermittent sprint protocol

Total distance covered was 7471 ± 1044 m, 7283 ± 1200 m and 7356 ± 1239 m for NC, P and PW, respectively (p > 0.05). No differences were observed between the conditions or over time for peak and mean speed, mean and peak power and total work done during the quarters (all p > 0.11). The coefficient for variation between conditions for total work done was < 5%. For the end of quarter sprints, no difference between conditions or over time for peak speed, peak and mean power and time to peak speed were apparent (all p > 0.37, Table 7.3). The percentage change in peak speed of the end of quarter sprints was similar between conditions (p = 0.51) and over time (p = 0.44). There was no effect of trial order on performance variables (p = 0.51).

Table 7.3 Performance data for the end of quarter sprints.

	NC	P	PW
Peak speed (m·s^{-1})	4.11 ± 0.66	4.08 ± 0.77	4.08 ± 0.71
Peak power (W)	380 ± 168	366 ± 157	386 ± 184
Mean power (W)	274 ± 145	263 ± 135	278 ± 155
Time to peak speed (s)	7.9 ± 3.0	7.5 ± 2.6	7.4 ± 2.4

7.4.4 Infra-red imaging

From the infrared images, whole anterior torso skin temperature reduced by 2.7 ± 0.6 °C after wearing the ice vest for 15 minutes. Whole posterior torso skin temperature reduced by1.6 ± 1.0°C (Figure 7.5). Images A3, B3 and C3 indicate which areas of the torso and back were in contact with the ice vest, shown by the regions of cooler skin temperature. Image A3

highlights that less cooling of the skin on both the anterior and posterior torso was provided by the ice vest than for the other two participants (B3 and C3). Whereas in C3, a larger area of cooler skin temperature is apparent than both A3 and B3.

7.4.5 Metabolic heat production

Metabolic heat production was similar over time ($p = 0.97$) and between conditions with a small ES (168 ± 22, 160 ± 22 and 166 ± 29 W/m^2, $p = 0.18$, ES = $0.1 - 0.4$) for NC, P, PW, respectively.
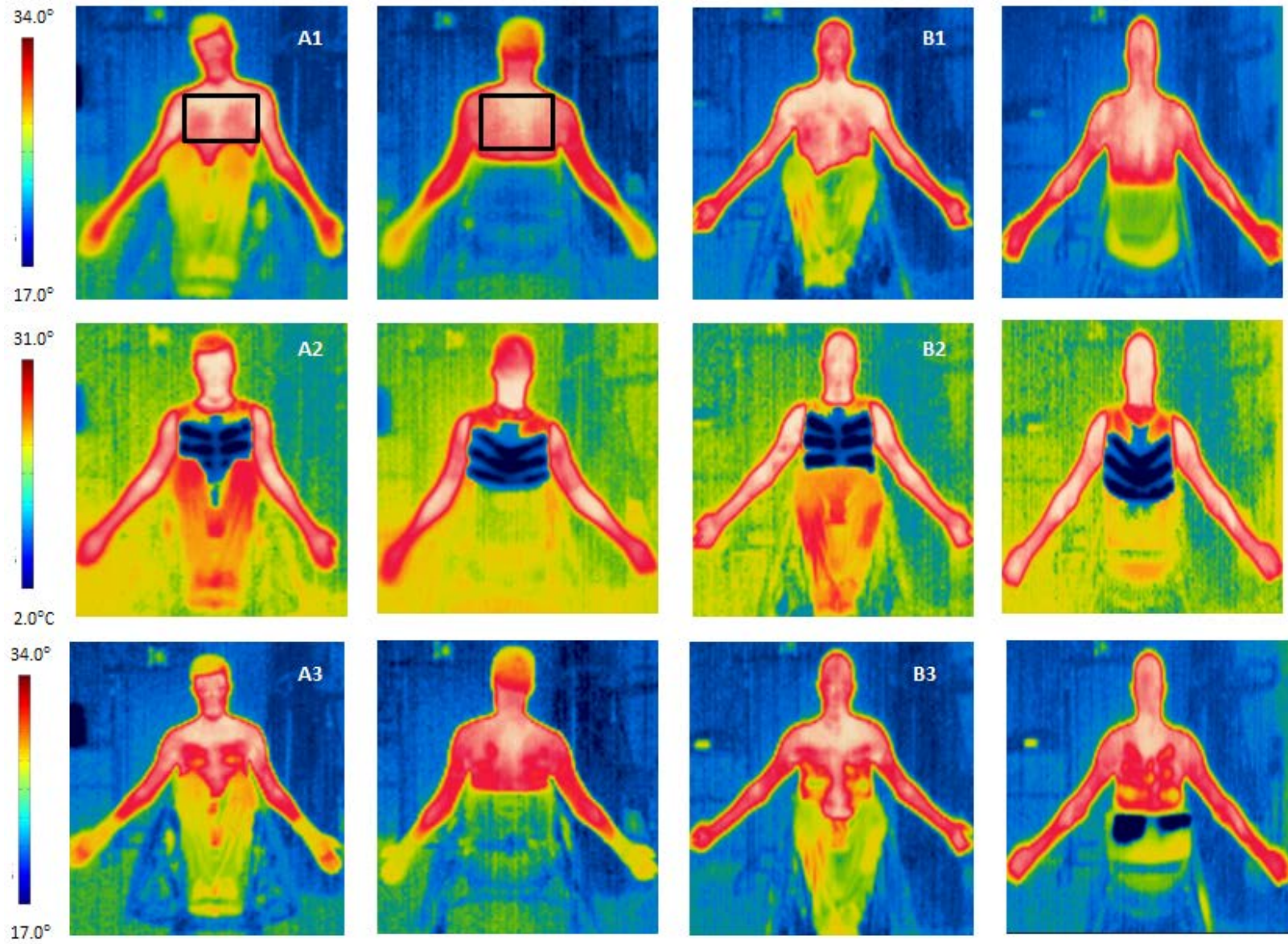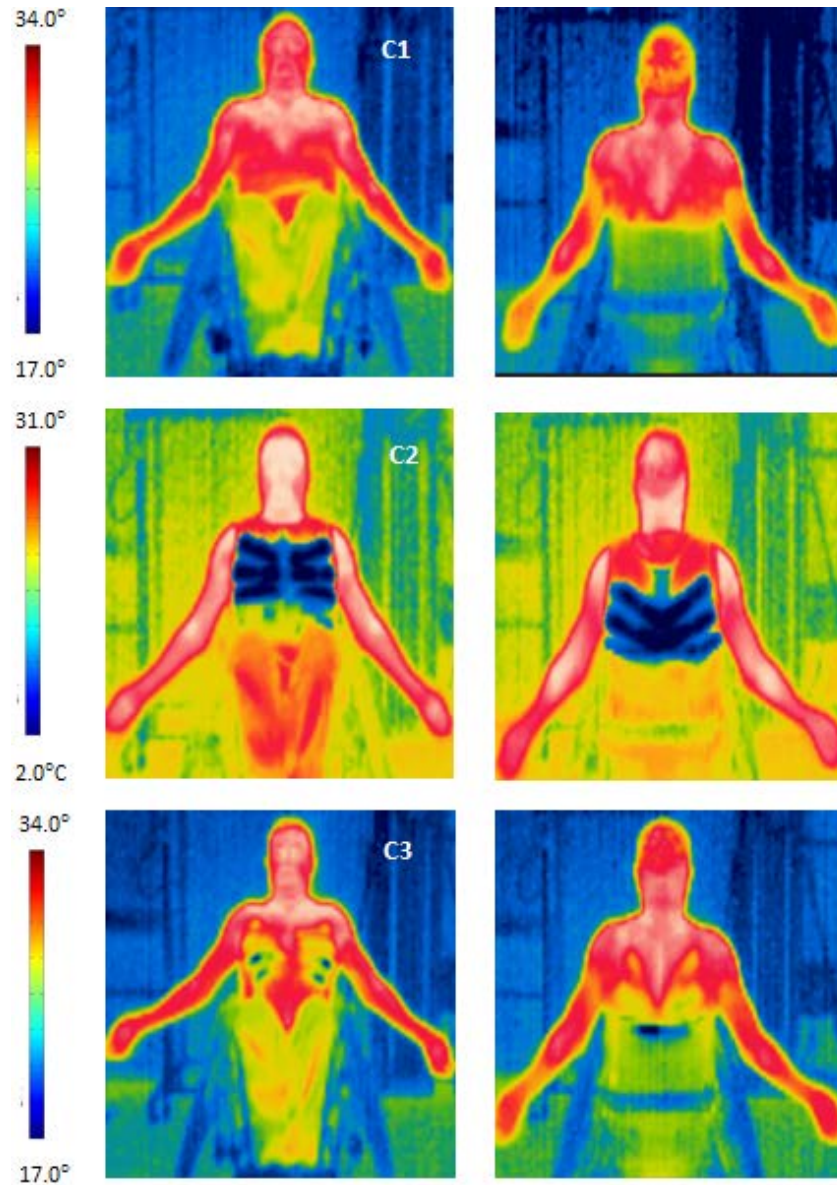
Figure 7.5 Infrared images (anterior and posterior) of the three participants (A,B,C) during 15 min rest period at time point; 1) start (with no top), and 2) after donning a top, ice vest and abdominal strapping and 3) at the end of the 15 min rest period to highlight the issue of garment fit. Black boxes on images A1 depict the areas used to determine whole anterior and posterior torso skin temperature. * note participant A donned gloves prior to the start of the third thermogram.

