Clothing Design for the Optimisation of Aerodynamics and Thermoregulation in Middle-Distance Triathlon

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Abstract

A triathlon consists of a swim, bike and run all completed in immediate succession. Events are either short (sprint) distance consisting of a 750m swim, 20km bike and a 5km run to long distance such as the world renowned Ironman® races that consist of a 3.8km swim, a 180km bike and a 42.2km run. The rules and clothing differ across the varying distance disciplines. Due to the short, technical and draft legal nature of the sprint distance, very little consideration is given to materials in terms of their impact on athlete thermoregulation and aerodynamics even in warm weather as it will probably have little to no impact on performance, where it is common for competitors to wear sleeveless, all in one racing suits. However, when it comes to the longer distances, the non-draft legal rule means competitors gain no aerodynamic advantage from each other and have to rely on their own position and clothing design to make their cycling most efficient. For a half-ironman, triathletes usually wear all in one suits with rough fabrics incorporated into the long shoulder fabric that covers the arm down to the elbows, to aid aerodynamics. Over this long distance, triathletes push high power outputs for prolonged periods of time, resulting in concomitant high heat production. Therefore, it is important that the avenues of heat loss, either before or during the race, provide the athlete with sufficient cooling to prevent excessive heat strain and negative performance effects, especially when competing in high environmental temperatures. Performance benefits have been observed with multiple pre-cooling methods including ice-vests and cold water immersion, whilst many beneifical per-cooling methods are just too impractical to be adopted during a race. During the cycling phase, the largest avenue of heat loss is through convective cooling however, this may be inhibited by the aggressive aerodynamic positions adopted by triathletes. During this phase there becomes an important trade-off between improving aerodynamic efficiency whilst also maintaining sufficient heat loss. One way heat loss can be practically optimised is by smart fabric selection in the triathlon suits. By improving the movement of heat away from the body through increased conductivity, more efficient wicking and evaporation of sweat could help maintain performance or allow triathletes to maintain a more aggressive aerodynamic position without such detriment to heat loss. Although it is difficult to select fabrics without first characterising them in terms of both their thermal and aerodynamic properties, which can be very costly, time-consuming and

usually involves the use of a thermal manikin, hot plate or a wind tunnel. At present, little is know as to what extent the differences in fabric properties impact an athletes thermo-physiological response whilst cycling in environmentally stressful conditions where an optimised suit would be considered most beneficial.

Therefore, the aim of this research was to test the reliability of a new, faster method of measuring thermal conductivity and thermal effusivity of sports performance fabrics using a C-Therm device (Chapter 4), characterise performance fabrics currently used in elite sporting garments in terms of their thermal and aerodynamic properties (Chapter 5), understand how differences in thermal conductivity and thermal effusivity impact both thermo-physiology and thermal perception (Chapter 6), investigate whether the aerodynamic data collected is applicable in a field setting (Chapter 7) and finally to investigate how direct fabric manipulations designed to increase the efficiency of sweat evaporation impacts thermo-physiology and thermal perception when cycling in the heat (Chapter 8).

Several findings emerged including: 1) When using the C-Therm to measure the thermal conductivity (k) and thermal effusivity (ε) of fabrics intended to be worn as a single layer on the body, only 10 single layers of fabric are needed. Although the multi-layer vs single layer methods of testing fabrics cannot be used interchangeably, a linear regression can be used to derive results from one method to another (Chapter 4). 2) Differences were observed in the thermal properties of the smooth fabrics and differences were identified in the aerodynamics properties of both smooth and rough fabrics. This allowed for fabric selection for specific triathlon suits based on the cycling speed of the athlete for which it is intended to be used (Chapter 5). 3) The magnitude of differences in thermal conductivity and effusivity measured were not enough to significantly impact thermo-physiology or thermal perception during exercise in an ambient temperature of 28°C and 65% relative humidity. In this instance aerodynamics should be prioritised. Individual differences should also be taken into account (Chapter 6). 4) Differences in the main body fabrics of a triathlon suit can reduce aerodynamic drag (C_dA) without a change in position (Chapter 7). Unless a significant thermoregulatory or perceptual benefit can be demonstrated in a fabric, the most aerodynamic fabric should be chosen over one optimised based on its thermal characteristics (Chapter 8). 5) The findings of this thesis guides researchers and athletes as to how performance fabrics can be tested in the most valid, reliable and time efficient way possible whilst also providing an initial environmental threshold whereby the importance of aerodynamics outweighs the importance of thermoregulation.

Keywords: Thermoregulation, aerodynamics, time trial, cycling, triathlon, thermal conductivity, performance, sports clothing, core temperature, thermal perception.

Statement

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Publications

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Faulkner SH. and Jobling P. 2021. The Effect of Upper-Body Positioning on the Aerodynamic-Physiological Economy of Time-Trial Cycling. *International Journal of Sports Physiology and Performance*,16(1) (Jan), 51-58.

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Notations and Abbreviations

AERO = Aerodynamically Optimised Triathlon Suit

BSA = Body Surface Area (m^2)

C_D = Drag Coefficient (Dimensionless)

C_dA = Coefficient of Aerodynamic Drag to Frontal Area (m^2)

CHO = Carbohydrate (g)

CON = Control Triathlon Suit

COV = Coefficient of Variance (%)

C_{res} = Conductive Respiratory Heat Loss (W or W · m^2)

C + R = Dry Heat Loss (W or W · m^2)

ε = Thermal Effusivity (Ws½/m²K)

E_{res} = Evaporative Respiratory Heat Loss (W or W · m^2)

EE = Energy Expenditure (kJ · min^{-1})

E_{max} = Maximum Heat Loss Potential (W)

E_{res} = Respiratory Heat Loss (W or W · m^2)

E_{req} = Required Heat Loss to Maintain Heat Balance (W or W · m^2)

f_{cl} = Clothing Area Factor (Dimensionless)

F_D = Drag Force (N)

H_{prod} = Heat Production (W or W · m^2)

HR = Heart Rate

I_{cl} = Insulation Value (I_{clo})

ICC = Intra-class Correlation

k = Thermal Conductivity (W/mK)

LT2 = Anaerobic Threshold

M = Metabolic Rate (W or W · m^2)

$\bar{T}_{sk}$ = Mean Skin Temperature (°C)

MTPS = Modified Transient Plane Source

ρ = Air Density (m^3)

P_B = Barometric Pressure

PPO = Peak Power Output (W)

PCM = Phase Change Material

R_{cl} = Thermal Resistance ($m^2K \cdot W^{-1}$)

RER = Respiratory Exchange Ratio

Re = Reynolds Number

RPM = Revolutions per minute

RH = Relative Humidity (%)

RPE = Rate of Perceived Exertion

T_a = Ambient Temperature (°C)

T_b = Body Temperature (°C)

T_{Bicep} = Skin Temperature at the Bicep (°C)

T_{Calf} = Skin Temperature at the Calf (°C)

T_{Chest} = Skin Temperature at the Chest (°C)

T_{comf} = Thermal Comfort

$T_{Forearm}$ = Skin Temperature at the Forearm (°C)

T_{gi} = Gastro-intestinal Temperature (°C)

T_{Hand} = Skin Temperature at the Hand (°C)

T_{Head} = Skin Temperature at the Forehead (°C)

THERM = Thermally Optimised Triathlon Suit

TRE = Polymer-treated Triathlon Suit

TT = Time Trial

T_{Thigh} = Skin Temperature at the Thigh (°C)

$T_{Scapula}$ = Skin Temperature at the Scapula (°C)

T_{sens} = Thermal Sensation

$\dot{V}O_2$ = Volume of Oxygen Uptake ($L\cdot min^{-1}$)

$\dot{V}O_{2max}$ = Maximum Volume of Oxygen Uptake ($ml\cdot kg\cdot min^{-1}$)

$\dot{V}CO_2$ = Volume of Carbon Dioxide Production ($L\cdot min^{-1}$)

W = External Workload (Watts)

WBGT = Wet Bulb Globe Temperature (°C)

W_{per} = Skin Wetness Perception

Chapter 1

General Introduction

This thesis will begin by reviewing the literature and introducing the methods by which humans attain heat balance. It will then discuss physiological heat sensing and its impact on subjective measures of thermal sensation and thermal comfort. The review will introduce what is currently understood in terms of the impact of methods of pre-cooling and per-cooling for endurance performance. Lastly, it will introduce the principles of aerodynamics including formd drag, friction drag and how these are influenced and optimised in cycling and triathlon. General methods used throughout this thesis are introduced in chapter 3. Chapter 4 introduces a new method for measuring thermal conductivity and effusivity of performance fabrics using a modified transient heat source method with C-Therm technology. Following this, chapter 5 investigates using this protocol to characterise performance fabrics in terms of their thermal characteristics and also aerodynamic characteristics using a subsonic wind tunnel. These data then inform the design choice of four triathlon suits; two for riding speeds over 40kmph, one being thermally optimised and one aerodynamically optimised. Two other suits for riding speeds between 30-40kmph. Chapter 6 then tests these triathlon suits with a human application investigating differences in thermo-physiological or perceptual responses to steady state exercise in the heat. Chapter 7 looks to identify whether there are any measureable differences in aerodynamic drag between the aerodynamically and thermally optimised triathlon suit designs on an outdoor veledrome. These data are then used to investigate whether any apparent differences are meaningful when modelling and predicting 90km TT performance. Following this, chapter 8 discusses the potential for futher thermal optimisation of fabrics by directly modifying the fabric surface using a polymer coating. The polymer coating has the potential to move the sweat and heat through the fabric for it to be evaporated more rapidly away from the body compared to the same non-polymer coated fabric. Finally, chapter 9 is a general discussion of the thesis including future directions and hypothesis'. Figure 1.1 displays the research questions of each experimental chapter throughout this thesis.

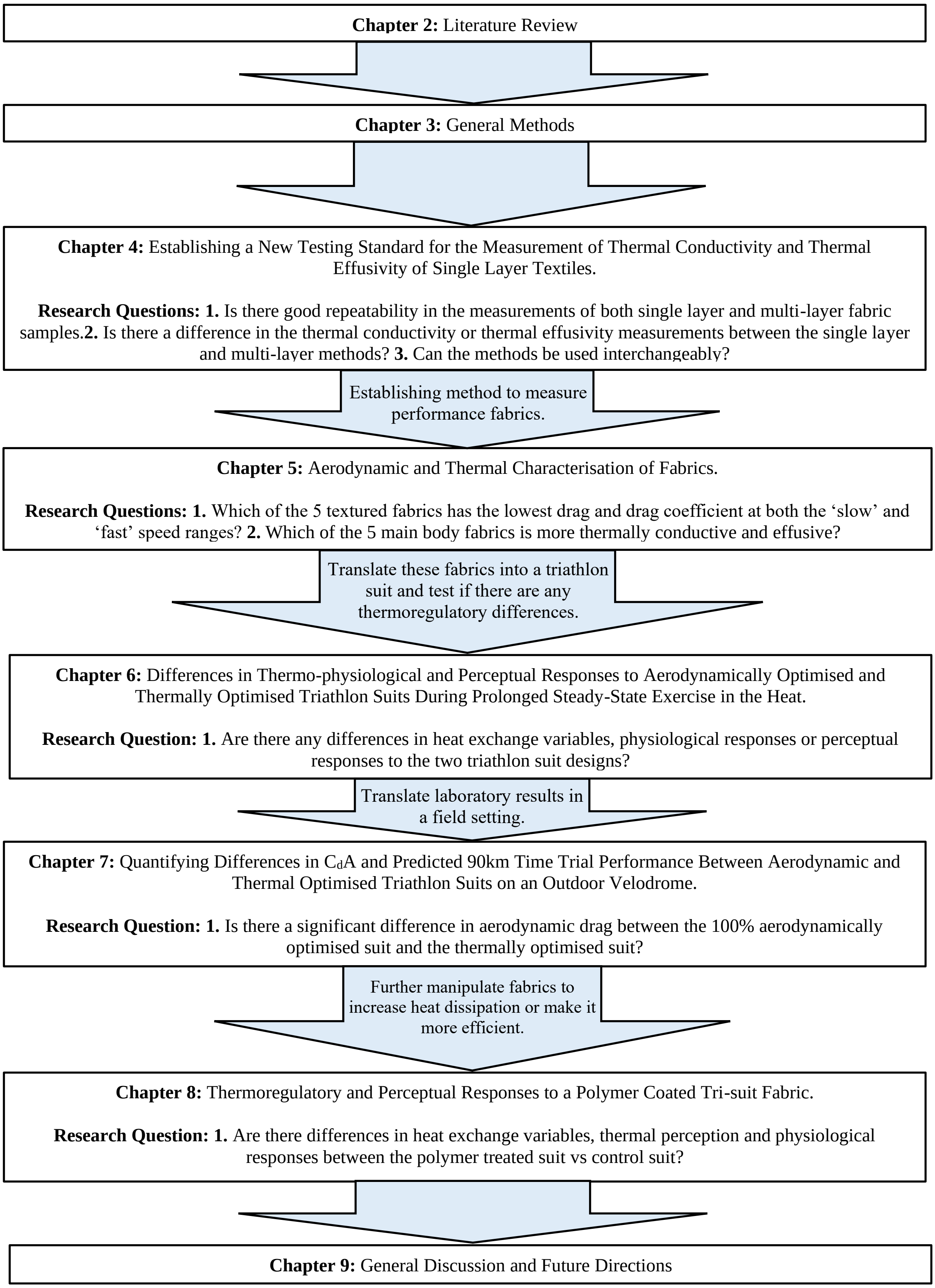


Figure 1.1: Chapter flow and research questions of each individual experimental chapter in the present thesis.

Chapter 2

Literature Review

2 Introduction

The threat that climate change currently poses to human life is at the forefront of many ongoing global discussions. Not only due to the frequently reported incidence of natural disasters but also from the ever-increasing reported mortality rate owing to more extreme seasonal temperature changes. These changes impact both high risk populations and those who struggle to adapt to large fluctuations in environmental conditions that they are not prepared for or acclimatised to.

The human body has the ability to regulate and maintain a body temperature (T_b) within a very narrow window through adjustments in metabolic activity, behaviour change and blood flow (Lim 2020). In turn, this allows for suitable adaptation in changeable and sometimes unpredictable environmental conditions. Although marginal variations occur between individuals, a normal deep T_b, when resting, is between 36°C – 37.5°C. Any significant change outside this window can negatively impact the body's ability to function and potentially result in either acute or chronic disability or even death. Thus, it is of significant importance to understand how humans thermoregulate to implement the most effective preventative and interventional measures. Not only to limit temperature related illness but also to prevent incidents during endurance sports.

Clothing can both support or inhibit the body's heat storage and heat loss mechanisms. Dressing appropriately for the environment becomes even more important for individuals in an environmentally stressful environment who concomitantly have high heat production from occupational exertion, during exercise or in elite sporting competition. The ability to measure the thermal properties of clothing is therefore extremely beneficial in selecting appropriate clothing for both hazardous occupational settings and in environmentally stressful sporting conditions too.

2.1 Heat Balance

To ensure effective thermoregulation in either any environment, the biophysics of heat transfer between the skin surface, clothing ensemble and ambient environment needs to be understood. Heat is the bi-product of biochemical processes associated with increased metabolism. It occurs during energy production for muscular contraction through the phosphorylation of adenosine diphosphate (ADP) and breakdown of adenosine triphosphate (ATP). Simply, changes in body temperature are a result of either positive or negative fluctuations in heat storage from metabolism and the avenues by which heat is lost or gained. This heat loss or gain is regulated through 4 primary physiological mechanisms; convection (C), conduction (K), radiation (R) and evaporation (E) and can be calculated using the heat balance equation:

$$\mathbf{S = M - W_k + K + R + C + C_{res} - E_{res} - E_{sk}} \quad \text{[Watts]}$$

Where; S = heat storage, M = metabolic rate, W_k = external work, K = dry heat exchange from the skin by conduction, R = radiation, C = convection, C_{res} = convective exchange of heat from respiratory tract, E_{res} = Evaporative heat loss from respiratory tract, E_{sk} = evaporative heat loss from the skin (Parsons 2014).

The thermal environment has a large impact on the human body and is determined by a number of factors. These include air temperature (T_a), air velocity (*v*), air humidity and radiant temperature (T_r). Depending on the ambient conditions and environment that an individual may find themselves in, heat will be lost or gained through sensible (convection, conduction and radiation) or insensible (evaporation) processes (Parsons 2014).

2.1.1 Convection (C)

Convection, with regards to heat loss from the human body, refers to the transfer of heat thorough the movement of air or water across the surface of the skin. There are two types of convection; natural and forced. Heat loss from natural convection occurs when the medium in the boundary layer of the body is heated, becomes less dense and therefore rises. A cooler medium is left in its place and a convective current cycle begins as the cooler medium begins to warm. Forced convection occurs due to human movement or by increases in air velocity and refers to air or water being driven across a body disrupting the natural convective boundary layer and forcing heat loss. The continuous cycling and replacement of a warm boundary layer with a cooler boundary layer reduces skin temperature, widens the core-skin temperature gradient and encourages further heat dissipation. If ambient temperature is similar to or exceeds skin temperature then the cycle is reversed. In this instance, heat loss is impaired due to the narrowing of the core-skin gradient and heat gain occurs (Luginbuehl, Bissonnette 2009). Convective cooling has a significantly positive effect on exercise performance especially in conditions that impose significant heat stress. In terms of physiological responses, lower heart rates, lower core temperatures, lower perceptual strain and increased rates of evaporative heat loss are reported with higher air velocities (Otani et al. 2018).

2.1.2 Conduction (K)

Conductive heat loss occurs through the direct transfer of heat at a molecular level through vibration. It occurs as heat dissipation from the core travels through the body to eventually be lost at the skin. This occurs in reverse in high ambient temperatures as the body gains heat. Neural changes initiate cutaneous vasodilation to re-direct blood away from the core towards the skin to allow for the conduction of heat carried in the blood to be lost to the skin and then to the environment (Charkoudian 2003). Conductive heat transfer also occurs when the body is in direct contact with surfaces as the heat moves across a gradient from the warmer skin to the cooler medium the skin comes into contact with.

2.1.3 Radiation (R)

Radiative heat transfer occurs where electromagnetic radiation is either absorbed by or emitted from the skin. Solar radiation is the largest source of radiation and results in an increased heat storage and increased body temperature. However, body position in relation to the source, clothing properties and clothing coverage over the body impacts this rate of heat transfer. Solar load has the potential to negatively impact sports performance with a significantly reduced time to exhaustion observed when cycling at 70% $\dot{V}O_{2max}$ when individuals exercise with a high solar load (800W·m^2, 23 ± 4 mins) compared to lower solar loads (500W·m^2, 30 ± 7 mins; 250W·m^2, 43 ± 10 mins; 0 W·m^2, 46 ± 10 mins) (Otani et al. 2016). Although no differences in rectal temperature were apparent, the condition with the highest solar load saw higher mean skin temperatures in comparison to all other conditions. Thus, a reduced core-skin gradient leading to a smaller drive for heat loss suggesting solar radiation impacts endurance exercise capacity even at lower solar loads of 250W·m^2.

2.1.4 Evaporation (E)

Sweating is one of the most important mechanisms for heat loss in high temperatures (Gagnon, Crandall 2018). The driving force that allows sweat to evaporate from the skin is the difference in water vapour pressure of the ambient air and the water vapour pressure at the skin. Much like temperature, this driving force works in a gradient, moving from high to low. In high humidity environments, where the ambient water vapour pressure is high, sweat from the skin cannot be easily evaporated and heat is lost slowly or not at all. Thus, environments with high ambient temperatures with concomitant high humidity exacerbate the potential for heat stress as heat balance is positive and sweating is inhibited.

Body morphology, metabolic heat production, clothing properties and environmental factors all effect the amount of required evaporative cooling (E_{req}) from the skin to maintain heat balance. It also restricts the maximal evaporative capacity (E_{max}) an individual has the potential to attain within specific environmental limits. If E_{req} is lower than E_{max}, this environment is described as compensable and individuals have the physiological capacity to maintain a sufficient heat balance. However, if E_{req} is higher than E_{max}, the environment is uncompensable and the individual will be in a positive heat balance (Cramer, Jay 2016).

$$\mathbf{E_{req}} = M – W = K + R + C + C_{res} – E_{res}$$

Where; M= Metabolic Rate, W= External Work Load, K= Conduction, R= Radiation, C= Convection, C_{res}= Convection via respiratory tract, E_{res}= Evaporation via respiratory tract.

$$\mathbf{E_{max}} = f_{pcl} \text{ x } h_e \text{ x } (P_s - P_a)$$

Where; f_{pcl} = permeation efficiency factor of clothing, h_e = evaporative heat transfer coefficient ($W/m^{-2}/kPa^{-1}$), P_s = partial water vapour pressure at the skin surface (kPa), and P_a = partial water vapour pressure of ambient air (kPa)(Cramer, Jay 2016).

2.2 Human Thermoregulation

2.2.1 Autonomic Thermoregulation

During thermal challenges, whether environmental, exercise induced, during fever or extreme stress, body temperature is meticulously controlled. In order to optimise its thermal environment and maintain an appropriate heat balance, the brain possesses various dedicated physiological pathways.

The autonomic control of thermoregulation is complex. The hypothalamus is commonly described as the main regulator of body temperature. Its location allows for the integrative processing of effector information of both core and cutaneous temperatures, whilst managing pre-motor pathways concerning thermo-affecter excitation and responses. Although researchers are now beginning to understand how this complex network functions, the pathway is not definitively distinguished due to the preoptic area (POA) being a principal mediator for so many functions including; mood, sleep, thirst, hunger, circadian rhythms and cardiovascular reflex activity (Mckinley et al. 2015; Gvilia et al. 2006).

Traditionally, the POA of the hypothalamus is the region associated with the effector signalling via sensing and integration of both internal and external affecter signals of skin and core temperatures. In rats, damage or inhibition to this area of the brain has shown a reduced ability to thermoregulate (Lipton, Hicks 1968; Satinoff et al. 1976).

In human skin, there are a several types of somatosensory neurons that sense physical stimuli including pressure, pain and temperature (Lumpkin, Caterina 2007). Depending on ambient environmental temperature conditions, warm and cold cutaneous thermal receptors transmit signals from the skin, through the dorsal root ganglia, to sensory neurons in the dorsal horn of the spinal cord. Cold sensory and warm sensory neurons then initiate the activation of neurons in the sub-nuclei of the lateral parabrachial nucleus. In turn, this drives the thermo-sensory signals to the POA. From here, specific thermoregulatory pathways are activated depending on the outputs from either cold-sensory or warm-sensory neurons, from the lateral parabrachial nucleus, sensed by cold sensitive (CSN) and warm sensitive neurons (WSN) in the POA, respectively.

Physiological effector responses occur as a result of temperature changes to both internal and external environments. Firstly, to increase heat storage and in cold defence we observe behavioural changes to reduce heat loss, cutaneous vasoconstriction (CVC), shivering thermogenesis in the skeletal muscle and non-shivering thermogenesis in brown adipose tissue (BAT). CVC reduces the amount of blood flow to the skin to prevent heat being lost through the skin to the environment whilst the metabolically active BAT helps produce heat to aid the maintenance of body temperature in cold temperatures (Castellani, Young 2016).