7.5 Discussion

The present study demonstrated that the combined methods of pre-cooling using an ice vest and water spraying (PW) between quarters attenuated thermal strain to a greater degree than solely employing a pre-cooling ice vest strategy (P) during simulated WCR match play, partially accepting the hypothesis. Pre-cooling reduced the change in T_{gi} throughout the second half of the ISP, compared to NC, providing a smaller, but still substantial attenuation of T_{gi} compared to PW. Yet, the greater negative change in T_{sk}, compared to NC, during the pre-cooling period was not long lasting. Interestingly, despite employing a protocol based on the activity profiles of WCR match play, neither cooling condition had an effect on WCR performance.

The ice vest's application during a 20 min rest period in previous studies showed similar reductions in T_{gi} (-0.3ºC) and T_{sk} (-1.7ºC, Webborn et al. 2010, Webborn et al. 2005). However, former studies have often overlooked the importance and influence that a warm-up has on the thermoregulatory responses of athletes (Webborn et al. 2010, Webborn et al. 2005). In the present study the strategy of pre-cooling during rest followed by a 20 min warm-up reflects the "real-world" preparation for matches, lowering T_{gi}, on average, by only 0.1ºC by the end of the pre-cooling period compared to NC. Thus, future studies should include a warm-up to ensure ecological validity of the protocol.

External work was similar between conditions, signifying that estimated heat production was also similar between conditions. Thus differences in T_{gi} and T_{sk} were due to the manipulation of heat loss. Although no cooling was applied during the ISP, the offset of T_{gi} from pre-cooling led to a smaller change in T_{gi} throughout in P compared to NC. Cooling the skin surface with the ice vest lowered peripheral tissue heat content sufficiently to act as a heat sink, enabling the blood returning to the central circulation from the periphery to be cooled. Thus this resulted in a lower heat accumulation in the body core during the ISP, even though the drop in T_{sk} was not long lasting. A lower T_{gi} was found in P compared to NC till the end of the 60 min protocol, with the addition of water sprays between quarters leading to a further attenuation of T_{gi} during the ISP. The water sprays, that covered the majority of the anterior torso, cooled the skin's surface, resulting in a lower T_{sk} response throughout the second portion of the ISP compared to P and NC.

In the AB, the use of a facial water spray during a 5 km run has been shown to lower thermal sensation without a significant reduction in T_{core} (Stevens et al. 2016). In contrast, in the present study cooling attenuated T_{gi} but the athletes did not perceive to be any cooler or more comfortable in the cooling conditions compared to NC. The correlational data reveals that, similarly to Studies 1-3 (Chapters 4- 6), due to only a small portion of their skin being sensate, the reporting of thermal perceptions may be limited to a small surface area in SCI (Attia et al. 1983). In addition to Studies 1-3 (Chapters 4- 6), the data from the current study questions the use of the perceptual scales when cooling is applied. If individuals with an SCI are unable to detect a change in their T_{core} and T_{sk} unreliable perceptual reporting of their physiological responses will be expected. Thus, research investigating the thermal perceptions of individuals with an SCI is greatly needed.