To increase heat dissipation or in heat defence we observe cutaneous vasodilation and sweating. Cutaneous vasodilation is primarily initiated by sympathetic activation and results in a shift of blood flow from the core to the skin (Johnson et al. 2014). This shift allows for more heat to then be lost from the skin to the environment. The cholinergic sweating response involves heat loss via evaporation of sweat from the skin. This causes a reduction in skin temperature, increasing the gradient between the core, skin and environment encouraging further heat dissipation. Consequently, sweat evaporation is one of the most important avenues of heat loss, especially when ambient temperature exceeds skin temperature (Gagnon, Crandall 2018).

2.2.1.1 Cold-Sensory Neurons

Cold-sensory neuron signalling from the lateral parabrachial nucleus activates interneurons, located in the median preoptic sub-nucleus, inhibiting warm sensitive neurons (WSN) to prevent the physiological responses associated with heat loss. CVC premotor neurons, located in the rostral raphe pallidus, receive an excitatory input that sequentially initiates BAT and shivering premotor neurones in the dorsomedial hypothalamus. This results in preganglionic sympathetic signalling and α and γ motoneuron signalling in the spinal cords ventral horn to start a number of physiological process. These include; of CVC of peripheral blood vessels, skeletal muscle shivering and thermogenesis through BAT (Morrison 2016).

2.2.1.2 Warm-Sensory Neurons

Warm-sensory signalling from the lateral parabrachial nucleus induces the excitation of both glutamatergic interneurons in the median preoptic sub-nucleus and WSN in the medial preoptic area. In this instance, E_3 receptors are bound to by prostaglandin E_2, inhibiting CVC, BAT and shivering responses. This occurs to prevent further thermogenesis. WSN inhibit sympathetic CVC neurons in the intermediolateral nucleus to increase skin blood flow and heat loss to the skin and thus, the environment (Morrison 2016).

While autonomic thermoregulation is relatively effective, it is limited by physiological parameters. However, there are almost unlimited human behaviours that enable the control and maintenance of core temperature and thermal comfort.

2.2.2 Behavioural Thermoregulation

Behavioural thermoregulation involves responses to thermal stimuli that trigger physical behaviours in attempt to avoid or prevent thermal stress. These include changing posture, the number of clothing layers worn, exercise pace or moving from outdoors to indoors. The mechanisms associated with conscious decision-making in response to changes in environment are difficult to specifically pinpoint due to individual differences in perception, skin sensitivity, regional sensitivity, methodological stimulation methods and subjectivity of the evaluation (Nakamura et al. 2008; Cotter et al. 2001). However, thermal sensation and thermal comfort are understood to be the primary factors influencing thermoregulatory behaviour change, thermal perception and adaptation (Nagashima et al. 2018). Thermal perception involves both the processing and interpretation of sensory information through the stimulation of thermosensitive neurons with changes in thermal sensation and/or thermal comfort often preceding changes in thermoregulatory behaviour (Schacter et al. 2011).

2.2.2.1 Thermoreceptors

As well as the skin forming a protective barrier around the body, it also serves to sense multiple stimuli, including temperature. Thermosensation provides afferent signalling to maintain homeostasis and protect the body from both noxious hot and cold stimuli. Once applied to the skin, these stimuli induce distinct thermal sensations allowing an individual to perceive it as either hot or cold (Hensel 1976). A human can sense these thermal stimuli to the skin comfortably over a wide range of temperatures. After a time, when exposed to temperatures within this certain comfort range, thermal sensation will adapt. However, when stimuli change skin temperatures outside this range, the magnitude and sensation of the stimuli can change significantly. For example a sensation can go initially from warm or cold to hot, freezing or even painful and comfort does not adapt (Schepers, Ringkamp 2009; Hensel 1974).

Compared to the more centrally based thermoreceptors, that are mostly warm-sensitive, peripheral thermoreceptors are more sensitive to cold and are 3-4 times more abundant that warm receptors

(Waldman 2009). Peripheral warm-sensitive thermoreceptors are also located at a deeper skin depth than peripheral cold-sensitive thermoreceptors (Romanovsky 2007). Within both these cold- and warm-sesntitve neurones lies different ion channels that are specifically receptive to thermal stimuli. These are called thermal transient receptor potential (thermoTRP) channels. The classification of these 11 channels of TRPs is based on the temperature thresholds at which they are activated (Ständer et al. 2009). This allows for specificity in temperature sensing as each TRP senses within a narrow range, whilst also being able to sense across a wide range of heat and cold stimuli from below 15°C to over 45°C, with a degree of overlap between receptor channels (Romanovsky 2007; Romanovsky 2018). Cold-sensitive receptors are termed TRPM8 (8-28°C) and TRPA1 (<17°C) and warm-sensitive receptors termed TRPV1 (>42°C), TRPV2 (>52°C), TRPV3 (>33°C), TRPV4 (25°C), TRPM2 (~33°C), TRPM3 (~40°C) and TRMP5 (15-35°C) (Romanovsky 2007; Ota et al. 2019; Held et al. 2015)(Figure 1.1). Each receptor increases or decreases its rate of firing depending on the intensity of the temperature it senses and thus, impacts the temperature processing of the brain and the subsequent thermal sensation felt (Bullock et al. 2001).

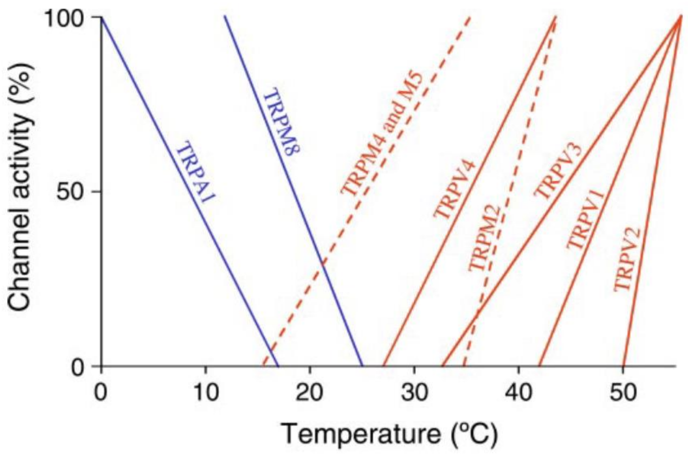


Figure 2.1: Thresholds for activation of cold (blue) and warm (red) activated thermoTRP channels (Romanovsky, 2007).

2.2.2.2 Thermal Sensation

Gagge et al. (1969) demonstrated a significant relationship between skin temperature and thermal sensation. Not surprising as, when nude, the skin provides an interface between the environment and the body. The degree of thermal sensation experienced is dependent on a multitude of factors including the ethnicity, sex, stimulus intensity, previous experiences, time of day and site of the stimulus (Croze, Duclaux 1978). However, the three main influences reported are: duration of the temperature stimulus, rate of onset of the stimulus and the spatial summation or area the thermal stimulus is applied to (Stevens et al. 1974; Hensel 1974). For example, the magnitude of the thermal sensation experience is dependent on the rate of exposure to the hot or cold stimulus. If fast exposure to temperature change occurs, the threshold for what is classed as uncomfortable is reduced. Whereas with a slower onset of temperature change, the threshold temperature at which is higher. This suggests that any exposure to large step changes causes a rapid firing rate of the thermoTRP, resulting in an overshoot in the sensation transduced and processed by the brain (Romanovsky 2018). Lastly, in relation to the area the thermal stimulus is applied, a completely submerged hand in water reportedly creates a greater thermal sensation that just exposing the fingertip (Weber 1996).

2.2.2.3 Thermal Comfort

Behavioural responses are considered highly influential to thermal comfort, although there is no data definitively comparing and quantifying the relative contributions of autonomic and behavioural responses. In ectotherms, body temperature control is largely influenced by behaviour as they are reliant on external sources of body heat. These sources contribute up to 4-5 times more to the temperature maintenance than the small contribution from their autonomic systems. Future temperature predictions by Sherwood and Huber (2010) concluded that with just a 7°C warming of global-mean temperature, small zones would appear where it will not be sustainable for humans to live as metabolic heat dissipation will be impossible (Sherwood, Huber 2010). In this instance, the only way in which humans could survive such extreme conditions is through behavioural responses. Thus, understanding how and why humans choose their thermoregulatory behaviour is important.

During instances of hyperthermia or raised core temperatures, individuals feel thermal discomfort (Schlader 2014). At this point, individuals seek cooling behaviours. These can either have a direct effect on metabolic heat production such as changing race pace or they can affect skin temperature by altering clothing layers. Either way results in feeling more thermally comfortable. However, thermal comfort does not relate linearly to core or skin temperature (Schlader, Vargas 2019; Gagge et al. 1969). During prolonged, compensable heat exposure, core temperature and skin temperature increase until heat balance is attained and a plateau in both variables is observed. Despite this plateau thermal discomfort continues to increase, suggesting that another factor contributes to this perceptive measure. Increases in skin wetness have been observed at very similar rates to thermal comfort during prolonged heat exposure and is now recognised as a primary factor determining thermal comfort during heat exposure (Vargas et al. 2020). These data also support research by Fukazawa and Havenith who demonstrated a linear relationship between skin wettedness and thermal comfort (Fukazawa, Havenith 2009)

Unfortunately, little research has been undertaken on the physiological mechanisms by which skin wetness is perceived. What is known is that humans can sense moisture on the skin and know when in contact with fluids however, unlike with temperature, there are no specific hygroreceptors that sense this and provide specific neural feedback. Instead, humans possess a multi-sensory integrative model that attempts to interpret the level of moisture on the skin. It has been demonstrated that when moisture is evaporated from the skin, it provides a cooling thermal sensation (Filingeri et al. 2013). Additionally, the mechanical movement of sweat, water or moist clothing across the skin gives the sensation of ‘stickiness’ (Filingeri et al. 2014). Both of these sensations are centrally integrated, contributing to the perception of skin wetness. Furthermore, at specific rates of cooling, participants experience the perception of wetness despite the skin not coming into contact with moisture. Thus, suggesting that it does not matter whether the degree of cooling comes from actual skin wetness or not, it is perceived cooling that impacts on the perceived wetness of the skin.

It is also possible to feel wetness in the absence of cooling by means of tactile movement of clothing against the skin. When comparing loose and tight fitted clothing for the same amount of skin wetness, rectal temperature and mean skin temperature, perceived skin wetness has been found to be reduced when wearing a tighter fitting ensemble (Filingeri et al. 2014). This was reportedly due to reduced tactile movement on the skin, thus not initiating the same degree of perceived skin wetness. When quantifying different wetness perceptions on specific areas of the body, it was found to be lower in the tight ensemble in the chest, back, arm and thigh compared to the loose ensemble even though the absolute amount of moisture that was on the skin was the same between conditions. Thus, even in the absence of cooling, tactile inputs significantly augment the perception of skin wetness. These data provide an interesting start to understanding what signals provide thermal discomfort. However, it does not indicate whether skin wetness stimulates cool seeking behaviour or if other factors, such as skin temperature, contribute further to this. Additionally, in contrast, tight clothing may not necessarily always prove beneficial to thermal perception. The 'bellows' effect, termed by Bouskill et al. describes the importance of air movement within clothing, especially when the material is impermeable to air. It is a method of forced convection of the microclimate within the clothing ensemble due to body movement and may be useful in sweat evaporation, heat dissipation and thermal perception (Bouskill et al. 2002).

It is first important to identify the classic work from Cabanac et al. (1971) who investigated changes in thermal behaviour by allowing participants to alter the temperature of their hand in a water-perfused glove. They exposed participants to progressive decreases in ambient temperatures and noted reductions in skin temperature and core temperature over time. However, core temperature changes were minimal and measured using tympanic temperature which is not necessarily the most valid measure. From this, they discovered that as skin temperature decreased, self-selected glove temperature also increased over time suggesting that skin temperature impacts thermal behaviour and comfort (Cabanac et al. 1971).

Vargas et al. (2020) modified the methodology used by Cabanac et al. to identify whether these changes in skin and core temperature contributed more towards cool-seeking behaviours in comparison to the impact of skin wetness (Vargas et al. 2020). The protocol involved participants donning a posterior neck brace continuously perfused with water at 34°C. At any time, participants could choose to cool their neck by increasing the flow rate and perfusion of cold water set at -20°C. Participants exercised on a cycle ergometer for 30-minutes in a moderate environment (27°C & 22% relative humidity). This was then followed by 120 minutes of recovery. As expected, during exercise the temperature of the fluid in the neck device was reduced and was slowly increased again during the recovery phase. A regression was used to then calculate the relative contribution of skin wetness, core temperature and skin temperature on changes in perfused water temperature. They discovered skin wetness contributed around 50% of the stimuli controlling perfusion temperature, compared to both skin and core temperature. These each contributed around 25% of the stimuli. From this, they concluded that skin wetness likely contributes to cool-seeking behaviour and the desire to thermoregulate to a much larger extent than skin and core temperature, individually.

Schlader and Vargas (2019) aimed to identify whether increased skin wetness would subsequently result in increased cool-seeking behaviour, independent of the temperature of the skin or core (Schlader, Vargas 2019). Skin temperature was therefore clamped using a water-perfused suit. Low vs high skin wetness conditions were created by altering ambient relative humidity to 30 and 70%, respectively. In these conditions, passive heat stress was sustained over a one-hour period. Similar to their previous study, the same neck device was used where participants were able to self-modulate 30 seconds of fluid at -20°C through the neck brace. Results showed that despite no differences in core or skin temperature throughout the protocol, increased skin wetness perception resulted in a longer time spent in cooling (more clicks to initiate cooling) and a lower neck device temperature at 35 and 45 minutes into passive heating in the high skin wettedness condition. Segmental regression also showed that a mean skin temperature threshold that is responsible for the initiation of cool-seeking behaviours was lower with higher skin wetness. This provides empirical evidence suggesting that when both skin and core temperature are elevated, increased skin wetness augments cool-seeking behaviour with signals originating from skin temperature thresholds. What is concluded is that neither environmental or physiological parameters or thresholds can directly predict what perceptual and behavioural reaction is to occur in response to changes. It is difficult to provide a definite answer due to complex inter-individual and intra-individual differences in both physiological and psychological reactions to certain thermal stimuli. Further to this, the relationships between improvements in comfort or sensation are not simply linear.

What is clear is both behavioural and physiological thermoregulation play important roles in maintaining a safe and comfortable body temperature for human function. However, it is essential to understand the biophysics of heat exchange in order to assess the risk potential.

2.3 Heat Stress and Performance

2.3.1 Endurance Performance

During sporting events such as triathlon, cycling and marathons, metabolic pathways must meet energy demands of the body in order to prevent fatigue and performance decrements. Performance efficiency, lactate threshold (LT) and $\dot{V}O_{2max}$ are three determinants identified to be key in successful endurance performance (Joyner, Coyle 2008). Thus, any variation in these factors will influence performance. During any exercise, but especially at an elite level, the body produces large amounts of heat as a bi-product of metabolism. Small increases in body and muscle temperatures are proven beneficial to performance through the modulation of nerve signal conduction, muscle contraction and metabolism which is why athletes perform a warm up prior to competition (de Ruiter, de Haan 2000; Kiernan et al. 2001). However, prolonged hyperthermia due to either high exercise intensities or high ambient temperatures are detrimental to performance through the initiation of fatigue and the trade-off between optimal performance and thermoregulation.

2.3.2 Cardiovascular Factors

Lee and Scott (1916) first described the role of the cardiovascular system in the physiological ability to maintain exercise performance under heat stress (Lee, Scott 1916). They reported the feeling of 'disinclination' to perform muscular work under hot and humid conditions with an earlier onset of muscular exhaustion attributed to a wider physiological origin than simply a 'cerebral condition' alone. Following this, Rowell (1974) described the cardiovascular responses to whole body heating during rest, reporting significant increases in cardiac output, as a result of cutaneous vasodilation, of 7-10 $L \cdot min^{-1}$ in order to maintain blood pressure and heat loss (Rowell 1974).

At rest and during low intensity exercise in the heat, elevations in heart rate are enough to compensate and maintain cardiac output. However, during prolonged moderate intensity or intense exercise, a larger amount of blood is redirected towards the periphery for cooling, placing further strain on the cardiovascular system. This vast dilation of venous beds enhances heat exchange by increasing blood flow and transit time through the vessels. However, as a result of this pooling in the extremities the fundamental mechanisms associated with maintaining blood pressure are impacted. This subsequently causes; impaired diastolic filling, reduced end-diastolic volume resulting in a reduced stroke volume and thus, plateaued or reduced cardiac output (Rowell 1974). To maintain arterial blood pressure with such a large shift of blood from the core to the periphery, heart rate must increase. In this instance, a competition arises between the metabolic and thermoregulatory systems as they demand simultaneous preservation of blood flow to the working muscles, vital organs and skin to maintain both muscular contraction, basic physiological functions and essential heat dissipation (González-alonso et al. 2008).

The control of heat balance is regulated by the adaptation and adjustment of the autonomic nervous system to redirect blood flow to regions of the body through selective vasodilation and vasoconstriction

(Charkoudian 2003). Although this is beneficial from a thermoregulatory perspective, an increase in venous compliance results in significant cardiovascular strain as heart rate increases to maintain both stroke volume, cardiac output and blood pressure as blood is redirected throughout the body. Any reduction of muscle blood flow will impact an individual's capacity to maintain exercise intensity and duration but reduced skin blood flow will restrict heat loss from the body as little is lost through convective cooling nor sweat evaporation from the skin surface. Thus, maintaining the balance between these is essential not only to exercise performance but also to health. When the balance is not maintained, core temperature rises. Further to this, continuous high muscle and skin perfusion plus sweating during prolonged periods impacts hydration levels which can pointedly negatively impact performance. A decrease in body mass >2% during performance, due to water loss, is reported to be enough to hinder thermoregulatory function, consequentially increasing cardiovascular strain and impacting endurance performance (Watso, Farquhar 2019; Craig, Cummings 1966). During endurance events or prolonged physical activity in hot environments, additional issues arise when paired with dehydration and hyperthermia with reports of decreased cardiac output and muscle blood flow compared to euhydration (Gonzalez et al. 1998). However, the studies reporting such data were laboratory based with poor ecological validity of real world race pacing strategies that would be adapted by an athlete during an outdoor race (Goulet 2011). Body mass reductions of up to 4%, without any increase in core body temperature or performance decrements, have been reported in ultra-marathon runners (Lebus et al. 2010). It is also seen that in ultra-marathon races, on average, a considerable amount of body mass is lost in the first 48km and is then sustained at the same level for the rest of the race with no differences in mass change between finishers and non-finishers of the race (Laursen et al. 2006). A positive tolerance to 3% body mass reduction was also observed during an Ironman® triathlon where, despite warm, humid conditions (23°C, 60% relative humidity), there was no evidence of thermoregulatory failure despite hypohydration. Average maximum core body temperature only reached 38.1 ± 0.3°C with no relation to changes in plasma sodium, potassium or chloride. Recommendations from a review by Holland et al. (2017) suggest that, for many, drinking to thirst is a beneficial strategy to maximise endurance performance (Holland et al. 2017).

2.3.3 Insufficient Heat Loss and Heat Exhaustion

Heat related illnesses are caused by long term exposure to high ambient temperatures or by undertaking intense exercise or work in such environment. Symptoms can occur either rapidly or more slowly over time. The term 'heat illness' encompasses a spectrum of disorders and occurs in response to the impairment of body heat dissipation and by and large is preventable.

Mild heat illness can exhibit symptoms such as muscle cramps caused by fluid and electrolyte depletion and peripheral oedema caused by cutaneous vasodilation and fluid leakage into the interstitial spaces. More moderate illness can firstly exhibit as heat syncope where an individual may feel dizzy and lose consciousness due to the significant vasodilation at the peripheries and reduced venous return, in an attempt to lose heat. Secondly, heat exhaustion may occur where an individual may be extremely thirsty, fatigued, have a headache, cold and clammy skin, show weakness, ataxia and a temperature of 38.3 - 40°C. Physiologically, individuals have hypotension, abdominal vasoconstriction and early signs of multiple organ dysfunction. Severe heat illness is termed heat stroke. Individuals may present with hypotension, tachycardia, seizures or may even be in a coma. At this severity of heat stoke, core temperatures are >40°C caused by a severe systemic inflammation, leakage of endotoxins and multiple organ dysfunction or failure (Gauer, Mayers 2019). To mitigate the onset of even mild heat illness, cooling strategies can be implemented.

2.3.4 Cooling Strategies

2.3.4.1 Pre-Cooling

The concept of pre-cooling aims to increase the body's heat storage capacity and prevent or delay the rate and onset of high body temperatures which are suggested to be one of the primary limiting factors to endurance performance (González-Alonso et al. 1999; Marino 2002). Thus, techniques aimed at reducing core temperature with the potential to improve performance are of high importance. Unfortunately, there is large heterogeneity in the design of studies investigating pre-cooling methods making it difficult to draw a definitive conclusion. Multiple techniques have been investigated including the use of; cold air exposure (Cotter et al. 2001), cooling garments (Duffield et al. 2003a; Faulkner et al. 2019), cold water immersion (Duffield et al. 2010; Kay, Taaffe, and Marino 1999) and ice slurry/cold water ingestion (Ihsan et al. 2010; Siegel et al. 2012).

Ice garments function to decrease skin temperature, via conduction, by directly covering the upper body or majority of the torso region. This decrease in skin temperature creates a wide skin to core gradient. Prolonged donning of ice garments results in a conductive decrease in core temperature and increases the specific heat capacity of the body. The role of skin temperature in exercise performance is important as it is a primary driver of self-paced exercise (Faulkner et al. 2015). Despite similar core temperatures being attained, over a 60 minute self-paced cycling exercise trial, more work was completed when donning a cold water-perfused suit that turned hot versus the same suit that started hot and turned cold. Additionally, the ratings of thermal sensation and thermal comfort were higher in the hot to cold condition despite no change in effort perception between the two conditions across the 60 minutes (Schlader et al. 2011). After 40 minutes of cooling using an ice jacket, Quod et al. (2008) also reported a 1.5% improvement in 40-minute time trial completion time, compared to control, owing to a higher mean power output and reduced body temperature (Quod et al. 2008). More recently, a 5.8% reduction in 1-hour time trial finish time was reported after just 30 minutes of ice-vest pre-cooling, compared to control (Faulkner et al. 2015).

Cold water immersion (CWI) is more complicated than that of conductive ice vest cooling and, although the principal is similar, the physiological response depends on the temperature of the water. The body possesses a thermoneutral zone whereby temperature regulation is obtained purely by control of the sensible or dry heat loss. In this zone, there is no activation of increased metabolic heat production nor evaporative heat loss (Kingma et al. 2014). During CWI, if the temperature of the water is below that of the human thermoneutral zone (33-34°C) the body will initiate peripheral vasoconstriction and increase metabolism in an attempt to protect core temperature. If the water temperature is cold enough, these two mechanisms are not sufficient and after a period of time, core temperature will reduce. When using CWI as a method for core temperature reduction prior to performance, significant improvements have been reported. Kay et al. (1999) reported an increase in distance cycled during a 30-minute self-paced trial in the heat (T_A; 31°C & RH; 60.2%) following 60 minutes of cold-water immersion at 8-11°C (Kay, Taaffe, and Marino 1999). These data were more recently supported by Maia-Lima et al. (2017) who reported a reduction in time to completion of a 30km cycling performance test in the heat (35°C & 68% RH), after 52 minutes of whole-body cold water immersion (24°C) compared to no pre-cooling (58.28 ± 3.30mins vs 60.62 ± 3.47mins, respectively). Additionally, significantly lower core temperatures were reported throughout and at the end of the 30km. It took longer to attain the core temperature of 38°C due to the prior reduction in core temperature instigated by the cold-water immersion.

Ingestion of fluids or ice that are lower than core temperature causes an increase in internal heat loss from the tissues in the body. The phase change of solid ice to liquid water occurs due to a large transfer of heat energy. This melting is termed 'enthalpy of fusion'. This phase change has resulted in significantly lower skin and muscle temperatures compared to cold water ingestion that does not require the phase change (Merrick et al. 2003). Ihsan et al. (2010) also provided evidence that, compared to tap water, ice slurry ingestion 30 minutes prior to exercise resulted in a 6.4% improvement in 40km cycling TT performance, in hot and humid environmental conditions (30°C; 74% RH). Performance improvements were owed to higher power outputs and a delayed onset of elevated core temperature rises during the TT. In contrast, Stanley et al. (2010) found that despite reporting a 1.9% improvement in performance using ice-slurry, it was not significantly different to cold water ingestion (4°C) (Stanley et al. 2010). Further to this, Burdon et al. (2010) reported no significant improvement in total work completed during a 15-minute cycling performance test using prior ice-slurry ingestion. However, they did report a high power output and 4.9 % higher work completion and when ingesting cold water prior to exercise compared to thermoneutral water. However, a number of limitations need to be considered. The study conducted by Burdon and colleagues included the ingestion of ice-slurry, every 10 minutes, during a 90-minute submaximal exercise bout in the heat prior to the performance test. Likewise, Stanley et al. used a 75-minute submaximal exercise protocol, in the heat, with ice-slurry ingestion during recovery and before the performance trial (Stanley et al. 2010). It is also now known that the consumption of ice-slurry during exercise in the heat can lead to an attenuation of sweating due to the rapid, large internal heat sink (Morris et al. 2016). Given this, dissimilar heat loss pathways may be initiated to those observed during static pre-cooling protocols.

Much of the research regarding pre-cooling methods points towards it providing a benefit to the athlete and subsequent performance. However, there are significant limitations to the use of pre-cooling methods prior to competition. These include; cost, equipment transportation, sport and somatotype specificity, the effect of warm-ups and ecological validity of methods. Further to this, the specific mechanisms by which each pre-cooling method occurs or how it specifically reduces heat strain and effects performance is still not completely understood. It is also apparent that there may be a limit to its benefits as exercise duration increases as the thermal gradient between core and skin temperature starts to decrease.

2.3.4.2 Per-Cooling

Many pre-cooling strategies have been beneficial in prolonging the onset of critical core temperatures and heat strain. However, their benefit tends to be of minimal use in races of increasing distance and their implementation highly impractical. Arngrimsson et al. reported a valuable reduction in both mean skin temperature and rectal temperature during a 35 minute warm up using an ice vest. However, after just 1.6km into the subsequent 5km running time trial, there was no difference in mean skin temperature between no-cooling and ice vest use. The ice vest also significantly reduced rectal temperature from 20 minutes into the warm up to 3.2km into the running time trial, compared to no cooling. However, by 5km there was no difference between rectal temperature between the two conditions questioning the efficacy of ice vest use prior to longer distance races (Arngrímsson et al. 2004). Ideally, to maintain the valuable impact of body cooling from the use of ice vest, methods would be executed during competition to help maintain higher body heat capacity.

Per-cooling signifies the cooling of the body during an event and is of increasing interest to researchers as many major sporting events are being held in countries with both hot and humid climates. Data shows that continuous exercise in the heat results in impaired performance with shorter times to exhaustion (Galloway, Maughan 1997) and slower performance times (Zhang et al. 1992) There is a presence of elevated core temperature, power output reductions and reduction in distance covered due to a combination of cardiovascular strain, fatigue, perceived effort changes, high exercise intensities and environmental heat stress (González-Alonso, Calbet 2003; Flouris, Schlader 2015; Gonzalez et al. 1999). In these extreme conditions where ambient temperature is high, it is difficult for the body to lose heat via dry heat loss (convection, conduction and radiation) and therefore sweating is the primary source of heat transfer. However, when humidity is also high, this becomes an issue due to sweat not evaporating from the skin in a quick or efficient manner as the E_{max} is reduced (Havenith et al. 2013; Muhamed et al. 2016). Therefore, per-cooling methods should either work to increase evaporative sweat potential or enable more conductive or convective heat transfer.

Research has shown the ingestion of cold water whilst donning a cooling vest during submaximal exercise decreases heart rate, indicating a reduction in cardiovascular strain (Smolander et al. 2004). Second to this, an increased time to exhaustion has occurred concurrently with both reduced core temperature, skin temperature and sweat loss (Hasegawa et al. 2004). These data are also supported more recently by Luomala et al. 2012 with the implementation of ice-vests 30 minutes after the commencement of intermittent 10-minute cycling bouts to exhaustion (9 minutes at 60% $\dot{V}O_{2max}$, 1 minute sprint at 80% $\dot{V}O_{2max}$) in both hot and humid conditions (30°C, 40% RH). Per-cooling resulted in a 21.4% increase in time to exhaustion, compared to control. The results of this specific study are interesting as the protocol reflects both the aerobic and anaerobic intensities of exercise that are encompassed in racing environments. Bain et al. (2012) investigated the impact of water ingestion at either 1.5°C, 10°C, 37°C or 50°C at 15, 30 and 45 minutes after the onset of steady state exercise at 50% $\dot{V}O_{2max}$. Despite no changes in metabolic heat production or net heat loss between conditions, the increased internal heat sink produced by the colder fluids were coupled with a proportional reduction in evaporative potential for heat loss at the skin, reflected in both lower sweat rates and skin temperatures (Bain et al. 2012). A proceeding study looked at whether ice slurry ingestion would affect these thermo-affector responses further due to it possessing twice the heat sink potential as cold water. Results showed ice slurry ingestion caused a disproportional decrease in skin temperature in relation to internal heat loss, compared to thermoneutral fluid ingestion. These data supported the previous findings with lower heat loss, greater heat storage and lower sweat rates. It must be considered that these studies were undertaken in warm, dry environments where complete sweat evaporation was permitted and realistically, these cooling methods are likely to be employed in higher ambient temperatures with concomitant high ambient humidity. In this case, if attenuation of sweating occurred in more uncompensable conditions, where sweating is the primary source of heat dissipation, cold water and ice slurry ingestion could exacerbate heat stress and inhibit performance.

Positive benefits of per-cooling have also been reported by Price et al. (2009) with the use of ice vests for pre- and mid-event cooling during a simulated soccer game (Price et al. 2009). As expected, the same reduction in core temperature occurred during pre-cooling prior to the soccer game. However, mid-event cooling proved to be more effective at delaying the onset of higher core temperatures during the second half of the simulated soccer game and reduced end-exercise heat content ($4.01 \pm 0.99 J \cdot g^{-1}$) compared to pre-cooling only ($5.10 \pm 1.45 J \cdot g^{-1}$) and no cooling ($6.20 \pm 1.59 J \cdot g^{-1}$). These data suggest employing a cooling strategy when individuals are already experiencing some degree of heat stress may also prove beneficial in addition to pre-event cooling alone. However, this protocol is only beneficial to sports where breaks can be taken and cooling methods can be adopted, again the methods that may provide most benefit cannot be adopted in many endurance sports or races that are continuous.

When studying these methods, it is important to understand the mechanism by which the cooling method mediates core, skin and body temperature and its interaction with exercise. An effective pre-cooling method may not be as efficacious as a mid-cooling method, especially in hot ambient temperatures. The use of ice vests, ice slurry and cold-water immersion have proven beneficial to performance as a pre-cooling method however, interesting results have been reported on the effect of cold water and ice-slurry ingestion during exercise.

2.3.4.3 Textile Modification

Research into the biophysics and modification of wearable textiles for thermal management and improved comfort are becoming more abundant (Tabor et al. 2020; Zhou et al. 2021; McQuerry et al. 2017). The aim of which is to help find an edge to improve performance, help vulnerable populations and help those under occupational physiological strain due to protective clothing. They can also provide a significantly more practical alternative to bulky ice-vests and ice drinks.

Menthol has been used to elicit a cooling sensation to the skin by activation of the TRPM8 receptors (McKemy et al. 2002). Although it is found in many forms, the L-isomer or L-menthol is found to elicit the largest non-thermal cooling sensation (Eccles et al. 1988). Its ability to block or reduce inhibitory signals that alter thermal perception is useful as it has the potential to prevent both neuromuscular and perceived effort changes during self-paced exercise. Application of non-cooling 8% topical menthol gel to the entire face was found to have a 21% increase in exercise performance, with no change in core temperature or sweat rate (Schlader et al. 2011). The performance benefit was attributed to shifts in thermal sensation. In contrast, menthol elicited no effect on exercise performance when sprayed onto garments during exercise (Barwood et al. 2015) suggesting the method of application impacts the perceptual response during performance.

The use of chemically treated fabrics is also now becoming more common in sports clothing. The primary aim is to enhance heat loss via energy transfer and release as well as increasing wicking ability to aid thermoregulation and improve thermal perception (Pascoe et al. 1994). Clothing chemical treatments come in the form of phase change materials (PCMs) that function by absorbing and releasing heat energy in response to different temperatures or wetness. Titanium dioxide inflused yarn woven into clothing is shown to have the potential to improve thermal comfort through increased thermal conductivity of heat away from the skin (McFarlin et al. 2017) whilst silicone emulsion coatings improve the wicking capability of garments (Chinta et al. 2013). However, many of the results published on the potential impacts of chemically treated fabrics are only undertaken in a laboratory conditions using thermal manikins or hot plates. Although this provides valuable modelling and evidence that PCM coatings may be beneficial, it does not allow for the quantification of other aspects of human heat exchange, simultaneously. For example, a material may have a measured increased wicking capability and thus higher evaporative cooling, but this characteristic may result in increased insulation and reduced thermal conductivity. It may subsequently tip the heat balance equation further towards heat storage rather than heat loss. This questions the ecological validity of these data as there are multiple factors such as skin temperature, sweating, movement and environmental temperature and humidity that are not accounted for. Lower reported rates of perceived exertion and 8% increase in exercise capacity has been reported with PCMs and active cooling components incorporated into a t-shirt worn during a 45 minute running ramp test in 35°C and 55% relative humidity (McFarlin et al. 2016). Unfortunately, there is limited further research on PCM treated sports clothing during exercise and more wearer trials need to be undertaken to validate laboratory fabric testing results.

When considering clothing design, is not only important to understand the characteristics of fabrics in isolated laboratory conditions but also how these characteristics can be optimised to positively impact thermal perception of the end-user and exercise performance. That may be translate to increased exercise efficiency, increased heat dissipation, increased sweat evaporation, lower rates of perceived exertion or lower perceived heat stress. However, in cycling and triathlon, aerodynamics plays an vital role in performance and can directly impact athlete heat management due to the positions held by athletes on the bike. There becomes a point where a trade-off occurs between heat balance and aerodynamics, especially in long duration races, as athletes want to be as aerodynamic as possible whilst trying to allow for as much convective heat loss as possible. Unfortunately, the relationship between these thermal and aerodynamic factors is rarely considered.

2.4 Aerodynamics

During cycling, the effect of aerodynamic drag accounts for 80-90% of total drag force (F_D) experienced by a rider, substantially impacting a rider's velocity (Kyle, Burke 1984). The importance of aerodynamics was prominently demonstrated during Francesco Moser's hour record of 51.151km in 1984 where he beat Eddie Merckx's previous record of 49.431km with the use of carbon-fibre disk wheels and an optimised position from prior wind tunnel analysis. Although, at this time, aerodynamic equipment and wind tunnel analysis was already utilised commercially and had a presence in literature, it was not prevalently implemented in elite cycling. However, there was an growing understanding of the importance of both frontal area and clothing on total cycling resistance.

It is now known there's a critical interaction of body position, ambient conditions, bike geometry and clothing that directly governs performance by affecting both the direction and pressure of the air flow around the body. Simple mathematical modelling of the aerodynamic forces impacting cyclists was available as early as 1894 (Bourlet, 1984). Understanding and appropriately optimising the total system characteristics of a rider-bike system, based on these parameters, can result in higher cycling velocity concomitantly with power and time savings (Broker et al. 1999; Garimella et al. 2020). For some time, athletes, coaches and engineers have managed to successfully optimise cyclist aerodynamics though the identification and systematic understanding of each factor contributing to the aerodynamic drag equation:

$$F_D = \frac{1}{2}\rho v^2 C_D A$$

Where, F_D = drag force (N), ρ = environmental air density (kg·m^3), v = speed of the system (m·s^{-1}), C_d = drag coefficient (dimensionless) and A = frontal area (m^2).

Reflecting on the above equations, it is clear that shape has a profound impact on aerodynamic drag. The characterisation of drag coefficient across a number different shapes has been calculated by numerous aerodynamicists, mathematicians and engineers to help inform building, aeroplane and bike designs (Xie, 2013). Cyclindrical and flat plate shapes are commonly the basic shapes used to model the aerodynamic drag exerted upon the limbs and upper torso of a rider during cycling.

Aerodynamic drag force (F_D) accounts for approximately 90% of overall resistive forces experienced by a rider (Kyle, Burke 1984). Thus, understanding the effect of each component on the rider-bike system can help optimise the system for faster performance.

F_D can be split into two types; form drag and friction drag. Form drag occurs as a direct result of a body shape and is a consequence of differences in the pressure distribution over and around a body as air moves past it (Defraeye et al. 2010). Calculating form drag can allow for the characterisation of how streamlined a body is (Blocken et al. 2018). For bluff bodies, such as a cylinder, a flat-plate or a human torso it is the main contributor to total F_D. Therefore, developing an effective strategy to reduce form drag can dramatically improve performance.

Delving further into the components of the F_D equation highlights a critical variable known as the drag coefficient (C_d). This is a dimensionless number commonly used in aerodynamics that describes and models a number of complex factors including the airflow conditions, shape and inclination of the object being measured as well as the compressibility and viscosity of the air. It factors in drag force (F_D), air density (ρ, kg·m^3), speed of the system (u, m·s^{-1}) and the object's frontal area (A, m^2):

$$c_d = \frac{2F_d}{\rho u^2 A}$$

In cycling, a more individual measure of aerodynamic resistance or C_dA is used and takes into account, ambient temperature, rolling resistance, drive chain efficiency, body weight, riding velocity and power output. When observing the F_D and C_d equations, it can be seen that one way to dramatically reduce both these parameters is to reduce frontal area.

Improved body position, increased drivetrain efficiency, changing bike frame shape, tyre pressure and wheel mechanics are just a few modifications that have been adopted in consequence to the better understanding of the rider-bike system ad aerodynamics. Exploiting these factors both wholly and as individual components has allowed for large speed gains with only minimal mechanical or biomechanical changes (Fintelman et al. 2014).

A mathematical model, validated by Martin et al. (1998), describes the distribution of a rider's total power output (P_{Total}), accounting for the number of resistive forces experienced whilst riding. These include the aerodynamic resistance (P_{AT}), rolling resistance resulting from the force between the tyre and the road surface (P_{RR}), the wheel bearing losses through friction as the wheels are turning (P_{WB}), changes in potential energy owing to the incline or decline of the riding surface (P_{PE}) the kinetic/inertial energy owing to changes in forward and rotational acceleration (P_{KE}) and the drive chain efficiency (E):

$$P_{\text{Total}} = \frac{P_{\text{AT}} + P_{\text{RR}} + P_{\text{WB}} + P_{\text{PE}} + P_{\text{KE}}}{E}$$

Following this, it is now evident that aerodynamic gains are just as important as the production of power for successful cycling performance. A large focus is now being placed on access to wind tunnels so athletes can measure and appropriately select their individual combination of equipment, clothing and position on the bike based on their specific body geometry and race type. In a wind tunnel, riders are set up on a force balance that is directly connected to the wheel axis' of their bikes. It is common to assess cyclists as they are dynamically riding rather than in static position and is achieved by mounting the bike onto rollers integrated into the floor. This entire system can also be mounted to a turntable that allows changed in yaw or wind direction to simulate different angles of approaching winds.

In the absence of a wind tunnel, computational fluid dynamics (CFD) technique allows the simulation of changes in frontal area, drag coefficient and aerodynamic drag in response to different body positions. CFD involves an individual to create an air or fluid flow problem. Parameters are then changed to model the domain in which the flow is to occur, the boundary conditions and the geometry of a rider, subsequently creating a computational grid that defines the resolution and accuracy of the simulation. CFD allows for accurate and precise modelling of an individual's aerodynamic characteristics without having to spend hours in a wind tunnel. It gives a visual output of differences in pressure coefficients that occur over the body and allows for a visualisation of the airflow over the body. This subsequently indicates where the highest areas of rapid air deceleration and drag force are occurring in different positions. Blocken et al. nicely presents data from CFD analysis showing the body position with the smallest frontal area and not necessarily the smallest C_d resulted in the smallest C_dA (Figure 2.2) (Blocken et al. 2019).

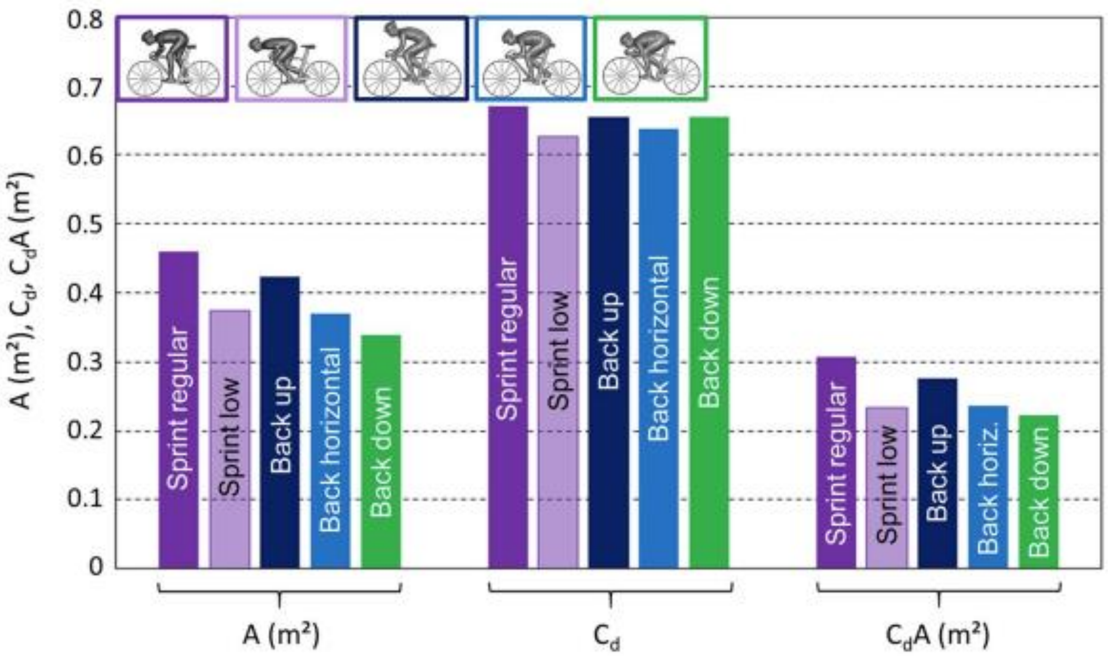


Figure 2.2: Frontal area, drag coefficient (C_d) and aerodynamic drag (C_dA) for five cycling positions (Taken from Blocken et al., 2019).

Changing rider body position has long been an interest to athletes and researchers in the search for speed. A 35% reduction in aerodynamic drag has been reported by simply shifting from an upright riding position to a more aerodynamic time-trial position (Hennekam, 1990). Reports have directly attributed these reductions in F_D to reduced cyclist torso angle which, for most, can be simply and successfully attained by lowering handlebars (Underwood et al. 2011). Despite this positive conclusion, other data suggests that the physiological efficiency, economy and performance outcome that occurs because of this change in position and thus, frontal area, depends largely on the velocity of the rider. It can be agreed that the higher the speed, the higher the F_D upon the rider therefore, when cycling at higher speeds (>46km/h) the need to decrease frontal area becomes significantly more important. At lower speeds (<30km/h), however, having an extreme position and lower torso angle is not necessarily beneficial as the loss in power that occurs with these lower torso angles can be detrimental to performance (Fintelman et al. 2015).

In this instance, there needs to be a strong consideration with regards to the trade-off between aerodynamic savings versus the loss in power with more extreme body positions. Faulkner and Jobling (2020) assessed aerodynamic-physiological economy (APE) during a staged submaximal exercise test at a range of hip angles including 12°, 16°, 20°, 24° and in the cyclists' regular position. A reduction in power output at 4mmol·L blood lactate was observed at 12° and 16° proposing a possible biomechanical disadvantage. However, when normalising power output to drag area ($W \cdot C_DA^{-1}$), there were no observed differences between the conditions. Furthermore, when normalising $W \cdot C_DA^{-1}$ to oxygen consumption to get a value for APE ($W \cdot C_DA \cdot L^{-1}$), a higher APE was observed in the 12° hip angle compared to 16, 20 and 24° hip angles, suggesting an improved performance potential. Although reductions in sustainable power output might be observed at more extreme hip angles, the savings made by being in a more aerodynamic position outweigh this, resulting in maintained cycling velocity at a lower metabolic cost to the rider (Faulkner, Jobling 2020). It appears that reducing hip angle or body position is benefical to reducing form drag and thus, overall F_D imposed on a rider (Figure 2.3).

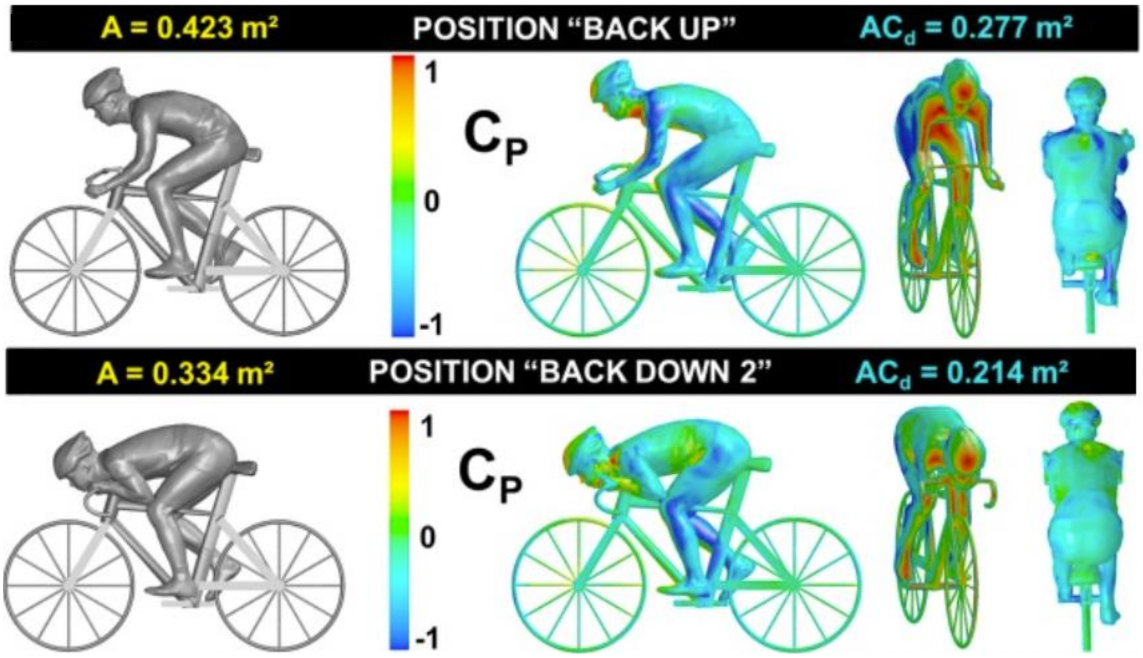


Figure 2.3: Differences in pressure coefficient (C_p) on both the bike and rider in two positions. Normal 'back up' position' and a more aerodynamic position of 'back down 2'. Both frontal area (A) and drag area (AC_d) are displayed. Taken from Blocken et al., 2018a.