Whilst playing a role in thermal comfort, garment fit is also important in active clothing to enhance cooling (Davis et al. 2013). The ice vest's cooling effectiveness may have been influenced by the garment fit due to the chest and abdomen being the only local skin temperatures cooler in the pre-cooling conditions compared to NC. The infrared images (Figure 7.5) were taken to highlight the issue of garment fit of the ice vest when wore by wheelchair athletes. The images highlight the cooler skin temperatures on the anterior than posterior of the torso at the end of the 15 min rest period, in addition to the variation in areas of cooler skin temperatures between participants. The variation in cooling between participants, provided by the ice vest, reinforces the issue of garment fit and inter-individual variability. Anecdotally the durability of the ice vest could also be questioned despite following the same activation and freezing procedure for each trial, the ice strips began to lose bulk and took longer to de-activate following frequent use. The issue of durability may also partly explain why only the change in T_{sk} was significantly different at the start and end of quarter 1 in P, whilst this was not the case in PW, even though the same procedure was followed. Developments in cooling garments have been made in recent years, as previously mentioned in Section 2.12.2. Yet only one previous study has investigated the use of a cooling vest consisting of renewable phase change material. The vest is reported to maintain at 15°C for 2-3 hours and was tested with individuals with both PA and TP, during either 60 min of wheelchair basketball or WCR (Trbovich et al. 2014). The authors found no significant differences in T_{gi} between the cooling vest and no cooling trial for either group, yet several limitations of the study are apparent, such as the exercise intensity of the exercise. Whether a cooling garment made from the aforementioned materials would provide a greater

thermoregulatory and/or performance benefit for athletes with TP during actual match play than the studied ice vest is thus currently unknown. Practically a durable cooling garment that accounts for the seated position of the athletes may be more suitable for the studied population potentially improving the cooling effectiveness of the garment.

Previously, studies have shown that the use of cooling strategies in the heat has a detrimental effect on fluid ingestion (Goosey-Tolfrey et al. 2008a). In the present study, cooling may have also influenced fluid ingestion as the greatest amount of fluid consumed was in NC. Coupled with an absence or minimal sweating a greater gain in body mass was apparent, akin to Study 3 (Chapter 6) and previous research (Black et al. 2013). Although a smaller amount of fluid was ingested in the cooling conditions, due to the individual's sweating dysfunction a significant difference between conditions in total mass loss was not apparent. Thus, the use of cooling strategies in this population group in the ambient conditions studied does not seem to have a detrimental effect on fluid ingestion.

It is important to consider that despite P and PW attenuating T_{gi}, the participants still had a continuous increase in T_{gi}. During competition, wheelchair rugby players often play multiple matches in one day, therefore players with tetraplegia may start the second match at a highlighted T_{gi} than the first match. From the recovery data in Study 2 (Chapter 5), T_{gi} continued to increase during 15 min of passive recovery in athletes with tetraplegia resulting in a T_{gi} 1.1°C higher than at the start of the ISP. Combining these results with the results of the present study, providing cooling to the player post-match and/or prior to the second match would therefore be recommended. However, it is also important to note that, depending on the cooling method, due to the small surface area in which to perceive their thermoregulatory state, players may report feeling cooler from post- match cooling whilst T_{gi} may still be heightened. As mentioned previously, being able to determine a player's thermal state from the use of perceptual scales is unreliable, potentially resulting in players beginning a second WCR match on the same day already under considerable thermal strain.

In addition to the physiological and perceptual responses, performance variables measured either during each quarter or end of quarter sprints were similar between conditions, which is in contrast to Webborn et al. (2010). Furthermore, the lack of differences in performance variables and percentage change in end of quarter sprints may indicate that substantial fatigue was not generated or participants were pacing their effort over the four sprints. This is consistent with ISP data which has shown that activity profiles of elite WCR players do not

significantly deviate across full matches (Rhodes et al. 2015), suggesting match play activity is not influenced by fatigue. Whether a difference in actual match play performance would have been found following similar cooling techniques is however unknown.

To replicate a WCR match in the laboratory the speed zones of the ISP were determined using the ISP data collected in Study 3 (Chapter 6). However, the distances covered by the participants by the end of the ISP were greater than the reported distances covered on court (7370 ± 1239 m vs 4842 ± 324 m for the ISP and on-court data from Study 3, respectively). During wheelchair propulsion, physiological demand is affected by a number of resistive forces including rolling resistance, internal friction and air resistance. Therefore, the discrepancy between the ergometer simulated match and actual game play could be partly due to differences in resistance between the ergometer and over-ground propulsion (van der Woude et al. 2001). In addition, on the WERG speed zones were condensed into longer periods of time, compared to multiple bouts of shorter duration on court, due to the feasibility of changing the target speed every few seconds, potentially affecting the overall distance covered.

7.6 Practical applications

The present study determined whether current cooling practices, ice vest and water sprays, used by athletes with TP were effective at reducing thermal strain. In spite of a change in performance between conditions, athletes with TP should employ the combination of pre-cooling using an ice vest and water sprays between quarters to lower thermal strain to a greater degree than solely employing a pre-cooling ice vest strategy. Although solely employing a pre-cooling strategy using an ice vest does provide a reduction in T_{gi} throughout the ISP compared to no cooling. The current study did not investigate whether water sprays alone reduces T_{gi} and T_{sk} and whether this strategy is advantageous compared to solely using an ice vest. Although due to time constraints of the studied participants this condition was not included, this could be an interesting addition to the study.

7.7 Conclusions

In conclusion, the present study aimed to determine the effectiveness of cooling methods currently used by athletes with TP on simulated WCR match play. Pre-cooling using an ice vest resulted in a greater reduction in T_{sk} during the pre-cooling period and although this response was not long lasting, the change in T_{gi} was still lower in P compared to NC

throughout the ISP. Even though neither cooling condition had a positive nor a detrimental effect on performance or perceptual responses, the combination of methods attenuated thermal strain during the ISP to a greater degree than pre-cooling.

Chapter 8

General discussion

8.1 Summary of main findings

The principal aim of the thesis was to examine the thermoregulatory responses of athletes with an SCI at rest and during "real-world" sporting scenarios. In order to achieve this, the following objectives were formulated:

1. To examine the differences in evaporative heat loss at rest between individuals with PA and TP in comparison to able-bodied individuals
2. To determine the thermoregulatory responses of athletes with TP compared to athletes with PA during intermittent wheelchair exercise.
3. To determine the thermoregulatory responses of WCR players with TP compared to players with NON-SCI during competitive on-court match play.
4. To establish the effectiveness of current cooling practices employed by athletes with TP.