One way to reduce the aerodynamic drag when athletes are riding together is through drafting. This entails a rider sitting close behind another rider so the rider at the front takes the impact of the high air resistance. The second rider sits behind in the lower pressure wake region which results in them needing to produce less power to maintain the same cycling velocity as the front rider. Figure 2.4 shows the mean wind speed and pressure coefficients for three different riding configurations. The benefits of drafting are clearly shown here where a reduction in overall pressure of up to 57% when riding behind a single rider and then two riders riding together (b), 48% if riding behind two rider and 54% if riding behind three other riders (f), compared to cycling alone.

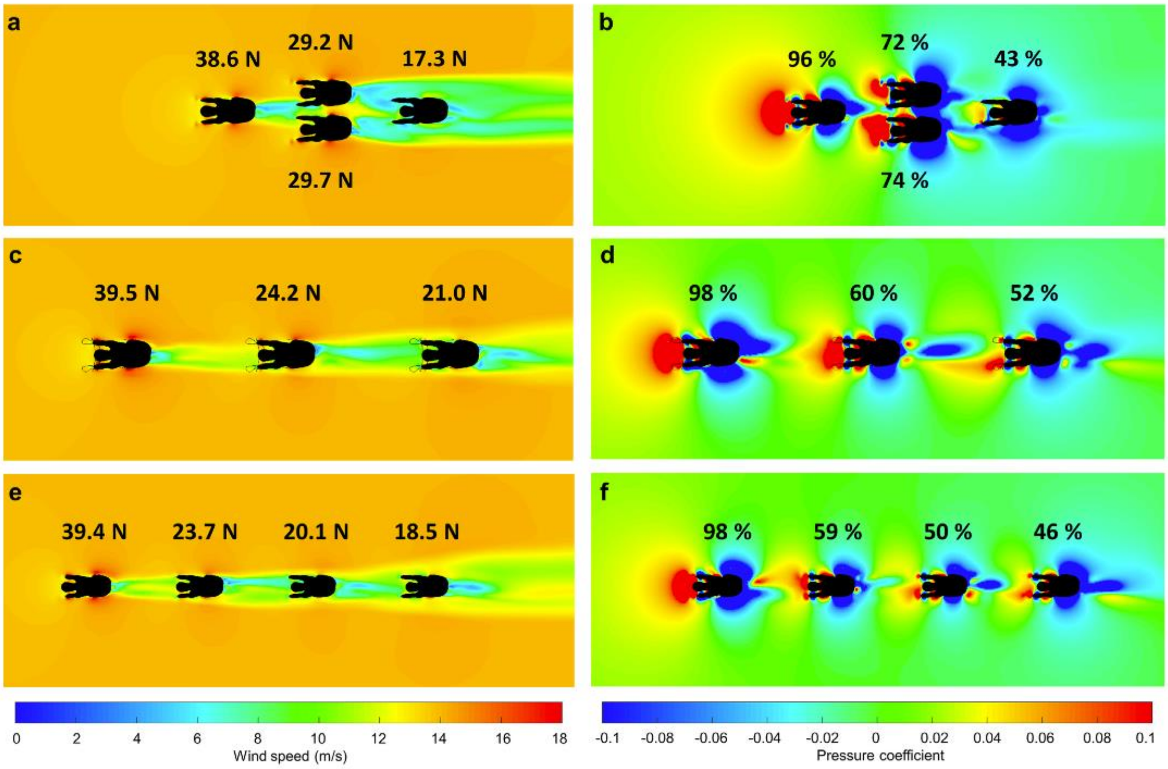


Figure 2.4: Mean wind speed (a, c, e) and mean pressure coefficient (b, d, f) for different riding configurations, measured at 1 metre above the road surface, in the horizontal plane. Drag forces for each rider are also displayed in a, c and e whilst fingures b, d and f dispay the percentage of drag of an isolated rider riding at 15m/s – this is 40.3 Newtons. Taken from Blocken et al., 2018b.

In criterium racing or duing short course triathlons of sprint and olympic distance, athletes take full advantage of drafting to ensure they are riding most efficiently. However, in middle distance triathlon such as during a 70.3 Half Ironman®, rules state that athlete must maintain a 22ft gap between them and the rider in front to prevent any performance gain through drafting. When overtaking, the rider has 15 seconds for their front wheel to pass the front wheel of the athlete they are overtaking. The athlete behind then has to drop back out of the draft zone so as to not incur a time penalty. Thus, while form drag has an undeniably large impct on aerodynamic drag, optimised through drafting, other methods of optimisation need to be considered in non-draft legal races.

One way to optimise drag, in a draf illegal race is by considering the secondary component of drag, termed 'friction drag,'. Although it is not the dominant cource of F_D, it still plays a large part. Increasing friction drag by a small amount can result in a large reduction in form drag due to the changes that manifest in consequence to airflow changes around the body. Ideally, the air flow across and around the body during cycling would remain laminar and undisturbed however, the shape of the human body makes this near impossible. Despite cyclists adopting strict aerodynamic positions, the high speed, high pressure free-stream air that meets a human's bluff body shape rapidly decelerates upon contact. Inevitably, as soon as the low-energy unstable laminar air flow hits the body, the air pressure gradient shifts from negative to positive, redirects around to the shoulders, slowing and reversing flow direction (Crouch et al. 2017). Here, the air rapidly detaches from the body, producing a large low-pressure wake behind the rider creating significant F_D (figure 2.5A).

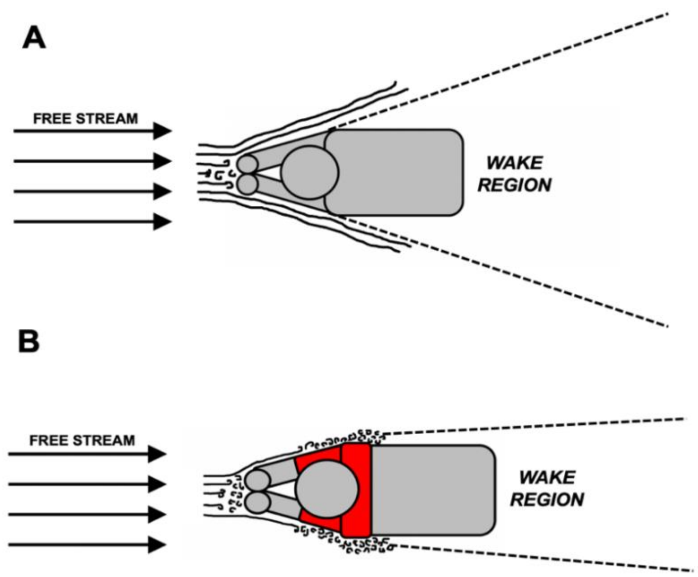


Figure 2.5: A, early separation of laminar air flow around a cyclist, in a time-trial position, donning a garment with a smooth shoulder fabric. B, early transition of laminar to turbulent air flow around a cyclist donning a garment with a rough shoulder fabric reducing the drag coefficient.

It is now understood to be more efficient for there to be an earlier transition of the boundary layer air flow from laminar to turbulent around the shoulders. Due to the effective mixing and higher near-surface momentum of turbulent air, it better retains its momentum and, as it hits the body, this momentum carries the air flow further around the shoulder, delaying separation and reducing both the wake behind the rider, decreasing the overall form drag (Brownlie et al. 2009) (figure 2.5B). This idea is now being translated and incorporated into fabric selection and triathlon clothing design. Attention has more recently moved more towards the modification of sports garments as an aid to further influence the airflow around the rider. This idea has received attention in not only cycling and triathlon, but also in speed skating and skiing (Oggiano et al. 2013).

The air flow around a cyclist and their bike is complex. Therefore, understanding of flow characteristics around the body is simplified and represented using geometrically simplified shapes such as cylinders or spheres (Chowdhury et al. 2010). This simplification of shape is often the first step in wind tunnel testing to characterise fabrics before being incorporated into a triathlon suit or skin suit (Moria et al. 2012).

By incorporating fabrics of different roughness in specific regions on the body, a transition from laminar to turbulent flow is initiated allowing the air to stick to the body for longer, which then reduces the area of the wake region. This occurs as the rough fabric increases the friction drag component and paradoxically reduces the form drag of that specific body area. Commonly, rough fabrics are placed on the shoulders and upper arms of triathletes and cyclists to allow the airflow to continue to stick round to the torso. The cylindrical nature of the limbs causes greater separation creating a greater separation of air from the body and increasing drag. Therefore, the implementation of rough fabric around these areas mean they are more likely to be sensitive to changes in airflow, benefiting form drag.

The flow separation that occurs when a rider is travelling is dependent on the Reynolds number (R_e). This is the ratio of inertial to viscous forces within the air around the rider and is calculated using:

$$Re = \frac{\rho u L}{\mu}$$

Where, ρ = environmental air density (kg·m^3), u = the speed of the system (m·s^{-1}), L = linear dimension of object and μ = dynamic viscosity of the air.

R_e allows for the identification of the airflow transition from laminar flow to turbulent flow, known as the drag crisis (figure 2.6). This drag crisis occurs at different R_e numbers for different fabrics with different characteristics. For example, rough fabrics will achieve their drag crisis point at lower R_e numbers than smooth fabrics due to the surface roughness tripping the boundary layer of the airflow (figure 2.6). With this transition from laminar to turbulent flow, a significant drop in C_d occurs. From an application point of view, this R_e number will correspond to a specific cycling velocity and thus, finding a rough fabric where the air transition occurs at the velocity a rider will be competing at implies the C_d of a rider can be reduced by incorporating this specific fabric into the shoulder section of a triathlon suit design.

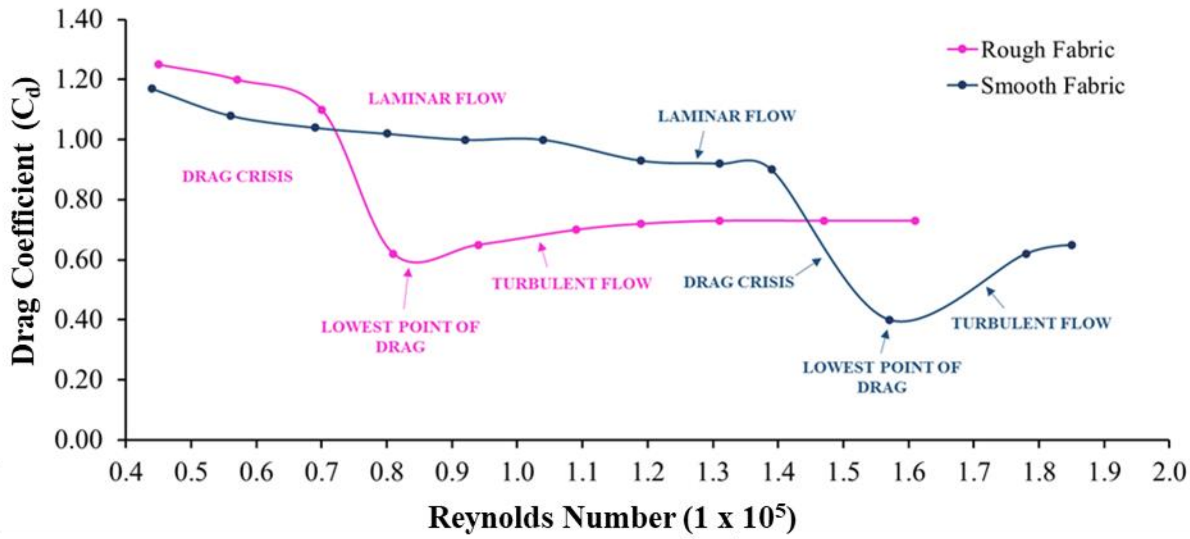


Figure 2.6 Changes in drag coefficient in smooth and rough fabrics due to the transition from laminar to turbulent airflow. Adapted from (Oggiano et al. 2007).

Although cycling is considered one of the most efficient exercises, approximately 70-80% of energy produced by the body to perform a required amount of external work is liberated as heat (Whipp, Wasserman 1972). In competition, many cyclists and triathletes produce large amounts of power over long periods of time and need to lose excess heat to maintain heat balance and prevent hyperthermia. When riding in compensable conditions, where heat balance is physiologically attainable, convective and evaporative heat loss usually suffice, even where riders adopt positions with closed hip angles. In this instance, the magnitude of heat storage may not necessarily inhibit an individual's ability to adequately thermoregulate or impact performance or health. However, a closed hip angle reduces the surface area open to convection as areas are blocked by other parts of the body, such as the arms in front of the torso. This also potentially reduces the amount of evaporative cooling. Attention must be given if an individual is producing prolonged high-power outputs and concurrent high heat production that cannot be sufficiently matched by the avenues of heat loss. This becomes an issue in longer duration races where heat storage can continue to build, potentially resulting in serious consequences to performance or health. In longer and more environemtnally stressful races, it may therefore be more beneficial for riders to adopt a more open hip angle and marginally increase their frontal area. If heat dissipation can be increased due to higher rates of convective cooling, this could help reduce the rate of cumulative heat storage and prevent early onset of fatigue or heat injury in the long term. This is particularly important in an elite population whereby motivated athletes are found to possess increased pain tolerance and thus may allow them to push through physiological cues that usually serve to intitate a slowing of pace down or termination of exercise (Pettersen et al. 2020).

2.4.2 Aerodynamics in Triathlon

Triathlon is a multi-discipline sport that comprises of a swim, bike and run completed in immediate succession. There are numerous distances from short sprint distances that comprise of a 750m swim, 20km bike and a 5km run to longer distances such as the world renowned Ironman® races that consist of a 3.8km swim, a 180km bike and a 42.2km run. Triathletes race all across the world in cold, hot, humid, dry and wet conditions, all imposing very different challenges to the body on top of the demand required just to complete the triathlon as fast as possible.

In the shorter races, the aerodynamics and thermoregulation of the triathlete is given very little thought as any minor differences in clothing is likely to have very little impact on the athlete due to the slower, more technical courses, short duration and draft legal nature of the race. For these races, most triathletes wear very similar one-piece triathlon suits with no fabric covering the shoulders. In a longer race such as a half-Ironman®, elite athletes can be racing upwards of 5 hours, spending around 2-3 hours on the bike. Athletes produce high amounts of metabolic heat as they compete and as the bike leg is not draft legal, a 20 metre gap has to be left in between riders during the race. The triathletes are therefore riding alone for the duration of the bike and need to maintain efficient energy production to preserve energy for the subsequent run and prevent further unnecessary heat production. One way to create a more efficient ride is by selecting fabrics that make the triathletes more aerodynamic in their position on the bike, allowing for the boundary layer of air to stay attached to the body for longer to reduce drag across the whole body. Smooth fabrics are placed into the main body sections of the triathlon suits to allow for undisturbed airflow across the body sections. Although this has proved extremely successful, the focus of clothing design at present is only focused on this aerodynamic side of performance and discounts the impact the selected fabrics may have on an individual's ability to thermoregulate. This becomes especially important when competing in hot and/or humid environmental conditions.

2.5 Properties of Performance Fabrics

The function of clothing is to protect the naked body from environmental stressors. However, it also represents a layer of insulation that provides thermal resistance, imposing a barrier to heat transfer, heat dissipation and sweat evaporation from the skin. In turn, in high metabolic states or in hot environments, clothing can contribute to significant increases in heat storage, stressing the body's normal thermoregulatory functions. This relationship between physiology, clothing material and the environment is dynamic and becomes even more complex when incorporating the impact of sweat. The six parameters that reportedly have the largest impact on human experience both in terms of thermal perception and physiological changes in temperature are ambient temperature, radiant temperature, environmental humidity, velocity of the air around the body and thermal properties of clothing (Parsons 2002). Understanding the thermal resistance of a clothing ensemble allows for modelling of the interaction between the body and ambient environment for thermal comfort, whether that be in an occupational or sporting context (Cramer, Jay 2016; Foster et al. 2022).

2.5.1 Measuring Fabric Properties

Thermal insulation incorporates both conduction ($W\ °C^{-1}$) and surface area (m^2). It is commonly represented using Clo, where 1 Clo is equal to $0.155\ m^2·°C·W^{-1}$ or $0.155\ m^2·K·W^{-1}$ and represents the thermal resistance of an ensemble whether a body is entirely covered or not (Gagge et al. 1941). Hot plates and thermal manikins are commonly used to measure the conductivity and resistance that a clothing ensemble may impose on a body. Properties can also be estimated from using available databases or literature where similar clothing ensembles are used. It allows for more specific control of environmental conditions and allows for a more isolated steady state maintenance of heat production.

Initially, linear regressions were established to calculate ensemble thermal insulation from thermal insulation tests on a thermal manikin (McCullough 2005). Through a meta-analysis of multiple sources of occupational and cold-weather clothing insulations, Havenith and Nilsson (2004) established a single correction equation to account for air movement through human movement and also environmental convection (Havenith, Nilsson 2004). Much of this research only provides a value for whole body clothing insulation which assumes a uniformity of resistance and insulation across the whole human body. However, due to the complexity of heat exchange, these models were deemed too simplistic for research needs. Therefore, development of studies measuring local thermal comfort using more advanced multi-node models of heat exchange saw the body divided into segments to allow for more precise insulation and comfort readings. Lee et al. subsequently investigated more local thermal insulation values of multiple areas using a 16-segment thermal manikin, measuring 40 different clothing ensembles (Lee et al. 2013). Following this, once again, localised corrections accounting for walking speed and subsequent air velocity were developed (Lu et al. 2015). Although the use of thermal manikins is the gold standard measure for the assessment of thermal comfort and heat stress, they are expensive and the protocols are time consuming limiting their wider use for fabric selection for sporting garments. At present, the most common alternative is to use the hot plate method however, they require precision in their building and environmental set up to yield valid results. Current standards of measuring thermal conductivity using the MTPS method requires all fabrics to be measured at >1mm thickness. However, these data are not ecologically valid, especially when considering a sporting application where the end-user wears a single layer of fabric. One way to rapidly measure the thermal conductivity of a fabric is using the C-Therm Tx Thermal Effusivity Touch Tester device where results can be obtained in minutes. However, it is not established whether the C-Therm Tx Thermal Effusivity Touch Tester device provides a valid and reliable measure of thermal conductivity and thermal effusivity of performance fabrics using the current 1mm standard currently used for solids, powders and liquids. There also is currently no standard for measuring the single layer fabric thermal conductivity and thermal effusivity using the C-Therm Tx Thermal Effusivity Touch Tester nor any data on the validity and reliability of these measurements, which is important for its sporting application.

2.6 Summary and Conclusions

Environmental temperatures of just 24˚C have reportedly profound negative effects on exercise performance (Faulkner et al. 2018). Methods of pre-cooling have proven valuable in providing both increased heat capacity and improved thermal perception but are only beneficial for a short time towards the beginning of a race (Ross et al. 2011; Quod et al. 2008b; Cotter et al. 2001). Per-cooling methods have good efficacy during exercise in reducing skin and core temperature but methods tested in laboratory studies prove very impractical during competition. It is therefore of interest to identify whether direct measurement and manipulation of fabric properties can influence heat loss, body cooling and thermal perception during exercise in environmentally stressful conditions.

Making positional changes and selecting appropriate triathlon suit fabrics can effectively reduce the drag experienced by a rider however, there is no consideration of the potential impact aerodynamic fabrics have on an athlete's thermoregulatory ability. Especially in environmentally stressful conditions such as high heat and/or humidity. Moreover, there is little empirical data detailing how the differences in thermal conductivity of fabrics can impact sports performance in warm and humid conditions. The current data on the impact of chemical fabric adaptations have only been predicted in isolation and sport specific clothing has not yet been tested on humans in an exercise environment reflecting race intensity. Finally, aerodynamic data from small wind tunnel testing is commonly used for identifying the most appropriate fabrics to be incorporated into either cycling or triathlon suits. However, it is not established whether these differences are still observed for all individuals during cycling in the field when incorporated into a suit. It is also not clear whether minor fabric differences in optimised suits can have such a measurable impact on aerodynamic drag in the field or impact predicted time trial performance.

2.7 Aims

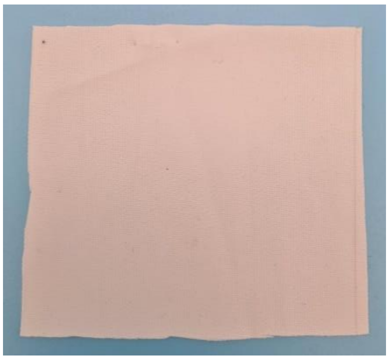
Therefore, the aim of this thesis was to firstly assess the repeatability of the MTPS method using the C-Therm Tx Thermal Effusivity Touch Tester device (Chapter 4). Secondly, to characterise fabrics to inform the design of aerodynamically optimised and thermally optimised triathlon suits suitable for a half-Ironman® triathlon (Chapter 5). Thirdly, to assess whether there were measurable impacts in thermoregulation and thermal perception between the two suits (Chapter 6). Fourthly, to assess whether differences in the aerodynamic properties of the fabrics could be measured in a field setting and how the differences may subsequently impact predicted 90km time trial performance (Chapter 7). Lastly, to assess the thermo-physiological and perceptual impact of a chemically treated triathlon suit (Chapter 9).

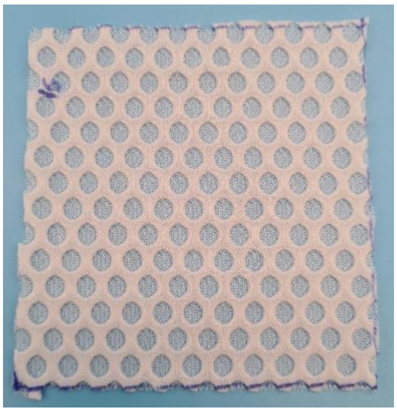
Chapter 3

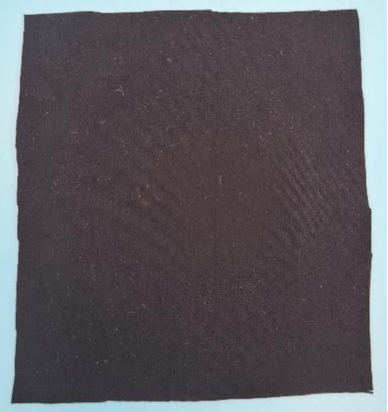
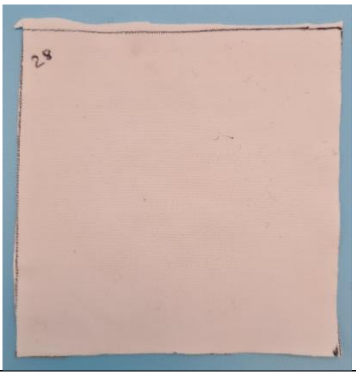
General Methods

3.1 Fabrics

Table 3.1: Names, codes and photographs of performance fabric used in the present thesis.

Fabric Name	Fabric Photograph
Fabric 'A' / Schoeller Rough	
Fabric 'B' / Taiana Smooth	
Fabric 'C' / UNKNOWN Smooth	

Fabric Name	Fabric Photograph
Fabric ‘D’ / UNKNOWN Rough	
Fabric ‘E’ / UNKNOWN Rough	
Fabric ‘F’ / UNKNOWN Rough	

Fabric Name	Fabric Photograph
Fabric 'G' / ESF Payen-Oxygene Smooth	
Fabric 'H' / Piave Maitex 9464 Smooth	
Fabric 'I' / UNKNOWN Rough	
Fabric 'J' / Piave Maitex 9300 Smooth	

3.2 Thermal Resistance and Heat Balance Calculations

The thermal resistance (R_{cl}) of the AERO and THERM suits was calculated from thermal conductivity ($W \cdot mK^{-1}$) and thickness (m) using:

$$R_{cl}\ (m^2K \cdot W^{-1}) = \frac{\text{Sample Thickness (m)}}{k\ (W/mK^{-1})}$$

From this, the dry insulative value (I_{cl}) of each of the triathlon suits was calculated using:

$$I_{cl}\ (I_{clo}) = \frac{R_{cl}\ (m^2K \cdot W^{-1})}{0.155}$$

The clothing area factor (f_{cl}) was calculated as:

$$f_{cl}\ (ND) = 1 + (0.31 \cdot I_{cl})$$

Energy expenditure (EE) was calculated by:

$$EE\ (kJ \cdot min^{-1}) = \dot{V}O_2 \cdot \left[\left(\left(\frac{RER-0.7}{0.3}\right) \cdot 21.13\right) + \left(\left(\frac{1.0-RER}{0.3}\right) \cdot 19.62\right)\right]$$

Which informed the calculation of metabolic heat production (M) using EE by:

$$M\ (W) = \frac{EE \cdot 1000}{60}$$

Heat production (H_{prod}) was calculated by:

$$H_{prod}\ (W) = M\ (W) - \text{External Power Output (W)}$$

Dry heat loss (C + R) was calculated by:

$$C + R\ (W) = \left(\frac{(T_{sk}\text{-}T_o)}{R_{cl}} + \frac{1}{f_{cl} \cdot h} \right) \cdot BSA$$

where; $T_{sk,}$ mean skin temperature, T_o, operative temperature.

The evaporative heat loss required to maintain heat balance (E_{req}) was found using:

$$E_{req}\ (W) = H_{prod}\ (W) - C + R\ (W) - C_{res} + E_{res}\ (W)$$

where; C_{res}, convective respiratory heat loss (C_{res}) and $E_{res,}$ evaporative respiratory heat loss (E_{res}).

C_{res} and E_{res} are calculated by:

$$C_{res}\ (W) = \left(0.0014 \cdot M\ (W{\cdot}m^2) \cdot (34 - T_a) \right) \cdot BSA$$

$$E_{res}\ (W) = 0.0173 \cdot M\ (W{\cdot}m^2) \cdot (5.86618428 - P_a) \cdot BSA$$

where; T_a, ambient temperature (°C), BSA, body surface area, P_a, ambient vapour pressure.

The maximal amount of heat loss achievable in the present conditions (E_{max}) was found using:

$$E_{max}\ (W) = \frac{w_{max} \cdot (P_{sk,s} - P_a) \cdot BSA}{R_{e,cl} + \frac{1}{f_{cl} \cdot h_e}}$$

Where; $w_{max,}$ maximum skin wettedness was 0.84 based on unacclimated status of participants (Ravanelli et al., 2018), $P_{sk,s,}$ water vapor pressure at the skin (kPa), P_a, ambient vapour pressure (kPa), BSA, body surface area (m^2), $R_{e,cl,}$ evaporative heat transfer resistance of clothing estimated to be 0.018 $m^2 \cdot kPa \cdot W^{-1}$ (Watson et al. 2018), $f_{cl,}$ clothing area factor, h_e, evaporative heat transfer coefficient.

Equations of other factors contributing to the further calculation of heat balance biophysics including the convective heat transfer coefficient (h_c), linear radiative heat transfer coefficient (h_r), combined heat transfer coefficient (h_r), operative temperature (t_o), Stefan-Boltzmann constant (σ) and evaporative heat transfer coefficient (h_e) are all detailed by Cramer and Jay (2016). Furthermore, fixed variables used in calculations in the present study are skin effusivity (ε) which was 0.965 to account for the position in between sitting and standing adopted on the bike, the effective radiative area of the body (A_r/A_D) was 0.725 to again account for the body position on the bike, the Lewis Relation (LR) was set to 16.6 $K \cdot kPa^{-1}$ to describe the heat mass transfer and the heat of vaporisation of water at 30°C maintained at 2430 $J \cdot kg^{-1}$.

3.3 Prediction Model Calculation

In the present study, the total bike-rider system was assumed to be riding at a consistent pace, on a flat surface, with no impact of wind, no changes in potential nor kinetic energy and constant impact of wheels and bearings. The 'required power' (P_r) equation was adapted from (Martin et al. 1998):

$$P_r = P_{ar} + P_{rr} + P_{twb}$$

Where, P_r = required power to maintain constant speed (W), P_{ar} = power owing to aerodynamic forces, P_{rr} = power owing to rolling resistance, P_{twb} = power owing to wheel and bearings. More specifically, looking at differences between the two suit conditions, the following equation was used:

$$P_{2r} = P_{1r}$$
$$(F_{2ar} + F_{2rr} + F_{2wb})V_2 = (F_{1ar} + F_{1rr} + F_{1wb})V_1$$
$$(F_{1ar} + F_{1rr} + F_{1wb})V_1 - (F_{2ar} + F_{2rr} + F_{2wb})V_1 = \Delta P$$
$$(F_{2ar} + F_{2rr} + F_{2wb})V_2 - (F_{2ar} + F_{2rr} + F_{2wb})V_1 = \Delta P$$
$$(F_{2ar} + F_{2rr} + F_{2wb})V_2 = \Delta P + (F_{2ar} + F_{2rr} + F_{2wb})V_1 = P_{1r}$$

Where, P_{1r} = total required power (W) for the AERO suit and for corresponding velocity V_1. P_{2r} = total required power (W) for the THERM suit and for corresponding velocity V_2. The corresponding forces (N) are F_{1ar} = aerodynamic drag force for AERO suit, F_{2ar} = aerodynamic drag force for THERM suit, F_{1rr} = rolling resistance force for AERO suit, F_{2rr} = rolling resistance for THERM suit, F_{1wb} = resistance force from wheels and bearings for AERO, F_{2wb} = resistance force from wheels and bearings for THERM, ΔP = is the change in required power output between AERO and THERM at V_1. The differences in required power output when riding between the two optimised suits can be translated into a predicted velocity difference value:

$$\frac{1}{2}\rho C_d A_2 V_2^3 + V_2(C_{rr}mg + F_{wb}) - \Delta P - (\frac{1}{2}\rho C_d A_2 V_1^3 + V_1(C_{rr}mg + F_{wb})) = 0$$

Where, C_dA_2 = product of the drag coefficient and frontal area for the THERM suit, C_{rr} = coefficient of rolling resistance.

3.4 Predicted 90km TT Time Saving

Time savings were calculated over a 90km distance to reflect the bike distance of a half-Ironman. These were calculated based on the C_dA, $\triangle P$ and V_1, so the AERO suit data was used as a 'control'. To find the differences from AERO to THERM suits, the following equation was used:

$$\Delta t\ (s) = d * (\frac{1}{V_2} - \frac{1}{V_1})$$

Where, d is distance, V_1 is the velocity for the AERO suit and V_2 is the corresponding velocity for the THERM suit.

Chapter 4

Establishing a New Testing Standard for the Measurement of Thermal Conductivity and Thermal Effusivity of Single Layer Textiles

4 Chapter Summary

This chapter aims to establish a new standard testing protocol for the measurement of thermal conductivity (k) and thermal effusivity (ε) in single layer sports textiles using the C-Therm Tx Thermal Effusivity Touch Tester (C-Therm). When testing fabrics on the C-Therm, the ASTM D7984 standard for modified transient plane source (MTPS) testing requires the use of >1mm material thickness. This ensures that the heat pulse sent through the fabric by the heating element does not fully penetrate the fabric. However, the suitability of these data is dubious, when applied to clothing science, as only one single layer of fabric is worn by the end user. It would therefore be useful to understand the repeatability and agreement of these measurements by testing single-layers (reflecting end-user) versus the multi-layer samples (required by ASTM D7984 standard). Therefore, the aim of this study was to determine the repeatability in the measurement of k and ε using both the single layer and multi-layer method. Secondly, to investigate whether there is a difference in the k and ε measured using the multi-layer method compared to a single-layer method and thirdly, whether the methods can be used interchangeably. The modified transient plane source (MTPS) method was used in the present study. Five different fabric textiles were tested; 80mm x 80mm fabric square, single layers were layered until a multi-layer sample was at least 1mm in thickness (current ASTM D 7984 standard for MTPS testing). Following this, the single layers that made up the 1mm multi-layer sample were then individually tested to assess both the differences between each single layer and the differences between the single layers and the 1mm multi-layer sample. An intra-class correlation showed excellent repeatability in both k and ε when testing both single layer and multi-layer samples. T-tests showed single layer measurements read consistently lower that multi-layer measurements and thus, they cannot be used interchangeably.

Bland-Altman analysis showed good agreement between the two methods meaning that a regression equation can be used to derive one from the other due to the consistency of the under-estimation observed in single layer measurements, compared to multi-layer. In conclusion, the single layer method should be used if the application is in single layer sports fabrics, especially if the results are to be used in thermal modelling. Excellent repeatability means only 10 single layers need to be used when testing using the C-Therm device. If using the multi-layer methods, measurement of 2 multi-layer samples is required.

4.1 Introduction

The C-Therm Tx Thermal Effusivity Touch Tester is used to measure the thermal conductivity (k) and thermal effusivity (ε) of several materials such as powders, ceramics, liquids, metals and polymers. It adopts the modified transient plane source (MTPS) method and complies with the ASTM D7984 industry standard (ASTM D7984 2016). The MTPS is a measurement technique used for quantifying k and ε of materials. It involves a heat element and sensor that provides a momentary heat pulse through the material. The sensor then quantifies the rate and magnitude of the interface temperature response between the sensor and the test material. The sensor possesses a guard ring around that prevents any lateral heat loss and maintains a constant one-directional flow of heat through the material being tested. At present, the C-Therm is commonly used in multiple engineering applications including heat exchange systems (Graves et al. 2019) and electronics (Yu et al. 2016) however, when it comes to clothing textiles there is ambiguity over the current testing standard and subsequent suitability in application. Studies using the C-Therm have largely focused on the thermal insulation of textiles with regards to their density and thickness (Legerská et al. 2020), with these parameters displaying a larger impact on thermal conductivity values than differences in environmental temperature (Venkataraman et al. 2015). Thus, showing the importance of standardising fabric thickness during measurements.

The current ASTM D7984 standard requires any sample tested on the C-Therm analyser to be at least 1mm in thickness to prevent complete penetration of the heat pulse through the fabric yielding invalid results. Providing a material sample >1mm is rarely an issue when testing solid plastics, building materials or liquids, however when it comes to fabrics there are very few garments that have a single layer thickness of 1mm, especially in sports apparel. This means that significant layering of fabrics is needed and conveys further questions as to the validity of results where air pockets are created between layers, increasing the fabrics' insulative properties and k and ε measurements. Although a 1mm sample allows for the characterisation of the fabric to the ATSM D7984 standard, it is far from reflective of the real-world application of single layer sports clothing. By identifying the differences in k and ε between single fabric layers, like that in sports clothing, and 1mm multi-layer samples, as required by the ATSM standard, a new standard method of data collection can be developed to help translate data from the C-Therm to real-life applications of thinner textiles. The first research question asks; Does the C-therm have good repeatability in measures of thermal conductivity and thermal effusivity when measuring both 1mm multi-layer samples and single layer specimens? Secondly, are there significant differences between the thermal conductivity and thermal effusivity measured in 1mm multi-layer samples and single layer specimens? Thirdly, can these two methods be used interchangeably to measure thermal conductivity and effusivity?

4.1.1 Aim

The primary aim of the present study was to test the repeatability of both k and ε measurements in both 1mm multi-layer samples and single layer specimens. Secondly, the study aims to investigate the differences in k and ε measurement between single layer fabric specimens versus 1mm multi-layer samples and thirdly to investigate whether the two methods can be used interchangeably.

4.1.2 Hypothesis

It was hypothesised that the C-Therm would be able to accurately and repeatably measure k and ε in both multi-layer samples and single layer specimens. Secondly, the k and ε measured for single layers would be different compared to the multi-layer and thirdly, the single layer and multi-layer methods would not be able to be used interchangeably.

4.2 Methods

4.2.1 Fabric Preparation and Pre-conditioning

All fabric preparation and pre-conditioning was undertaken as required by ATSM D1774 'Standard Practice for Conditioning and Testing Textiles'. Fabrics were left flat for 24-hours, prior to cutting, to prevent any wrinkling or warping of the fabric impacting the final fabric structure for cutting and testing. Single layers were then hand-cut with scissors into 80mm x 80mm squares with no single specimen containing the same thread (figure 4.1). To control for the impact of environmental temperature and humidity on the transmission of heat and moisture through the fabrics, environmental conditions were maintained at an ambient temperature of 21 ± 1°C and relative humidity of 65 ± 2% (Kestrel 5400 Weather Station, Kestrel Instruments, Pennsylvania, USA) in an environmental chamber (TIS Services, Peak Performance Chamber). The single fabric layers were left, test face upwards, in the controlled environment for 2-hours prior to testing to ensure total temperature and moisture equilibrium was attained before commencing subsequent testing.

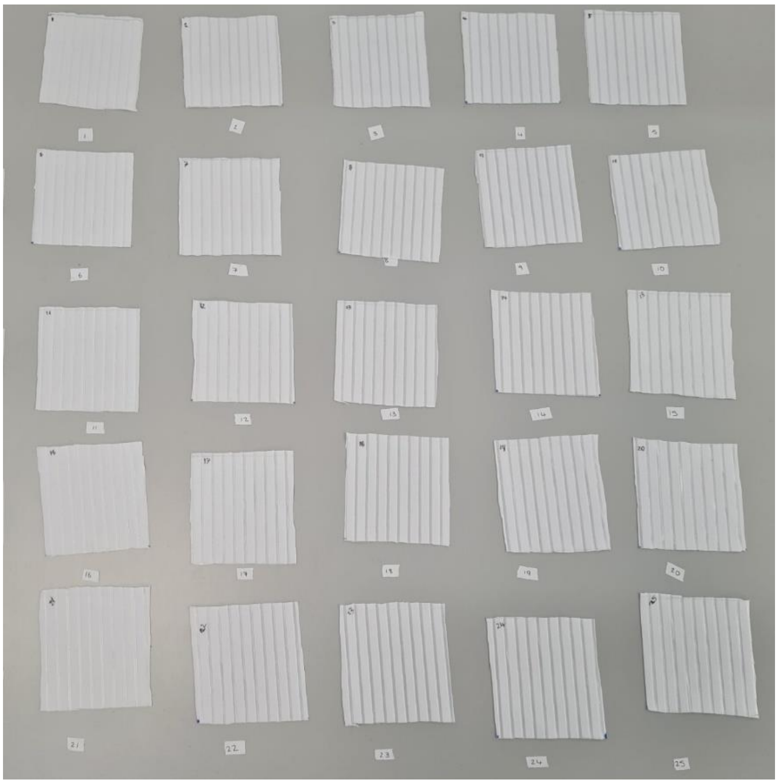


Figure 4.1: Fabric preparation of single fabric layers prior to testing.

4.2.2 C-Therm TCi Calibration

The C-Therm device (Tx Thermal Effusivity Touch Tester, C-Therm, New Brunswick, Canada), employs the modified transient plane source (MTPS) method to allow for the measurement of both k and ε. This method employs a one-sided heat reflectance sensor that sends a single heat pulse through the fabric and measures the rate and magnitude of its response at the interface. The device comprises of a small spiral heating element (figure 4.2, dark green spiral) and a guard ring (figure 4.2, dark green circle) to ensure one-dimensional heat exchange between only the element and the fabric sample mounted upon it. An electrical current is applied to the spiral heating element causing it to increase in temperature. This concomitantly results in an increased interface temperature between the sensor and the mounted fabric causing an increased resistance and thus, a voltage drop in the spiral element. Both the temperature and voltage changes are monitored by the device to allow it to establish the k and ε values. The test method described in this chapter complies with ASTM D 7984.

Figure 4.2: C-Therm spiral heat reflectance sensor with guard ring.

Prior to fabric testing, a reference test was undertaken on a specific ceramic reference material with known and stable *k* and *ε* values. Before placing the reference materials onto the device, using a pipette, 0.5ml of water was placed directly onto the heating element, acting as a contact medium. The pyroceram cube, supplied by the manufacturer, was then placed centrally onto the element with 500g metal weight on top to ensure contact security. Three complete heat-cooling cycles were conducted to ensure recorded values lay within an acceptable pre-determined range of *k* (3.876-4.284W/mK) and *ε* (2804.4-3099.6 Ws½m^{2}K).

4.2.3 Experimental Protocol

Each individual fabric was tested on the same day to ensure any difference in environmental conditions did not impact the within-fabric results.

4.2.3.1 Single Fabric Layer Testing

Firstly, individual layers were mounted onto a small bespoke 3D printed plastic holding ring that was then hooked onto the device's force gauge during testing (figure 4.3 & 4.4). The holding ring prevented slip and maintained continuous fabric stretch throughout the testing period. The orientation of the fabric was kept identical when mounting the squares to ensure uniform stretch across each fabric.

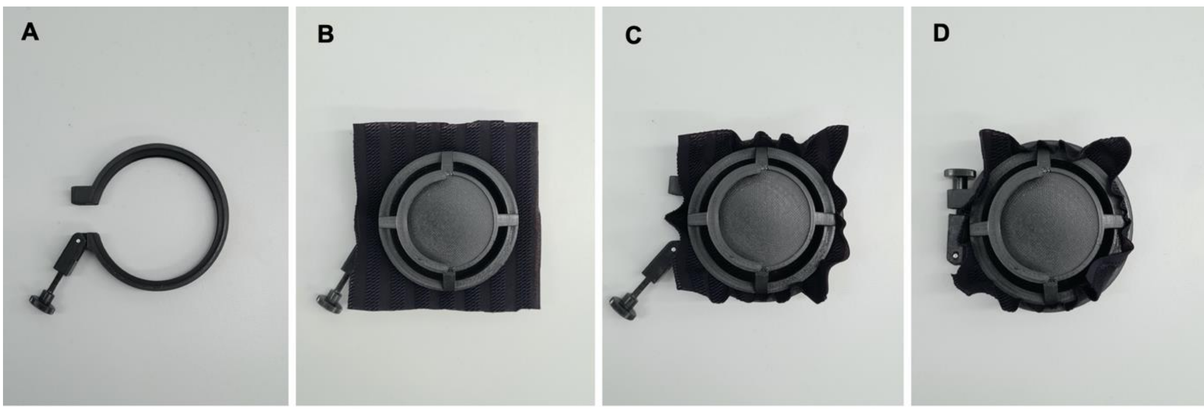


Figure 4.3: Mounting and securing single layer specimen onto bespoke 3D printed holding ring.

Once fitted to the C-Therm, the test piece was lowered down onto the heating element until a 20kPa ($2N \cdot cm^2$) pressure was exerted across the test piece (figure 2.4). Any pressure reduction outside these parameters, due to fabric slip, was altered during the cooling periods, prior to the subsequent heating cycle. The main protocol consisted of 4 heat-cooling cycles. One heat-cooling cycle was as follows; heat cycle of 1.2s, sampling time of 2s and cooling period of 80s. This was then repeated for every single layer for each fabric.

Figure 4.4: Set up of holding ring and fabric on C-Therm device.

4.2.3.2 Multi-layer Fabric Testing

The multi-layer samples were then created by grouping together multiple 80mm x 80mm single layers to make 5 multi-layer samples per fabric. The single layers were layered in the same order for each fabric sample. When layering the single layers together, each specimen was rotated by 30° clockwise, in reference to the previous specimen, to ensure that no yarns were aligned (figure 4.5). Layering was repeated until multi-layer thickness exceeded >1mm, using an electronic micrometer, (SF-500, 0-

25mm, Beslands®, China) to ensure the heat pulse conducted by the heating element did not fully penetrate the fabric sample and as is required in ASTM D7984. The multiple layers were then stapled together to ensure the same orientation whilst moving and mounting. The sample was mounted identically to the individual specimens, as described above. The same heat-cooling cycle protocol of 1.2s heating, 2s sampling time with an 80s cooling period, repeated four times was utilised for testing samples. This was then repeated for each of the multi-layer samples created for every fabric.

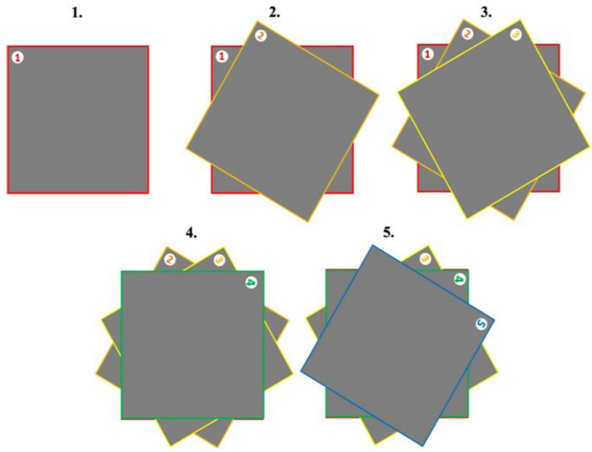


Figure 4.5: Graphic depicting the 30° tessellation of each fabric specimen when building multi-layer sample thickness.

Thermal effusivity is the quantification of how 'warm' or 'cool' a fabric feels to the touch. At room temperature (~24°C), wood has a thermal effusivity of 380 Ws½m^{2}K and a 'warmer' touch compared to copper which has an effusivity of 37,140 Ws½m^{2}K and a 'cooler' touch. Effusivity is associated with the velocity of heat energy propagation in a material as its temperature changes and is a measure of the disparity between the interface temperatures of two materials of different temperatures. Thermal effusivity was calculated through the C-Therm software as:

$$\varepsilon = \sqrt{k}\rho c_p$$

Where; k = thermal conductivity, ρ = density and c_p = specific heat capacity.

Thermal conductivity is defined as the rate of heat transfer per unit time, via conduction, through a unit cross-sectional are of a material (Ratna 2012). It is calculated as:

$$k = \frac{\mathrm{Q}d}{A\Delta T}$$

Where; Q = amount of heat transferred, d = distance between the two isothermal planes, A = surface area, Δ = difference in temperature.