The findings from the four experimental chapters combine to broaden the knowledge of thermoregulation in athletes with an SCI, with a particular emphasis on athletes with TP. Furthermore, the exercise studies of the thesis employed "real-world" sporting scenarios to determine the extent of the thermoregulatory impairment for these individuals. Study 1 explored the fundamentals of thermal physiology in individuals with an SCI. The study examined how evaporative heat loss, and subsequently heat balance at rest, is altered as a result of an SCI compared to the AB, in order to determine the effect lesion level has on this response. Study 2 examined the difference in thermoregulatory responses between athletes with PA and TP during intermittent sprint wheelchair exercise in conditions representative of a "real-world" sporting environment. Study 3 extended the findings from the laboratory and determined whether thermoregulatory responses differed between players with TP and players with NON-SCI during competitive WCR match play. In addition, the study

determined whether the thermoregulatory responses of the players were related to their activity profiles and/or their physical attributes. Lastly, Study 4 examined the effectiveness of cooling practices (e.g. ice vest and facial water spraying), that are currently employed by athletes with TP during participation in wheelchair sports. Figure 8.1 provides a summary of the main findings of the experimental chapters (Chapters 4-7) of the thesis.

Study 1: Differences in evaporative heat loss between the able-bodied and individuals with a spinal cord injury of different lesion level

Outcome: Despite metabolic heat production being similar between groups, evaporative heat loss in individuals with tetraplegia was not large enough to balance the heat load. Even individuals with paraplegia experienced a continual increase in both gastrointestinal temperature and mean skin temperature signifying at temperatures above mean skin temperature latent heat loss is insufficient to attain heat balance.

Exercise studies encompassing "real-world" sporting scenarios

Study 2: Thermoregulation during intermittent exercise in athletes with a spinal cord injury

Outcome: Athletes with tetraplegia experience a greater increase in gastrointestinal temperature for the same external work load compared to athletes with paraplegia.

Extending the findings from the laboratory to competitive sports specific on-court match play

Study 3: Thermoregulatory responses during competitive wheelchair rugby match play

Outcome: 1) Wheelchair rugby players with tetraplegia were under greater thermal strain despite covering less distance and having slower mean speeds compared to players with a non-spinal related physical impairment.

2) Those players with tetraplegia who had a greater $\dot{V}O_{2peak,}$ body mass, lean mass and, were a higher point player covering greater distances and achieving faster speeds on court had a greater end gastrointestinal temperature.

Application of current cooling practices employed by athletes with TP

Study 4: Effects of cooling before and during simulated match play on thermoregulatory responses of athletes with tetraplegia

Outcome: The combination of pre-cooling using an ice vest and water sprays between breaks during simulated wheelchair rugby game play lowered thermal strain to a greater extent compared to pre-cooling only and no cooling. Although neither cooling procedure had a positive or negative effect on performance.

Figure 8.1 Schematic representation of experimental chapters.

8.2   Contribution to scientific understanding and application of findings

8.2.1   Differences in heat loss at rest

Aside from exercise studies reflecting "real-world" sporting scenarios, to gain a greater understanding of the thermoregulatory consequences as a result of an SCI, it is also important that studies are conducted at rest, removing the additional metabolic heat production from exercise. Current studies have not investigated how the heat exchange avenues are altered as a result of an SCI, affecting the maintenance of heat balance. Study 1 (Chapter 4) aimed to determine how evaporative heat loss and heat balance are altered as a result of an SCI compared to the AB and the effect lesion level has on this response. The experimental protocol reduced heat loss by dry heat exchange by conducting the testing in a hot ambient temperature (37°C), and manipulating evaporative heat loss throughout, by reducing the water vapour pressure gradient in a stepwise manner. Results revealed that despite groups producing similar amounts of metabolic heat, individuals with TP had a greater T_{gi} and T_{sk} compared to the AB. After a period of stabilisation in T_{gi} the AB demonstrated a clear inflection point where a critical environment limit (80% RH) was reached. Above this limit heat balance was unattainable as evaporative heat loss could no longer balance the heat load. In contrast, for individuals with TP heat balance was not attained throughout the protocol. Even though individuals with PA have a greater sweating capacity than individuals with TP, both T_{gi} and T_{sk} continually increased throughout the protocol, also signifying an inability to attain heat balance. Nevertheless, further investigation is needed to determine whether thermoregulatory responses would differ between individuals with PA with high and low lesion levels. Due to the number of participants this additional comparison could not be studied in Study 1.

It was concluded that when evaporative heat loss is the primary avenue for the dissipation of heat, both individuals with PA and TP will be unable to attain heat balance at rest. Thus, the findings highlight real concerns when these individuals are exercising in comparable environments, during general daily activities or during a period of prolonged abnormal hot weather, i.e. a heatwave.