4.3 Data Analysis and Statistics

All single layer and multi-layer analyses were undertaken within each fabric with no between fabric comparison carried out. Therefore, any text below relating to the calculation of a mean and standard deviation (SD) of specimens and samples will always apply to one fabric type.

4.3.1 Environmental Conditions

Both ambient temperature and relative humidity were recorded during the heating/sampling sections of the cycle for every test undertaken.

4.3.2 Differences Between Single Layers

Three out of the four heating-cooling cycles were used to calculate mean and SD for both k and ε of each single layer. The discarded outlier was identified by finding the average and standard deviation of three cycles with the most repeatable reading and the smallest standard deviation as directed by the manufacturer. The coefficient of variance (CV) for each of the 5 single layers was calculated by finding the mean and SD of 15 heat-cycles (3 cycles x 5 single layers). The mean was then divided by the SD and multiplied by 100. A one-way analysis of variance (ANOVA) was undertaken to analyse the differences between the single layers. If significant, post-hoc multiple comparisons were undertaken, using a Bonferroni correction to control for family-wise error and a Greenhouse Geisser correction was used to control for any lack of sphericity. A two-way intraclass correlation (ICC) was undertaken to assess the repeatability between the k and ε values measured using the single layer method on the C-Therm device. The three heat-cooling cycles were used to represent one single layer. Data for 25 single layers per fabric were used for the ICC. The repeatability from the ICC analysis was interpreted using the classification reported by Koo & Lee whereby <0.5 is poor, 0.5-0.75 is moderate, 0.75-0.9 is good and >0.9 is excellent (Koo, Li 2016).

4.3.3 Differences Between Multi-Layer Samples

As above, three out of the four heating-cooling cycles were used to calculate mean and SD for both k and ε of each multi-layer sample. The discarded outlier was identified by finding the mean and SD of the three cycles with the most repeatable reading and the smallest SD. The CV between the multi-layer samples was calculated by finding the mean and SD of 15 heat-cycles (3 cycles x 5 multi-layer samples). The mean was then divided by the SD and multiplied by 100. A one-way analysis of variance (ANOVA) was undertaken to analyse the differences between individual samples. If significant, post-hoc multiple comparisons were performed, using a Bonferroni correction to control for family-wise error and a Greenhouse Geisser correction was used to control for any lack of sphericity. A two-way intraclass correlation was undertaken to assess the repeatability between the k and ε values measured using the multi-layer method on the C-Therm device. Three heat-cooling cycles were used to represent one multi-layer sample. Data for 5 multi-layer samples per fabric were used for the ICC.

4.3.4 Differences Between Single Layers and Multi-Layers

The sample mean and SD was calculated using each viable heat-cooling cycle of the 5 multi-layer samples and 25 single layers as described above. An independent t-test was performed to analyse the difference between the multi-layer sample measurements and single layer measurements in both k and ε. A Pearson's correlation was undertaken to identify a relationship between the mean of all fabric multi-layer samples and all fabric single layers. The correlational method of analysis only presents an estimated linear relationship between the two methods and not their agreement and may be displaying a misleading meaningful relationship. Thus, to further explore this relationship, it was of more interest to analyse the mean and standard deviations of the measurement methods using Bland-Altman analysis. This plots the mean difference between the two methods of multi-layer method vs the single layer methods against the mean of all measurements of *k* and *ε*. Method A represents multi-layer samples and method B represents single layers. The upper limit of agreement was set using mean difference +1.96 x SD of the mean difference between the two methods. The lower limit of agreement was set using mean difference –1.96 x SD of the mean difference (Bland, Altman 1999).

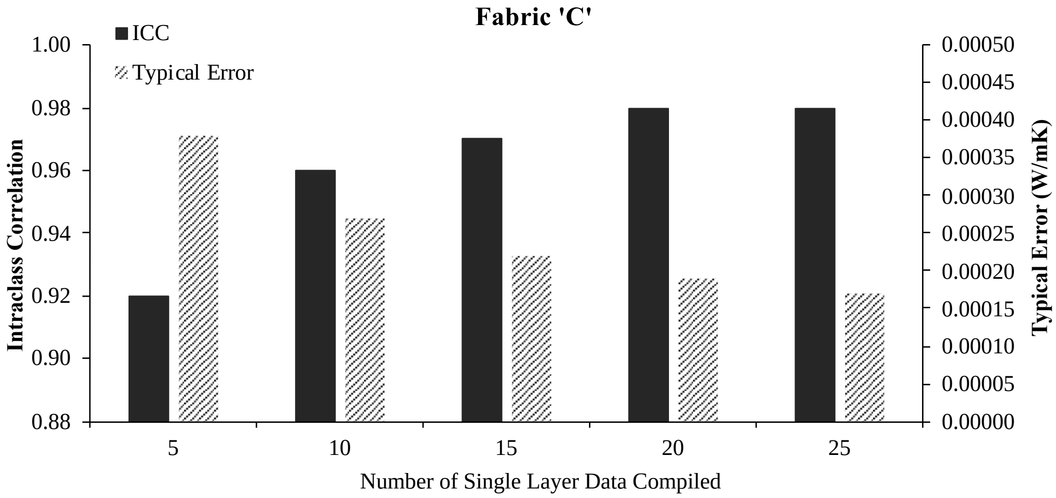
4.4 Results

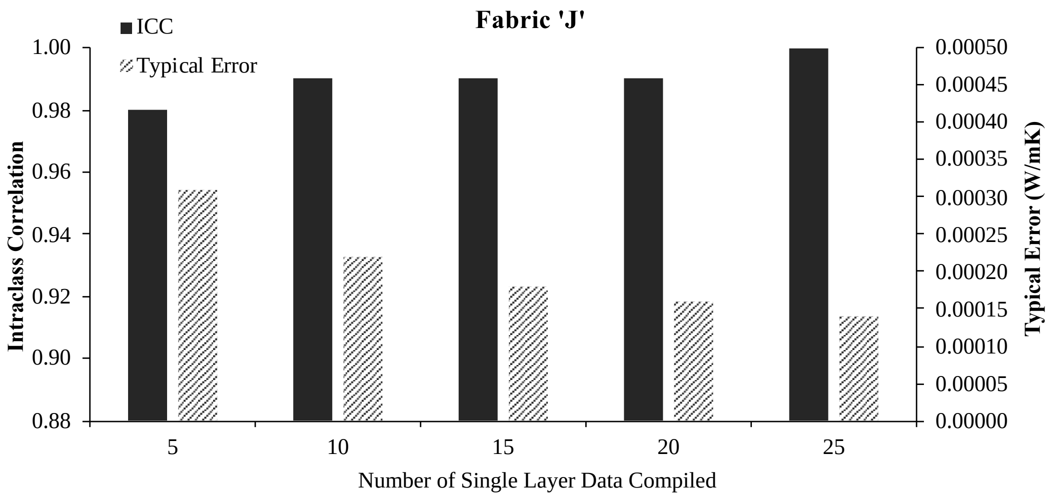
4.4.1 Environmental Conditions

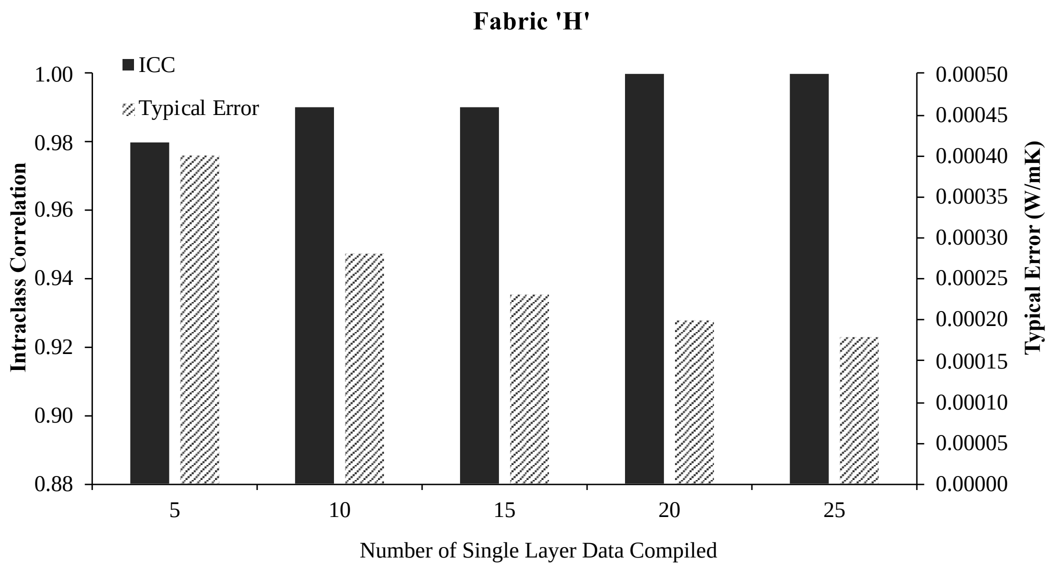
Throughout all fabric testing sessions, ambient temperature and relative humidity in all fabric testing sessions were kept within the standard limits for fabric testing set out in ASTM D1776 at 21 ± 1°C and 65 ± 2%, respectively.

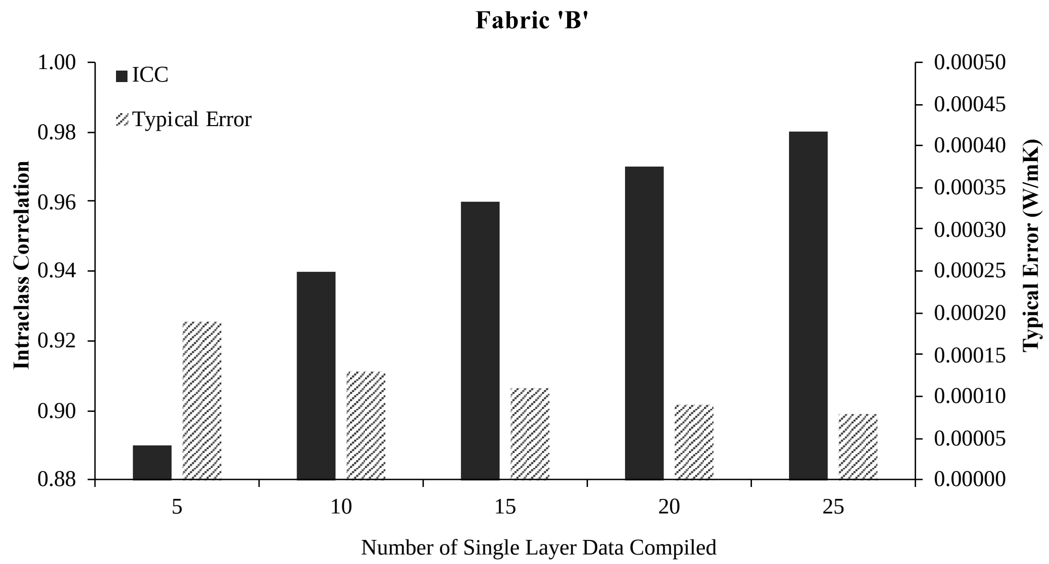
4.4.2 Single Layer Measurement Repeatability

Results from the ICC show there is excellent repeatability in the measurement of both *k* and *ε* using the single layer method in fabrics 'C', 'J', 'H' and moderate in 'B' and 'G' (Koo, Li 2016). Fabrics C', 'J', 'H' and 'B' all showed an ICC >0.89 and typical error <0.00040 W/mK in *k* (figure 4.6) and <1 Ws½/m^{2}K in *ε* (figure 4.7). In Fabric 'G', the ICC for the collation of measurements from 5 single layers was moderate at 0.68 for both *k* and *ε* and an error of 0.00048 W/mK and 1.8 Ws½/m^{2}K, respectively. For this same fabric (G), after collating and analysing the variability in measurements from 10 single layer measurements, the ICC classification increased to excellent at 0.81. There was also a smaller error of 0.00034 W/mK and 1.2 Ws½/m^{2}K for *k* and *ε*, respectively.


Fabric 'C'
ICC
Typical Error
Intraclass Correlation
Typical Error (W/mK)
Number of Single Layer Data Compiled
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.00050
0.00045
0.00040
0.00035
0.00030
0.00025
0.00020
0.00015
0.00010
0.00005
0.00000
5
10
15
20
25


Fabric 'J'
ICC
Typical Error
Intraclass Correlation
Typical Error (W/mK)
Number of Single Layer Data Compiled
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.00050
0.00045
0.00040
0.00035
0.00030
0.00025
0.00020
0.00015
0.00010
0.00005
0.00000
5
10
15
20
25


Fabric 'H'
ICC
Typical Error
Intraclass Correlation
1.00
0.98
0.96
0.94
0.92
0.90
0.88
Typical Error (W/mK)
0.00050
0.00045
0.00040
0.00035
0.00030
0.00025
0.00020
0.00015
0.00010
0.00005
0.00000
5
10
15
20
25
Number of Single Layer Data Compiled


Fabric 'B'
ICC
Typical Error
Intraclass Correlation
1.00
0.98
0.96
0.94
0.92
0.90
0.88
Typical Error (W/mK)
0.00050
0.00045
0.00040
0.00035
0.00030
0.00025
0.00020
0.00015
0.00010
0.00005
0.00000
5
10
15
20
25
Number of Single Layer Data Compiled

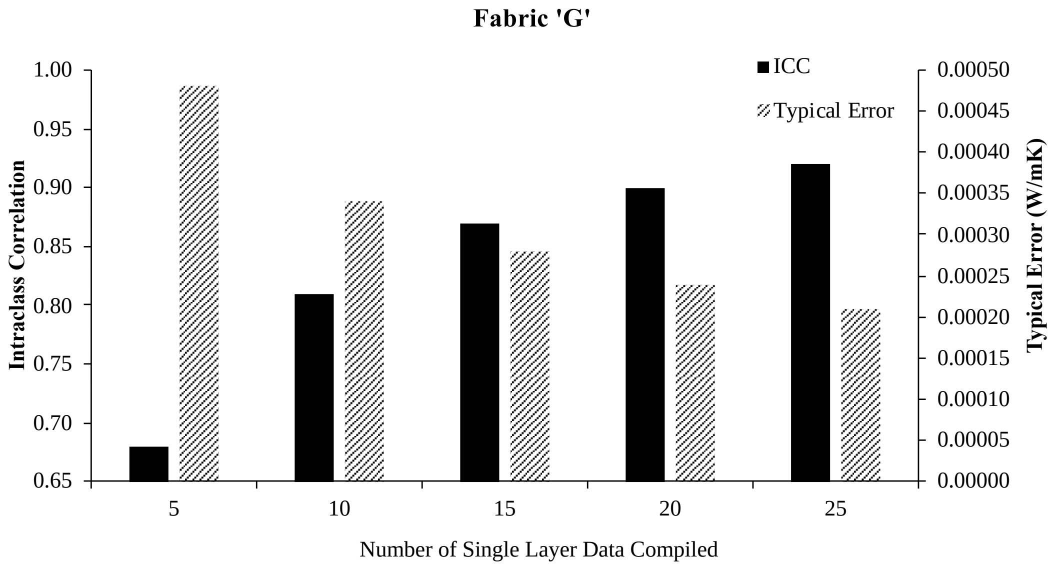
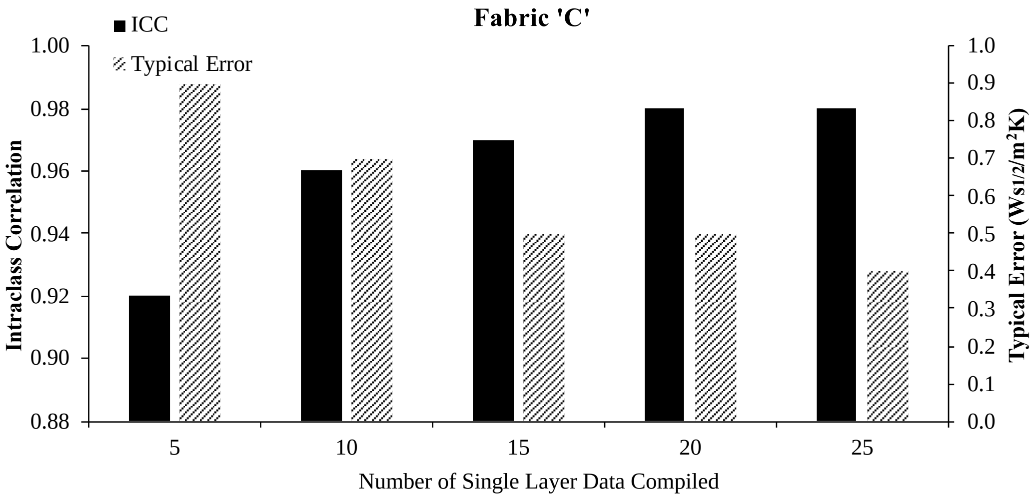
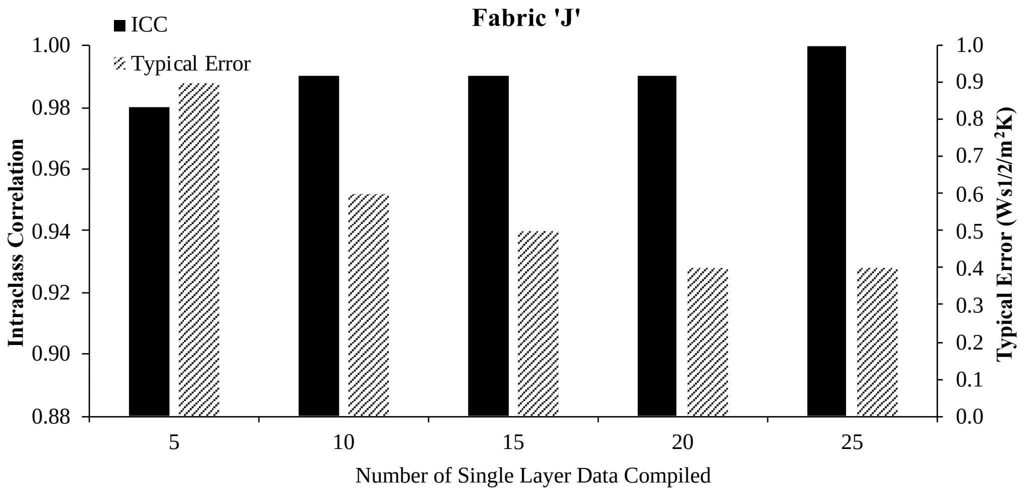
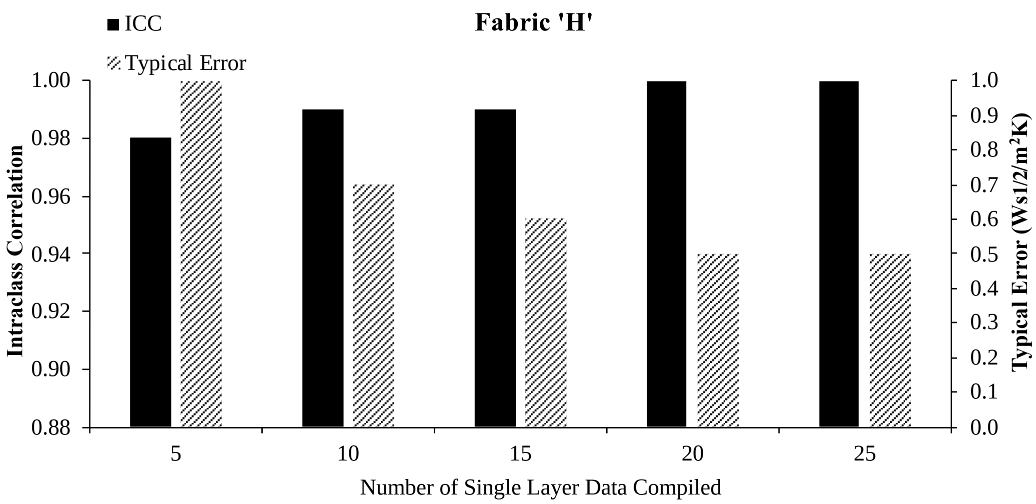


Figure 4.6: Differences in typical error and intraclass correlation results of thermal conductivity measurement when compiling data from 5, 10, 15, 20 and 25 single layers in five smooth fabrics.