Although in comparison to the other three experimental chapters this study did not employ highly trained athletes, participants were all recreationally active. Even though the effect of fitness on heat tolerance in individuals with an SCI has not been studied, one study has shown that trained individuals with TP had a greater sweat gland density and sweat output
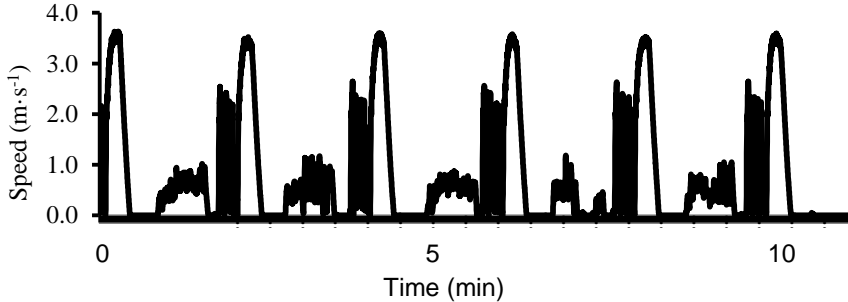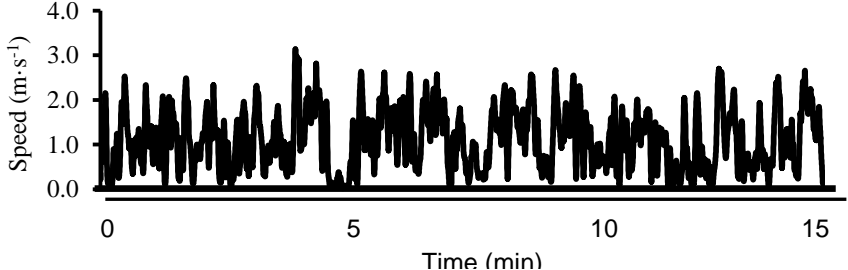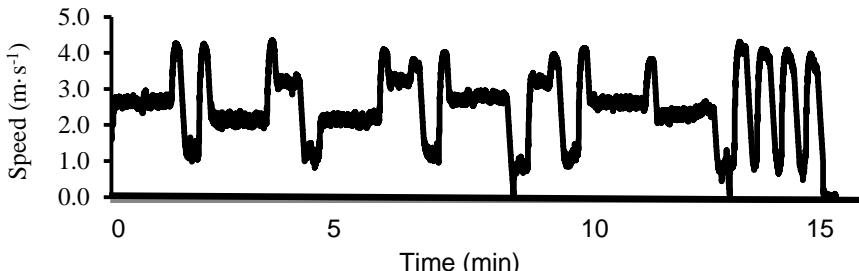
above the lesion level compared to untrained individuals with TP (Yaggie et al. 2002). The authors stated that this may be due to increased glandular cholinergic sensitivity as a result of physical training. Nevertheless, no study has investigated this finding further. Unfortunately the aerobic fitness of the participants in Study 1 was not determined; hence fitness cannot be compared to the other three experimental chapters. Due to the recreationally active nature of the participants the findings also have applications for the wider SCI population than just purely the athletic SCI population. For instance, the findings of the study highlight the heightened thermal strain of individuals with PA and TP and the need for guidance and advice when travelling abroad or during heat waves, in addition to athletes travelling to hot climates for competitions.

8.2.2 Exercise studies

Prior to this thesis, few exercise studies had been conducted investigating the thermoregulatory responses of athletes with TP (Webborn et al. 2010, Webborn et al. 2005, Price et al. 1997, Price et al. 2003, Price et al. 1999b, Gass et al. 1992). Over the years, protocols have been developed that better reflect wheelchair court sports. Yet they still lack ecological validity, whether in relation to the modality, protocol or ambient conditions used. Moreover, due to the small sample sizes of many of the aforementioned studies (Price et al. 1999b, Gass et al. 1992), the ability to draw firm conclusions based on these studies is limited, especially due to the heterogeneous nature of the SCI population.

Table 8.1 summaries the three exercise studies of the thesis (Chapters 5-7). These studies aimed to reflect the sporting scenarios of indoor wheelchair court sports, in particular WCR, addressing the need for ecological valid protocols in the SCI literature. The table also highlights the development of the protocols throughout the thesis.

Table 8.1 A summary of the exercise studies (Studies 2-4) of the thesis highlighting the participants, ambient conditions, modality and speed profile of each study. Note: the graphs depict individual data from a participant with tetraplegia from each study. Ambient conditions are mean ± SD.

Study	Participants	Ambient conditions (°C, RH)	Modality	Protocol (speed, m·s⁻¹)	
Study 2 (Chapter 5)	PA + TP	20.6 ± 0.1°C, 39.6 ± 0.8% RH	WERG		One quarter of data (10.5 min) from the 60 min intermittent sprint protocol.
Study 3 (Chapter 6)	TP + NON-SCI	19.0 ± 1.1°C, 36.8 ± 12.3% RH	Overground		One quarter of data (15 min) from the wheelchair rugby match, recorded by the indoor tracking system.
Study 4 (Chapter 7)	TP	20.2 ± 0.2°C, 33.0 ± 3.1% RH	WERG		One quarter of data (15 min) from the 60 min intermittent sprint protocol.

8.2.3 Thermoregulatory responses of athletes with tetraplegia during intermittent exercise

The primary focus of Study 2 (Chapter 5) was to ensure that the protocol reflected a "real-world" WCR and basketball sporting scenario using highly trained athletes. To achieve this, the ISP aimed to simulate an on-court training session for wheelchair court sports using the mode of wheelchair propulsion. The training session was designed by a Great Britain wheelchair rugby coach and has been used previously by Leicht et al. (2012a). The main findings of the study revealed that despite external work being similar between groups, T_{gi} increased at a greater magnitude in athletes with TP than athletes with PA. The results are comparable to continuous arm cranking exercise in similar ambient conditions (Price et al. 1999a). Thus the results signify that the breaks within and between exercise blocks provided no further reduction in thermal strain for the athletes with TP.

Despite this, the ISP may not have been wholly reflective of a wheelchair basketball or rugby match since subsequent data collected by an indoor tracking system during matches of WCR (Rhodes et al. 2015) have reported distances covered to be 4316 ± 626 m compared to only 2316 ± 258 m covered by players on the WERG in Study 2. Thus, these results signify that the thermal strain of the athletes with TP may be even greater during on-court match play due to the greater amount of work. Consequently, to fully understand the extent of the thermoregulatory impairment in athletes with TP, using a combination of laboratory (Study 2) and field based studies (Study 3) are essential.

8.2.4 Thermoregulatory responses of wheelchair rugby players with tetraplegia during competitive match play

Study 3 (Chapter 6) extended the research findings of Study 2 (Chapter 5) by examining the thermoregulatory responses of WCR players with TP during competitive on-court match play. The match play accounted for any possible underestimation of work done in Study 2. More importantly, while match play conditions provide a physical challenge of on-court wheelchair manoeuvrability, they also create psychological stress that is difficult to replicate in a laboratory (Goosey-Tolfrey et al. 2013).

The study's novel approach investigated both physiological responses and activity profiles during match play, by incorporating an indoor tracking system. A recent change to the classification system of the IWRF has meant both players with TP and non-spinal related physical impairments are now eligible to play WCR. Hence the study allowed the positional

roles of players and dynamics of team sport to be accounted for, whilst enabling a greater understanding of whether a player's impairment, activity profile or physical attributes predisposes them to a greater amount of thermal strain. Findings revealed that despite covering ~17% less distance and pushing on average ~10% slower (thus generating a smaller amount of heat), WCR players with TP had a greater increase in T_{gi}. Hence, players with TP were under a greater amount of thermal strain compared to their teammates with non-spinal related physical impairments, due to their reduction in heat loss capacity as a result of their SCI and not due to the amount of work performed. These data therefore reinforced the findings reported in Study 2.

The indoor tracking system enabled the work load of the match to be quantified, which has not been previously possible for indoor wheelchair court sports. Whilst the physiological data adds another dimension to the existing research on activity profiles of players in WCR (Rhodes et al. 2015). Preliminary data from the study provided an insight into whether certain physical attributes or activity profiles were related to T_{gi} at the end of the match for players with TP. The findings highlight that players with a greater $\dot{V}O_{2peak}$, larger body mass, larger lean mass and/or were a higher point player, showed a greater end $T_{gi,}$ covering a greater distance and had a greater mean speed. Consequently, this additional information provides coaches and support staff the first indication that particular players may be under greater thermal strain than others and allow for the implementation of targeted cooling strategies.

8.2.5 Effectiveness of current cooling practices

There has been some research interest in cooling strategies in individuals with an SCI, with to date ten published studies. Yet, these studies have used varying cooling methods, protocols and participants, discussed in Griggs et al. (2015). Eight of these studies were previously discussed in Section 2.11. Consequently, this variation between studies has made it difficult to establish the optimal cooling method for athletes with an SCI. Furthermore, previous studies examining the effectiveness of cooling strategies in this population group have lacked ecological validity and have mainly focused on strategies in isolation. Thus, Study 4 (Chapter 7) aimed to investigate the effectiveness of current cooling practices (ice vest and water sprays), used by WCR players with TP. In addition, to ensure ecological validity the indoor tracking data from Study 3 (Chapter 6) was used to design the WERG protocol ensuring that the work load of the protocol was as ecologically valid as possible.

The main findings of the study demonstrate that the combined methods of pre-cooling with an ice vest and water spraying between quarters attenuated thermal strain to a greater degree than pre-cooling alone. Although the attenuation of T_{sk} was not long lasting, T_{gi} was still lower in pre-cooling only compared to no cooling throughout the 60 min protocol. Despite these results, neither cooling condition had a positive or negative effect on performance.

While this study aimed to investigate the current cooling practices used by athletes with TP, alternative cooling methods may provide a greater attenuation in T_{gi} and T_{sk} than the studied methods. Future research employing ecologically valid protocols need to investigate whether other practical cooling methods, such as cooling garments and internal cooling methods, studied in the able-bodied are more effective than the ones studied in this thesis.

8.3 Application of research findings

The research presented in the current thesis has highlighted the following practical applications:

- In environments where evaporation is the primary source of heat dissipation and evaporation is fully permitted, specific advice such as effective cooling strategies, requirement of air conditioned rooms and avoidance of spending long periods of time in hot conditions should be given to athletes with TP (who compete indoors) to avoid a continual increase in T_{core} and minimise the risk of heat related illnesses.

- Caution should additionally be given to athletes with PA as heat balance is also unattainable in conditions where evaporation is the primary source of heat dissipation and evaporation is fully permitted.

- Support staff should be mindful that despite WCR players with TP covering less distance and having slower mean speeds during a competitive match than their NON-SCI teammates, they are under a greater amount of thermal strain.

- Support staff should be aware that WCR players with TP that have a greater $\dot{V}O_{2peak}$, larger body mass, larger lean mass and/or are a higher point player are likely to have a greater T_{gi} at the end of a competitive match. These players are also likely to cover a greater distance and have a greater mean speed due to their greater functional ability. Hence these players may need longer recovery between matches and/or appropriate post-match cooling.

- In athletes with TP, T_{gi} continues to rise during post exercise recovery, which may be an additional concern if multiple matches are played in succession. Players could be starting the second match significantly warmer than resting levels which could negatively impact performance, but also increase the risk of heat injury.

- Despite WCR players being classified according to their physical impairment, physiological responses greatly differ between players of the same classification affecting their activity profile during a match.

- In spite of having a positive impact on performance, athletes with TP should employ the combination of pre-cooling using an ice vest (35 min duration including rest and warm-up) and water sprays between quarters to lower thermal strain to a greater degree than solely employing a pre-cooling ice vest strategy.

- If the above strategy is not feasible, pre-cooling using an ice vest does lower T_{gi} throughout subsequent intermittent wheelchair exercise (60 min) to a greater extent than no cooling.

8.4 Directions for future research

The main findings of the experimental chapters, give rise to a number of additional research questions, the most pertinent of which are discussed below.

8.4.1 Mean skin temperature calculation

Mean skin temperature was calculated using the Ramanathan formula in all experimental chapters, which uses the skin temperatures sites of the chest, upper arm, thigh and calf shown below.

$$T_{sk} = 0.3t_{chest} + 0.3t_{arm} + 0.2t_{thigh} + 0.2t_{calf} \qquad (1)$$

Where: t_{chest} = chest skin temperature, t_{arm} = upper arm skin temperature, t_{thigh} = thigh skin temperature, t_{calf} = calf skin temperature.

The Ramanathan formula is a recommended method in the able-bodied population group and has been used previously for individuals with an SCI enabling comparison between studies (Pritchett et al. 2010, Webborn et al. 2010, Webborn et al. 2005). However, the response of regional skin temperature sites above and below the lesion level differ, due to muscular atrophy and the loss of sweating capacity and vasomotor control below the lesion level. This

leads to skin temperatures across the body showing less uniformity than in the able-bodied population group. Hence thermal gradients between the skin surface and the environment in addition to the ability to dissipate heat will differ between the two body regions (above and below the lesion level). For instance, in individuals with an SCI, at rest in thermoneutral conditions, skin temperature below the lesion level is lower than above the lesion level, e.g. calf and thigh skin temperatures of ~28-31ºC. One could argue that this results in the body having two different 'shells,' one above and one below the lesion.

The relationship between T_{core} and skin temperatures above and below the lesion also differs depending on the ambient environment. For instance, when skin temperature is warmer than the environment, skin temperature below the lesion level remains fairly stable whilst T_{core} increases. In contrast, when skin temperature is cooler than the ambient environment, skin temperature below the lesion level increases in line with an increase in T_{core}. Therefore, for the reasons mentioned above a formula specific for use by the SCI population with specific weightings appropriate to both skin temperature sites above and below the lesion level, and consideration of the ambient environment, should be explored.