Fabric 'C'
ICC
Typical Error
Intraclass Correlation
Typical Error (Ws1/2/m2K)
Number of Single Layer Data Compiled


Fabric 'J'
ICC
Typical Error
Intraclass Correlation
Typical Error (Ws1/2/m2K)
Number of Single Layer Data Compiled


Fabric 'H'
ICC
Typical Error
Intraclass Correlation
Typical Error (Ws1/2/m2K)
Number of Single Layer Data Compiled

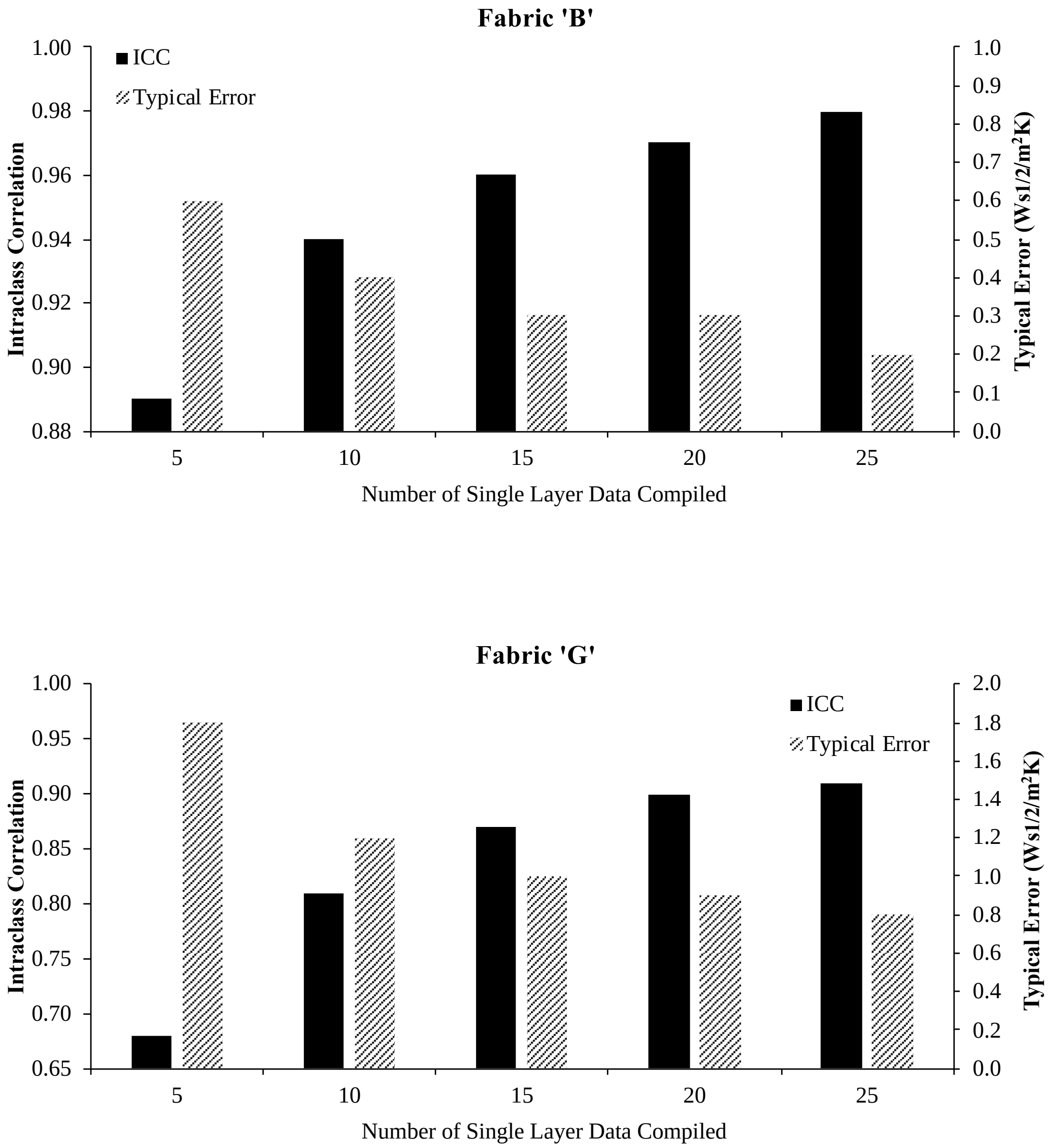
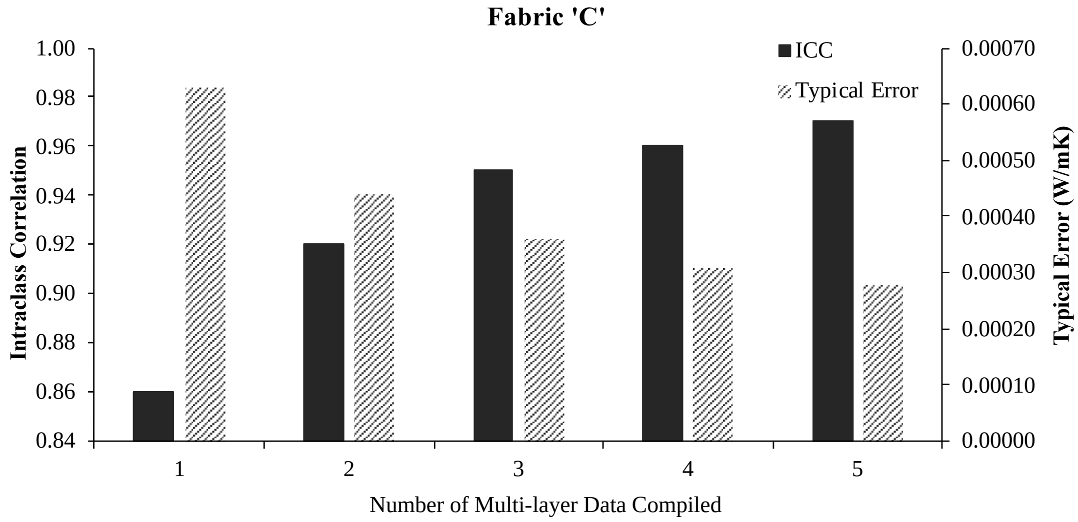


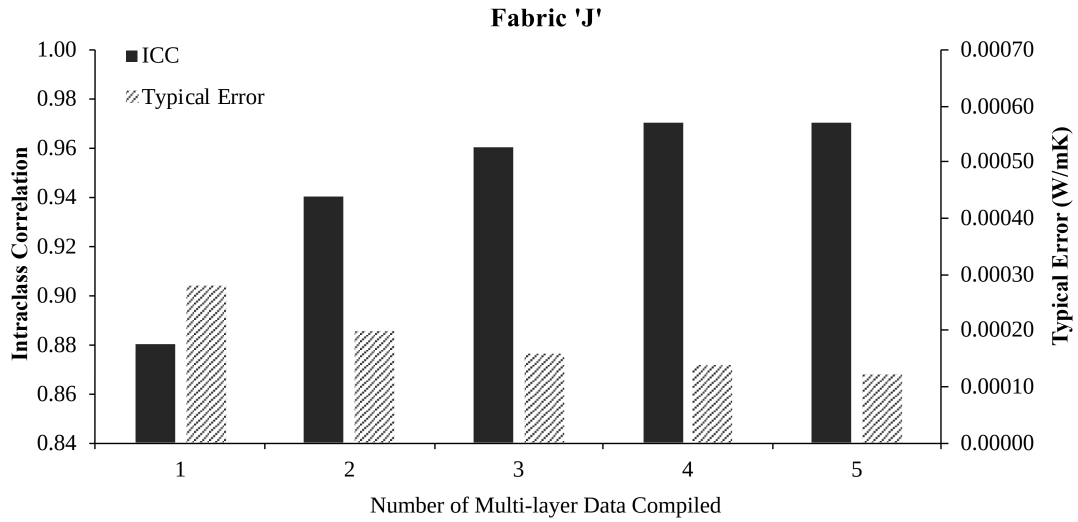
Figure 4.7: Differences in typical error and intraclass correlation results of thermal effusivity measurement when compiling data from 5, 10, 15, 20 and 25 single layers in five smooth fabrics.

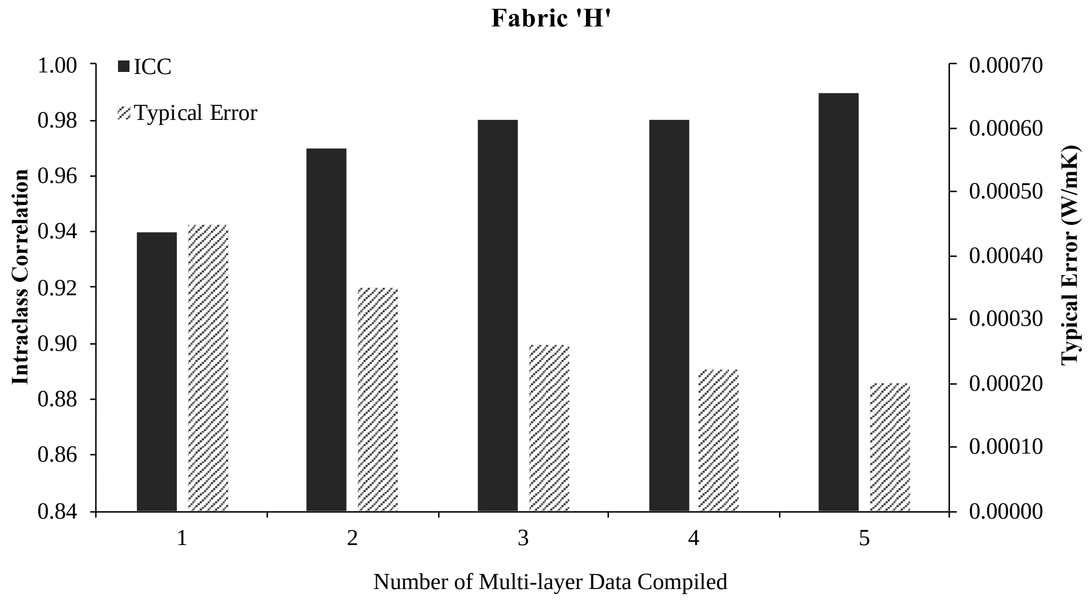
4.4.3 Multi-Layer Measurement Repeatability

Results from the ICC show there is good repeatability in fabrics ‘C’, ‘J’ and ‘B’ and excellent repeatability in fabrics ‘H’ and ‘G’ from measuring just 1 multi-layer sample using the multi-layer method. All fabrics showed an ICC >0.85 and typical error <0.00063 W/mK in *k* and <1.8 Ws½/m^{2}K in ε after one multi-layer sample measurement which increased to <0.92 with a typical error of

<0.00044 and <1.2 Ws½/m^{2}K after the collation of measurements from two multi-layer samples (figure 4.8 and 4.9).






Fabric 'H'
ICC
Typical Error
Intraclass Correlation
Typical Error (W/mK)
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0.84
0.00070
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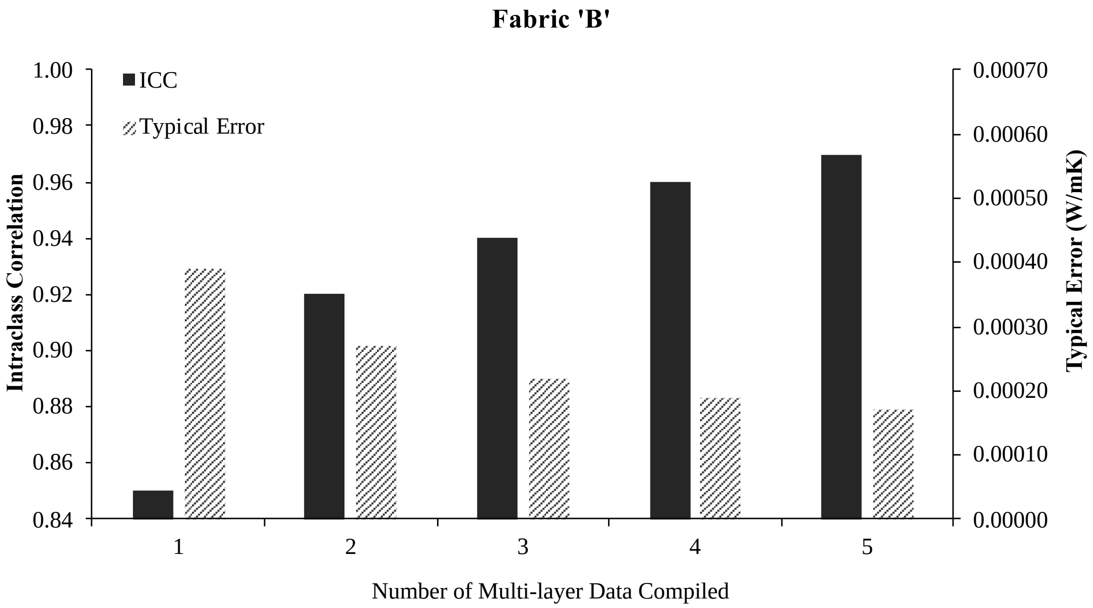
1
2
3
4
5
Number of Multi-layer Data Compiled


Fabric 'B'
ICC
Typical Error
Intraclass Correlation
Typical Error (W/mK)
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0.84
0.00070
0.00060
0.00050
0.00040
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2
3
4
5
Number of Multi-layer Data Compiled

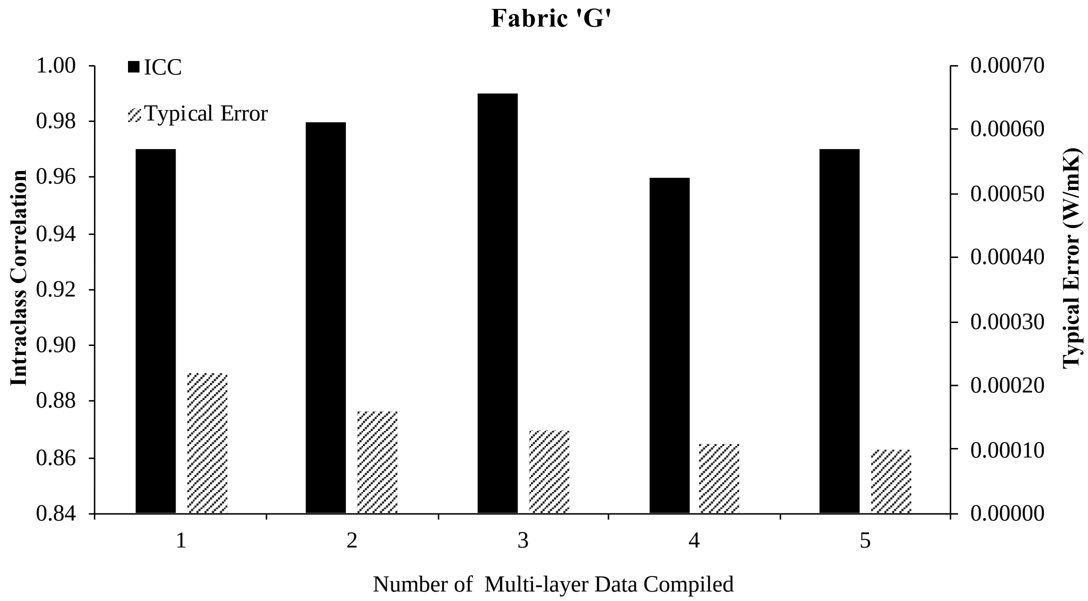
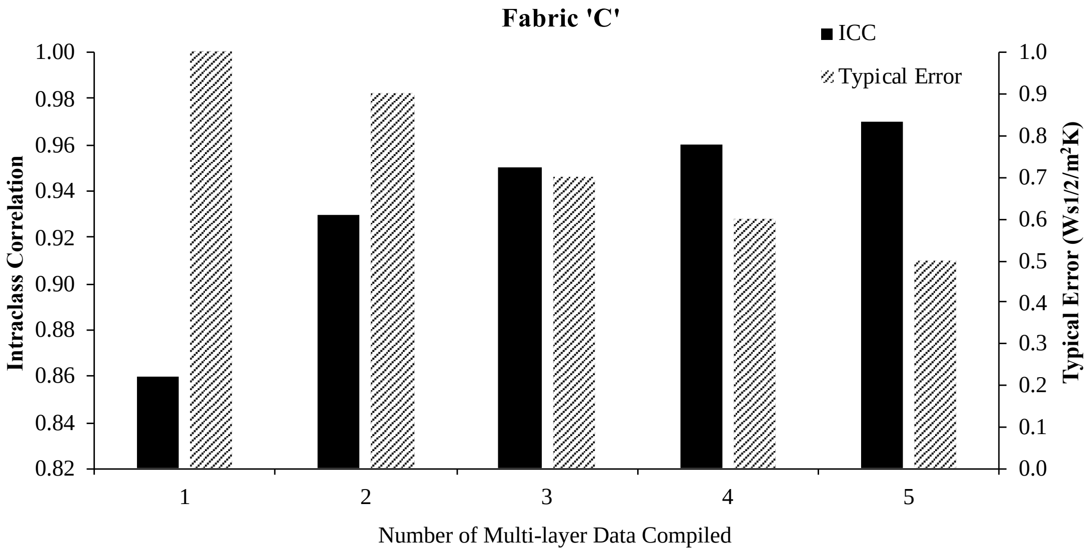
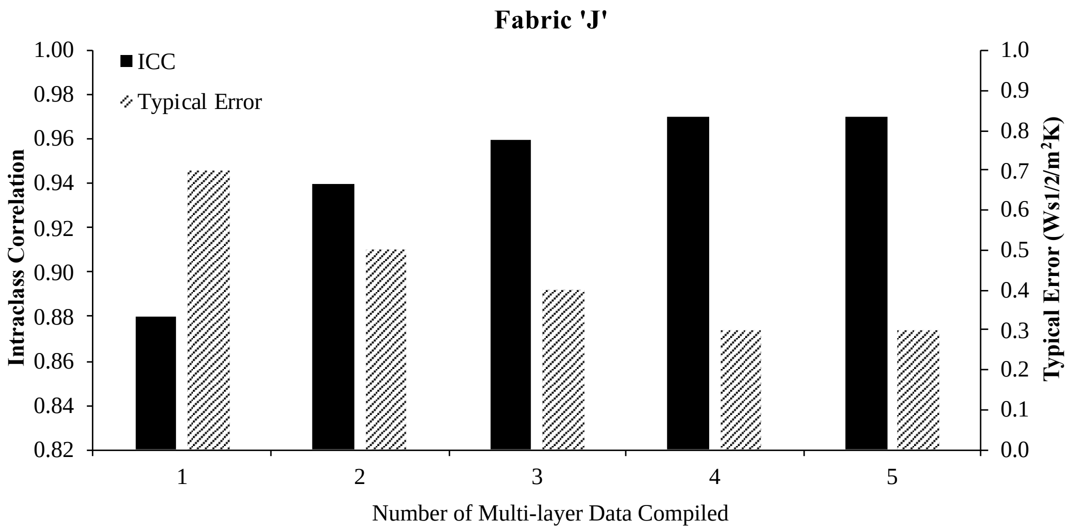
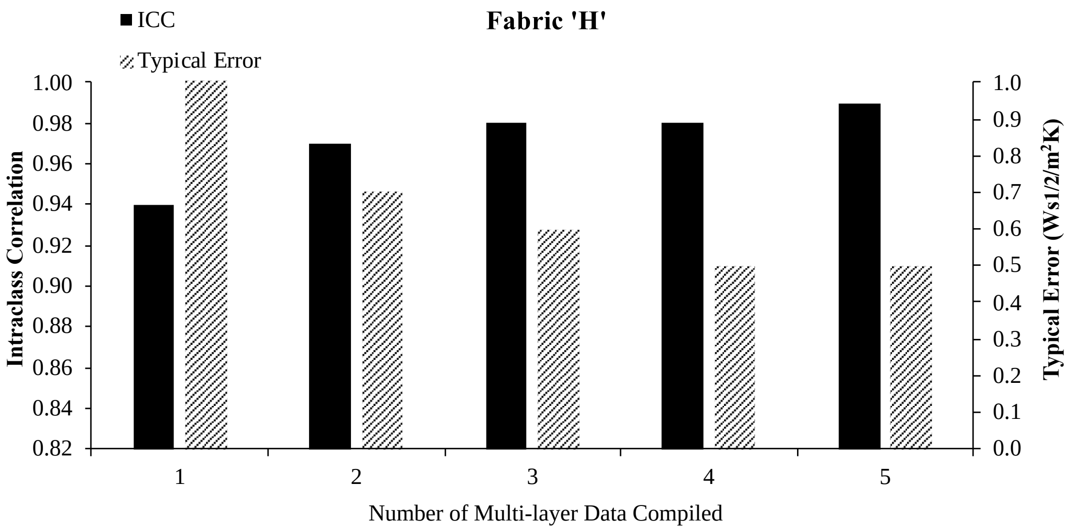


Figure 4.8: Differences in typical error and intraclass correlation results of thermal conductivity measurement when compiling data from 1, 2, 3, 4 and 5 multi-layer samples in five smooth fabrics.


Fabric 'C'
ICC
Typical Error
Intraclass Correlation
Typical Error (Ws1/2/m2K)
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0.84
0.82
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
Number of Multi-layer Data Compiled


Fabric 'J'
ICC
Typical Error
Intraclass Correlation
Typical Error (Ws1/2/m2K)
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0.84
0.82
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
Number of Multi-layer Data Compiled


ICC
Typical Error
Fabric 'H'
Intraclass Correlation
Typical Error (Ws1/2/m2K)
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0.84
0.82
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
Number of Multi-layer Data Compiled

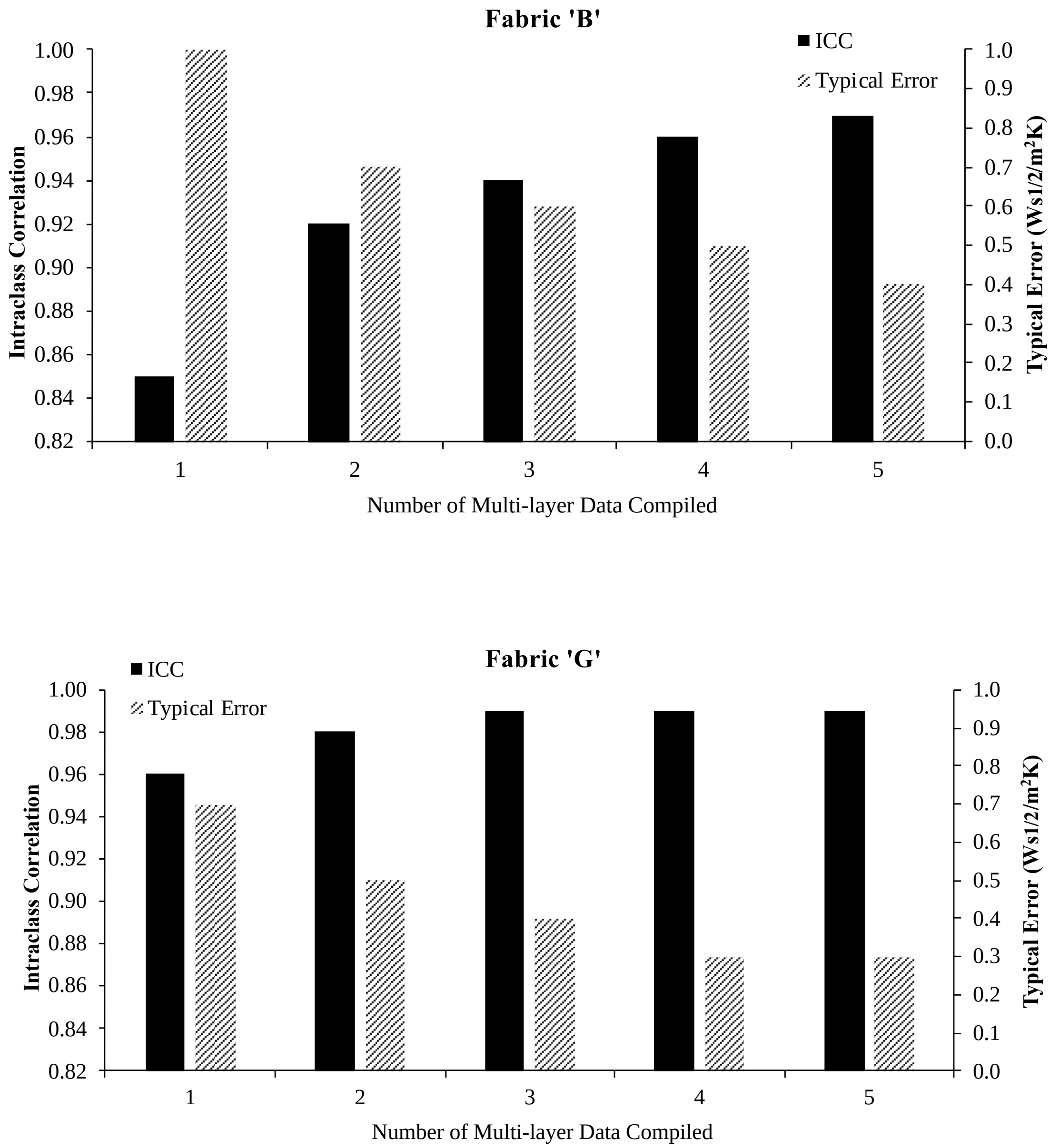


Figure 4.9: Differences in typical error and intraclass correlation results of thermal effusivity measurement when compiling data from 1, 2, 3, 4 and 5 multi-layer samples in five smooth fabrics.

4.4.4 Differences Between Single Layers

Differences in both k and ε were found between single layers (Table 4.1 & Table 4.2, respectively). This was found in every fabric apart from Fabric 'G' where there were no significant differences in k and ε between any single layers tested. All CVs between the single layers, in both k and ε, were <5%.