8.4.2 Critical environmental limits during exercise

To further the understanding of dissipation of heat in individuals with an SCI, future research could include the additional measures of local sweat rate of each skin temperature region, i.e. representative of each body region, and skin blood flow above and below the lesion level. In Study 1 (Chapter 4) skin blood flow was not measured due to the Laser Doppler monitor being unable to cope with the upper humidity range.

Whilst Study 1 (Chapter 4) was conducted at rest, a significant number of athletes with PA and TP compete outside in hot and humid conditions, such as wheelchair tennis players, track and field athletes, hand-cyclists etc. Yet our knowledge of the thermoregulatory responses of these athletes, in particular wheelchair tennis players, taking into account the varying activity profiles of matches and specific game requirements, is scarce (Girard 2015, Veltmeijer et al. 2014).

Understanding the magnitude of the thermal strain experienced during exercise by these individuals across a range of environmental conditions, whilst matched for metabolic heat production would be an interesting addition to Study 1. To achieve this, the typical work load of each sport would need to be determined. The study should then allow for optimal exercise

times to be established, i.e. when the individual can no longer physiologically tolerate both the environmental and metabolic heat. This information could then be used to determine in which conditions the risk of thermal strain would be too high for these individuals and suggest how often breaks in play should be taken etc. The findings could potentially inform the amount of cooling that would be needed for varying environmental conditions and different lesion levels. Nevertheless, exercise could only be conducted under steady state conditions, which would have implications for intermittent sports, such as wheelchair tennis.

8.4.3   Identifying WCR players under the greatest thermal strain

Furthering knowledge from Study 3 (Chapter 6), additional physiological variables, plus a larger sample size, could be explored to enable support staff to determine players with TP under the greatest thermal strain in WCR. For instance, autonomic completeness has been suggested to be an important determinant of resting cardiovascular function and exercise (West et al. 2013b) and endurance performance in athletes with TP (West et al. 2015). In addition, no relationship has been found between autonomic completeness and motor/sensory completeness of injury (West et al. 2015, West et al. 2014), suggesting that to fully understand the physiological responses of an athlete with TP, it is imperative that autonomic completeness of the individual is also considered. For this reason, previous research has suggested that individuals with intact vasomotor pathways should be identified as part of the classification process (West et al. 2014). Determining whether the autonomic completeness of an SCI relates to the amount of thermal strain experienced by a player during WCR match play could, therefore, be an interesting addition to the study. This supplementary information could aid support staff in targeting specific players who are likely to be under the greatest thermal strain and implement appropriate tactics and cooling strategies accordingly.

Understanding the thermoregulatory responses of players in other sports in which athletes with TP compete, such as wheelchair tennis and wheelchair racing is also warranted. Even though one study has monitored wheelchair tennis players during a match, the ambient environment had a WGBT score of < 20°C and only 3 players with an SCI and 5 players with a non-spinal related physical impairment were tested, making drawing conclusions from this data set limited (Veltmeijer et al. 2014).Wet bulb globe temperature limits are in place in wheelchair tennis to try to reduce the likelihood of heat injury (28°C in wheelchair tennis and 30.1°C in able-bodied tennis), yet the physiological responses and activity profiles of players with TP has not been quantified during a typical match. During able-bodied tennis, effective

playing percentage is reduced whilst the duration of time between points is increased in matches played in the heat (~34°C WGBT) compared to cool (~19°C WGBT) conditions (Periard et al. 2014). Whether a similar behavioural strategy is adopted in wheelchair tennis would be a novel comparison.

8.4.4   Cooling strategies and heat acclimation

Current cooling practices used by athletes with TP have primarily been based on existing literature in the able-bodied population. A priority for future research is the development of cooling practices for athletes with an SCI, in particular athletes with TP. In relation to cooling garments, further work is needed to explore garments consisting of materials other than ice (i.e. substances that melt at a greater temperature) and specifically designed for athletes with an SCI, taking into account their seated position during exercise. This has the potential to increase both the cooling power and effectiveness of the cooling garment. As well as the use of water sprays, in indoor playing environments (~20ºC), the additional air movement provided by a fan would increase the evaporative heat loss from the skin's surface, potentially lowering both T_{sk} and T_{gi}. Broadening the range of the experimental conditions studied in Study 4 (Chapter 7), with two additional conditions of water sprays alone and the combination of water sprays and fan, would provide further information on which combination of cooling strategies has the greatest reduction of thermal strain.

Furthermore, a greater understanding of which body regions would be the most appropriate and effective to cool pre-exercise for athletes with an SCI is warranted. The variation in heat exchange across the body is likely to be in proportion to the lesion level and completeness of the lesion, thus if certain body regions allow for a greater amount of heat exchange these regions could be primary targets for cooling prior to exercise. To address this research question, a water perfused suit, covering the body's entire surface area except from the face (Figure 8.2), could be used to determine the amount of heat exchange at individual body regions in response to cooling. This would be achieved via a series of cooling and re-warming cycles targeting individual body regions. The water perfused suit would enable water temperature to be manipulated at a required body region whilst water temperature to the remaining zones was maintained. The proposed study should enable the determination of individual body regions to target for pre-cooling for athletes with both PA and TP.
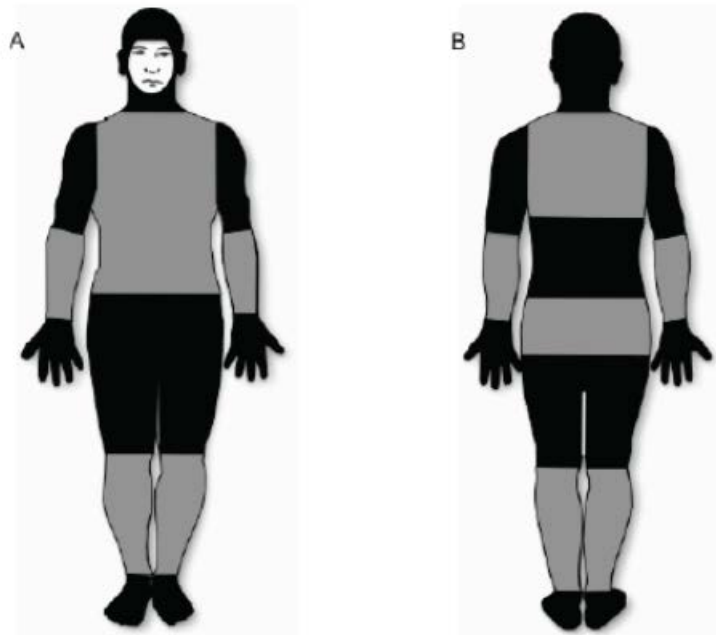
Figure 8.2 A representation of the individual body regions within the water perfused suit. A) head, torso, upper arms, forearms, hands, front thigh, lower legs and feet; B) head, upper back, lower back, upper arms, forearms, hands, buttocks, rear thigh, lower legs and feet.

Although not currently studied in the SCI population, the use of internal cooling methods, such as ingesting cold ice/fluids, have received considerable interest over recent years in the able-bodied population, showing significant reductions in T_{core} and performance improvements (Siegel et al. 2012, Siegel et al. 2010, James et al. 2015, Ihsan et al. 2010, Stevens et al. 2013). The ingestion of an ice slurry approximately doubles the internal heat sink, compared to cold fluid ingestion, as a result of the amount of heat transfer associated with the enthalpy of fusion of ice (Morris et al. 2016).

However, a recent study has shown that the use of ice slurries during exercise may actually hinder net heat loss. Morris et al. (2016) reported that a larger reduction in whole body sweating, thus evaporative heat loss from the skin, is found during steady state cycling (34°C, 20% RH), compared to the amount of internal heat lost to the ingested ice slurry. Therefore the authors advised that ice slurry ingestion should be used solely as a pre-cooling method and not during exercise in warm, dry conditions. Yet in individuals with an SCI, evaporative heat loss is already reduced as a result of their impairment, thus the effect of this method as a pre-cooling or during exercise tool is an interesting avenue of research.

In theory spraying the skin's surface with water compared to the ingestion of cold fluid or an ice slurry has a larger cooling potential. For instance, the amount of energy required to evaporate water is 2430 J·g, compared to the heat capacity of water and ice being 4.184 J·g·°C^{-1} and 2.108 J·g·°C^{-1}, respectively. Even though an additional 334 J·g of energy is required for the latent heat of fusion of ice, a greater amount of energy and therefore the greatest cooling potential would still be provided by spraying the skin's surface with water. Lowering the temperature of the water in the spray, thus increasing the thermal gradient between the skin and water temperature would further increase the cooling potential of the water spray. Nonetheless, an individual is likely to consume more fluid or ice slurry than is sprayed on the skin's surface. Increasing the amount of fluid consumed, increases the heat exchange between the fluid and body, attenuating T_{core} rise. Therefore, the practicality of each method, the amount of fluid (whether ingested or sprayed on the skin's surface) and its temperature is paramount when choosing an appropriate cooling method.

Practically the amount of ice slurry that should be ingested to warrant a thermoregulatory and performance benefit could be a concern for some wheelchair athletes with an SCI. Individuals with an SCI usually drink frequent low volumes of fluid to decrease the risk of urinary complications, particularly as ingestion of large amounts of fluid, leading to frequent voiding, could increase the risk of autonomic dysflexia (Goosey-Tolfrey et al. 2015). Therefore, further investigation into whether this internal method would be beneficial and practical for athletes with an SCI is greatly needed.

Aside from cooling methods, heat acclimation is recommended for optimising performance in hot conditions in the able-bodied population (Racinais et al. 2015), whilst also providing ergogenic effects during cooler conditions (Corbett et al. 2014). Despite this, only one published study to date has investigated the effect of a period of heat acclimation on the thermoregulatory responses of athletes with an SCI (Castle et al. 2013). The authors stated that partial acclimation could be achieved for these individuals after 7 days acclimation in 33°C, 65% RH. Participants undertook 60 min of heat exposure involving 20 min of arm crank ergometry followed by passive heat exposure or simulated shooting practice. Results revealed reductions in resting aural temperature and perception of effort and increased plasma volume. Yet the small sample size (n = 5) and participants with a range of impairments; PA, TP, spina bifida and Polio, makes drawing firm conclusions from this study fairly limited. Furthermore, subsequent observations (Price et al. 2011) have found a lack of heat acclimation, using a protocol similar to Castle et al. (2013), in athletes with PA and TP.

One study to date has shown that trained individuals with TP have a greater sweat gland density and sweat output than untrained individuals (Yaggie et al. 2002). Yet further research is needed to confirm this finding and determine whether sweat glands above the lesion level for individuals with an SCI are trainable and could adapt through heat acclimation protocols. To further understanding of the sweating response of individuals with an SCI, investigating the amount of active sweat glands and sweat output per gland at sites above and below the lesion level for both athletes with PA and TP, will help determine the extent of any remaining sweating capacity at the level of the sweat gland. If sweat glands are trainable above the lesion, whether heat acclimation could improve any remaining sweating capacity of both athletes with PA and TP, would be an interesting avenue for research.

8.4.5   Thermal perceptions

In all of the experimental chapters thermal perceptions (thermal sensation, thermal comfort and wetness sensation) were not different between the able-bodied and athletes with PA and TP, during exercise or at rest. This is despite athletes with an SCI, in particular athletes with TP, being under greater thermal strain. Furthermore, in Study 4 (Chapter 7) athletes with TP were unable to judge the magnitude of thermal strain when cooling was applied. These data indicate that individuals with an SCI are unable to judge their thermal strain reliably and the use of the thermal perception scales used in the experimental chapters cannot be used as a reliable indicator of thermal strain. Further work is needed to understand whether perceptual responses in individuals with an SCI can be used as a tool to reliably determine the degree of thermal strain with specific perceptual scales.

8.5   Closing statement

This thesis identifies the extent of the thermoregulatory impairment in athletes with an SCI at rest and during "real-world" sporting scenarios. The combination of laboratory and field based studies enabled the thermoregulatory impairment of athletes with TP to be quantified compared to the AB, athletes with PA and within the sport of WCR. Furthermore, even though current cooling practices used in wheelchair sports were effective at attenuating the thermal strain of these athletes, potential avenues for future cooling strategy research have been highlighted.

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Appendices

Appendix A   **Heat tolerance questionnaire used in Study 1 (Chapter 4)**

Appendix A

Heat Tolerance Questionnaire

1. Generally how do you feel in hot and humid conditions?

2. Have you had many experiences of hot/humid conditions?
    a. Where have these been?

    b. What kind of conditions?

3. Have you had any major or minor issues in the heat previously?
    a. When/where was this?

    b. What was it attributed to?

    c. How hot? How humid?

    d. What did it feel like?

    e. Were there any lasting effects?

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