*Table 4.1: Differences in thermal conductivity in same-fabric single layers. * sig. vs layer 1, † sig. vs layer 2, Δ sig. vs layer 3, • sig vs layer 4, all p<0.01. Mean and SD are shown for each sample number.*

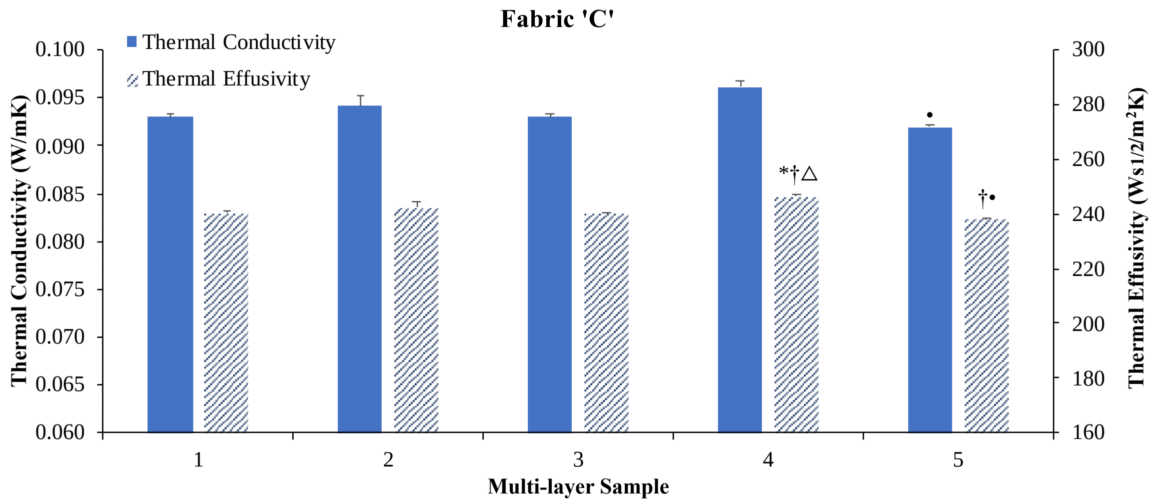
Fabric	Sample No.		Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Coefficient of Variance (Absolute)	Coefficient of Variance (%)
Fabric 'C'	**1**	Mean	**0.07573**	**0.07605**	**0.07773**	**0.07515**	**0.07758**	**0.02**	**1.8**
		SD	0.00024	0.00132	0.00060	0.00067	0.00170		
	2	Mean	**0.07684**	**0.07612**	**0.07623**	**0.07217***†Δ	**0.07554**•	**0.03**	**2.5**
		SD	0.00154	0.00067	0.00075	0.00058	0.00083		
	3	Mean	**0.07742**	**0.07706**	**0.07623**	**0.07324***†Δ	**0.07618**•	**0.02**	**2.2**
		SD	0.00011	0.00042	0.00126	0.00065	0.00037		
	4	Mean	**0.07531**	**0.07642**	**0.07811***	**0.07616** Δ	**0.07689**	**0.01**	**1.4**
		SD	0.00031	0.00081	0.00026	0.00053	0.00092		
	5	Mean	**0.07711**	**0.07680**	**0.07599** *†	**0.07732**	**0.07767**	**0.01**	**1.3**
		SD	0.00088	0.00118	0.00102	0.00095	0.00058		
Fabric 'J'	**1**	Mean	**0.07374**	**0.07078***	**0.06653**	**0.06844***	**0.06784***†	**0.04**	**4.1**
		SD	0.00020	0.00012	0.00025	0.00057	0.00161		
	2	Mean	**0.06786**	**0.06793**	**0.06877**	**0.06877**	**0.07080***†	**0.02**	**1.7**
		SD	0.00004	0.00120	0.00043	0.00043	0.00077		
	3	Mean	**0.06676**	**0.07287***	**0.06679**†	**0.06720**†	**0.06726**†	**0.03**	**3.4**
		SD	0.00008	0.00053	0.00052	0.00039	0.00071		
	4	Mean	**0.06702**	**0.06727**	**0.06711**	**0.06765**	**0.06393**†•	**0.02**	**2.5**
		SD	0.00062	0.00009	0.00081	0.00151	0.00074		
	5	Mean	**0.06726**	**0.06836**	**0.06756**	**0.06726**	**0.06627** †	**0.01**	**1.2**
		SD	0.00025	0.00068	0.00029	0.00040	0.00014		
Fabric 'H'	**1**	Mean	**0.06925**	**0.06827**	**0.06883**	**0.06933**	**0.06900**	**0.01**	**1.3**
		SD	0.00178	0.00054	0.00042	0.00058	0.00100		
	2	Mean	**0.06804**	**0.06986**	**0.06987**	**0.06833**	**0.06900**	**0.02**	**1.8**
		SD	0.00157	0.00148	0.00036	0.00058	0.00100		
	3	Mean	**0.06694**	**0.06680**	**0.06805**	**0.06700**	**0.06967***†•	**0.02**	**1.8**
		SD	0.00087	0.00007	0.00012	0.00000	0.00058		
	4	Mean	**0.06847**	**0.06654**	**0.06704**	**0.06300***†Δ	**0.06100***†Δ	**0.05**	**4.5**
		SD	0.00054	0.00091	0.00007	0.00100	0.00100		
	5	Mean	**0.06329**	**0.06198**	**0.06580**†	**0.06133** Δ	**0.06200** Δ	**0.03**	**2.9**
		SD	0.00042	0.00082	0.00043	0.00058	0.00173		
Fabric 'B'	**1**	Mean	**0.06583**	**0.06448**	**0.06538**	**0.06509**	**0.06465**	**0.01**	**1.0**
		SD	0.00053	0.00015	0.00026	0.00038	0.00071		
	2	Mean	**0.06571**	**0.06500**	**0.06518**	**0.06451**	**0.06505**	**0.01**	**0.8**
		SD	0.00057	0.00038	0.00024	0.00050	0.00016		
	3	Mean	**0.06437**	**0.06417**	**0.06603** †	**0.06543**	**0.06645** *†	**0.02**	**1.6**
		SD	0.00079	0.00029	0.00027	0.00029	0.00053		
	4	Mean	**0.06449**	**0.06428**	**0.06534**	**0.06520**	**0.06543** †	**0.01**	**0.8**
		SD	0.00032	0.00021	0.00021	0.00021	0.00047		
	5	Mean	**0.06524**	**0.06567**	**0.06559**	**0.06504**	**0.06577**	**0.01**	**0.7**
		SD	0.00022	0.00053	0.00043	0.00055	0.00014		
Fabric ’G’	**1**	Mean	**0.05327**	**0.05359**	**0.05349**	**0.05345**	**0.05134**	**0.02**	**2.1**
		SD	0.00098	0.00127	0.00044	0.00038	0.00047		
	2	Mean	**0.05206**	**0.05410**	**0.05225**	**0.05144**	**0.05137**	**0.03**	**2.7**
		SD	0.00073	0.00022	0.00024	0.00004	0.00249		
	3	Mean	**0.05360**	**0.05306**	**0.05358**	**0.05358**	**0.05133**	**0.03**	**2.9**
		SD	0.00049	0.00190	0.00201	0.00201	0.00162		
	4	Mean	**0.05361**	**0.05119**	**0.05210**	**0.05187**	**0.05152**	**0.02**	**2.2**
		SD	0.00051	0.00052	0.00167	0.00063	0.00063		
	5	Mean	**0.05230**	**0.05174**	**0.05179**	**0.05309**	**0.05212**	**0.01**	**1.4**
		SD	0.00032	0.00031	0.00112	0.00029	0.00064		

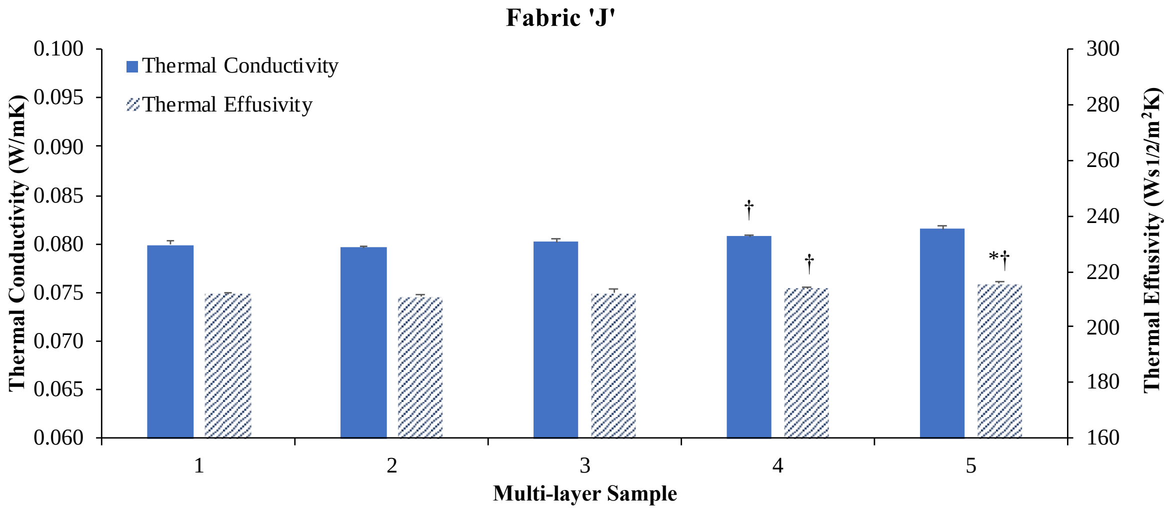
*Table 4.2: Differences in thermal effusivity in same-fabric specimens. * sig. vs layer 1, † sig. vs layer 2, Δ sig. vs layer 3, • sig vs layer 4, all p< 0.01. Mean and SD are shown for each sample number.*

Fabric	Sample No.		Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Coefficient of Variance (Absolute)	Coefficient of Variance (%)
Fabric 'C'	1	Mean	**201.5**	**202.3**	**206.5**	**200.0**	**206.1**	**0.02**	**1.7**
		SD	0.6	3.3	1.5	1.7	4.2		
	2	Mean	**204.2**	**202.5**	**202.8**	**192.2*†Δ**	**201.0**	**0.02**	**2.4**
		SD	3.8	1.7	1.9	1.5	2.1		
	3	Mean	**205.7**	**204.8**	**202.7**	**195.1*†Δ**	**202.6•**	**0.02**	**2.1**
		SD	0.3	1.1	3.2	1.7	0.9		
	4	Mean	**200.4**	**203.2**	**207.4***	**202.6 Δ**	**204.4**	**0.01**	**1.4**
		SD	0.8	2.0	0.6	1.3	2.3		
	5	Mean	**204.9**	**204.1**	**202.1**	**205.5**	**206.3**	**0.01**	**1.2**
		SD	2.2	2.9	2.6	2.3	0.5		
Fabric 'J'	1	Mean	**196.4**	**188.5**	**176.5*†**	**182.0***	**180.2***	**0.04**	**4.2**
		SD	0.5	0.3	0.7	1.6	4.6		
	2	Mean	**180.3**	**180.5**	**181.3**	**182.9**	**188.5*†**	**0.02**	**1.8**
		SD	0.1	3.4	2.1	1.2	2.1		
	3	Mean	**177.2**	**194.1***	**177.2†**	**178.4†**	**178.6†**	**0.04**	**3.5**
		SD	0.2	1.4	1.5	1.1	2.1		
	4	Mean	**177.9**	**178.6**	**178.2**	**179.7**	**168.7†•**	**0.03**	**2.7**
		SD	1.8	0.3	2.3	4.3	2.3		
	5	Mean	**178.6**	**181.8**	**179.5**	**178.6**	**175.7†**	**0.01**	**1.3**
		SD	0.7	1.9	0.8	1.2	0.4		
Fabric 'H'	1	Mean	**184.2**	**181.5**	**183.5**	**184.8**	**181.7**	**0.01**	**1.4**
		SD	4.9	1.5	1.5	1.3	0.9		
	2	Mean	**180.8**	**185.9**	**186.0**	**180.7**	**179.9**	**0.02**	**2.1**
		SD	4.5	4.1	1.0	1.4	2.7		
	3	Mean	**177.7**	**177.3**	**181.1**	**178.0**	**183.4*†**	**0.02**	**1.5**
		SD	2.5	0.2	0.4	1.1	1.7		
	4	Mean	**182.1**	**176.5**	**177.2**	**165.6*†Δ**	**161.5*†Δ**	**0.05**	**4.7**
		SD	1.5	2.7	0.9	2.0	2.2		
	5	Mean	**166.8**	**162.7**	**174.3*†**	**161.2Δ**	**164.7Δ**	**0.03**	**3.0**
		SD	1.3	2.6	1.2	1.3	1.8		
Fabric 'B'	1	Mean	**174.5**	**170.4**	**173.1**	**172.3**	**170.9**	**0.01**	**1.1**
		SD	1.6	4.0	0.8	1.1	2.1		
	2	Mean	**174.1**	**172.0**	**172.5**	**170.5**	**172.1**	**0.01**	**0.9**
		SD	1.7	1.1	0.7	1.5	0.5		
	3	Mean	**170.1**	**169.5**	**175.0†**	**173.3**	**176.3*†**	**0.02**	**1.7**
		SD	2.4	0.9	0.8	0.9	1.5		
	4	Mean	**170.5**	**169.8**	**173.0**	**172.6**	**173.2†**	**0.01**	**1.0**
		SD	1.0	0.6	0.6	0.6	1.4		
	5	Mean	**172.7**	**174.0**	**173.7**	**172.1**	**174.3**	**0.01**	**0.8**
		SD	0.6	1.6	1.3	1.6	0.4		
Fabric 'G'	1	Mean	**133.2**	**134.4**	**134.0**	**133.9**	**126.1**	**0.03**	**3.1**
		SD	3.6	4.6	1.6	1.4	1.8		
	2	Mean	**128.8**	**136.2**	**129.5**	**126.5**	**126.1**	**0.04**	**4.1**
		SD	2.7	0.8	0.9	0.1	9.4		
	3	Mean	**134.4**	**132.4**	**133.1**	**134.3**	**126.0**	**0.04**	**4.4**
		SD	1.8	7.0	4.1	7.4	6.1		
	4	Mean	**134.5**	**125.5**	**128.9**	**128.1**	**126.8**	**0.03**	**3.3**
		SD	1.9	2.0	6.2	2.3	2.4		
	5	Mean	**129.7**	**127.6**	**127.7**	**132.6**	**129.0**	**0.02**	**2.1**
		SD	1.2	1.1	4.2	1.1	2.4		

4.4.5 Differences Between Multi-Layer Samples

Results identifying the differences in k and ε, between five multi-layer samples within the same fabric, are detailed in figure 4.10. Like the single layer data, there were some significant differences between the multi-layer samples in both k and ε. The CV again shows low variability in both the k and ε data (<3%).





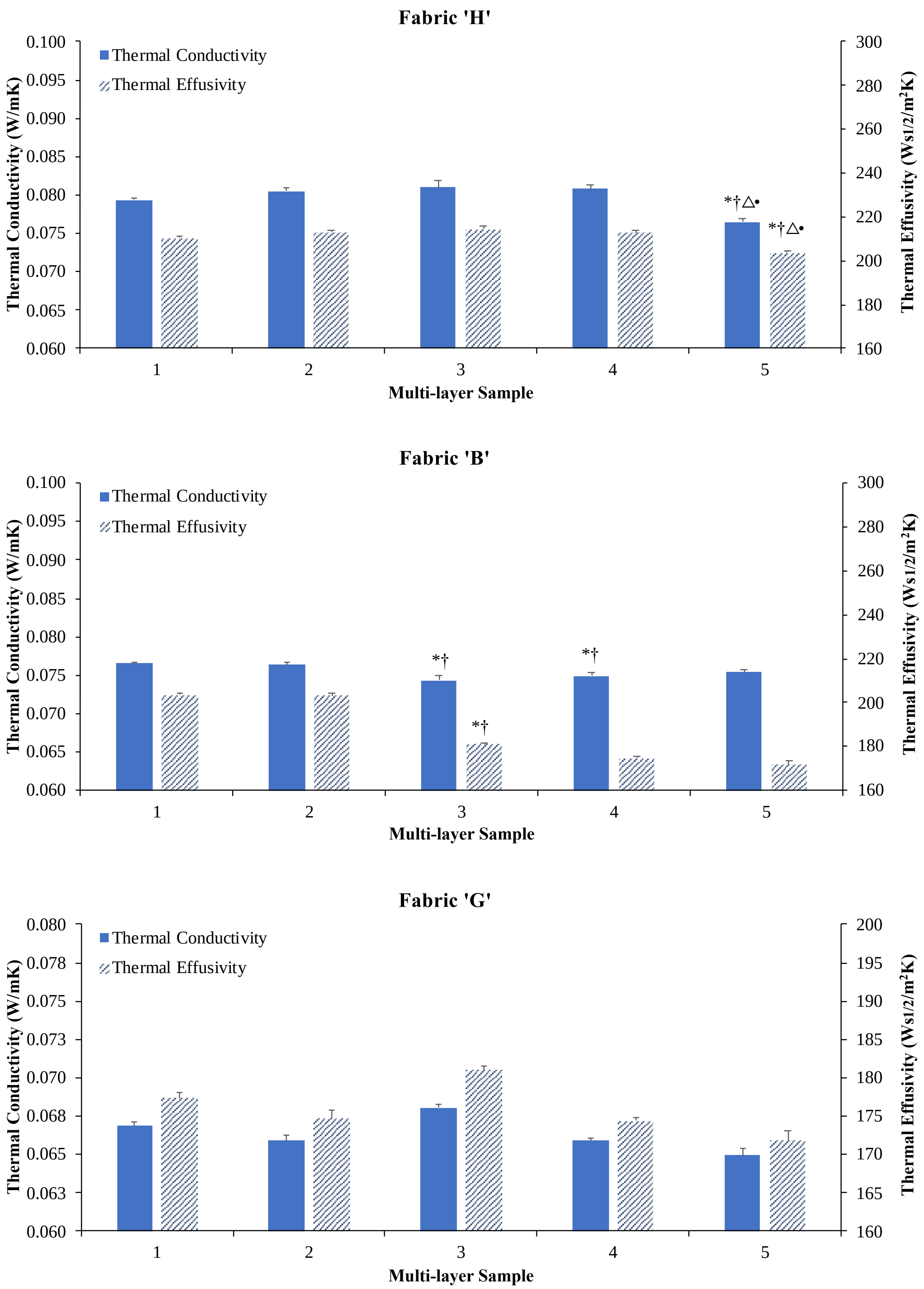


*Figure 4.10: Differences in thermal conductivity and effusivity in same-fabric samples. * sig. vs sample 1, † sig. vs sample 2, Δ sig. vs sample 3, • sig vs sample 4, all p<0.01 in same variable.. Mean and SD are shown for each multi-layer sample.*

4.4.6 Differences Between Single Layers and Multi-Layer Samples

In all five fabrics, the mean k of all multi-layer samples was significantly higher than that of all single layers (all $p<0.0001$). The percentage differences between the mean of the multi-layer samples to the mean of all single layers was -18.6% in fabric ‘C’, -15.3% in fabric ‘J’, -16.1% in fabric ‘H’, -13.7% in fabric ‘B’ and -20.9% in fabric ‘G’(figure 4.11).

Similarly, in all five fabrics, the mean ε of all multi-layer samples was significantly higher than the mean of all single layers (all $p<0.0001$). The percentage differences between the mean of the multi-layer samples to the mean of all single layers was -16.0% in fabric ‘C’, -15.0% in fabric ‘J’, -16.2% in fabric ‘H’, -14.2% for Fabric ‘B’ and -25.9% for fabric ‘G’ (figure 4.12).

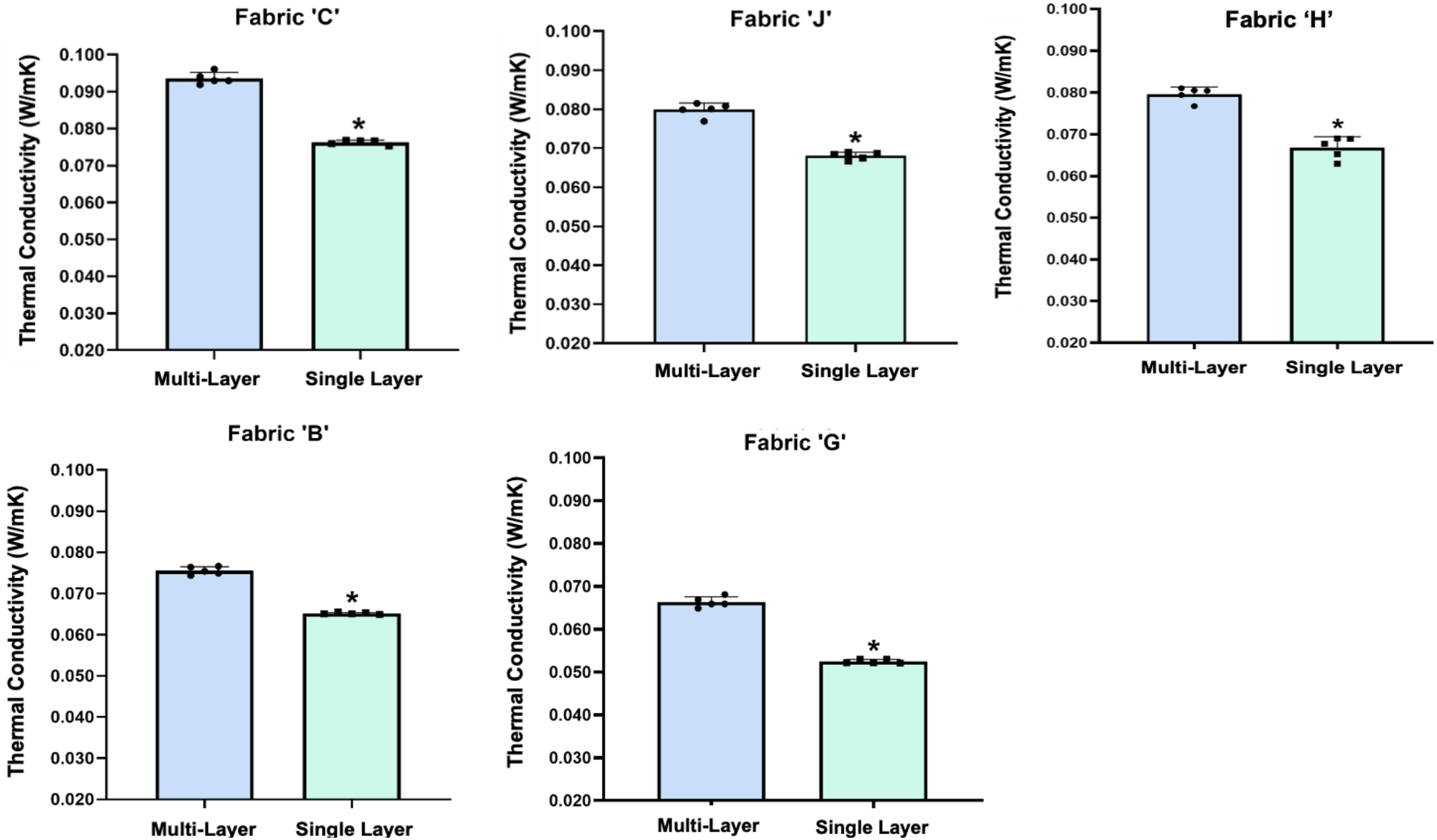


*Figure 4.11: Differences in k between multi-layer samples and single layers within each fabric. *, significantly different to multi-layer sample.*

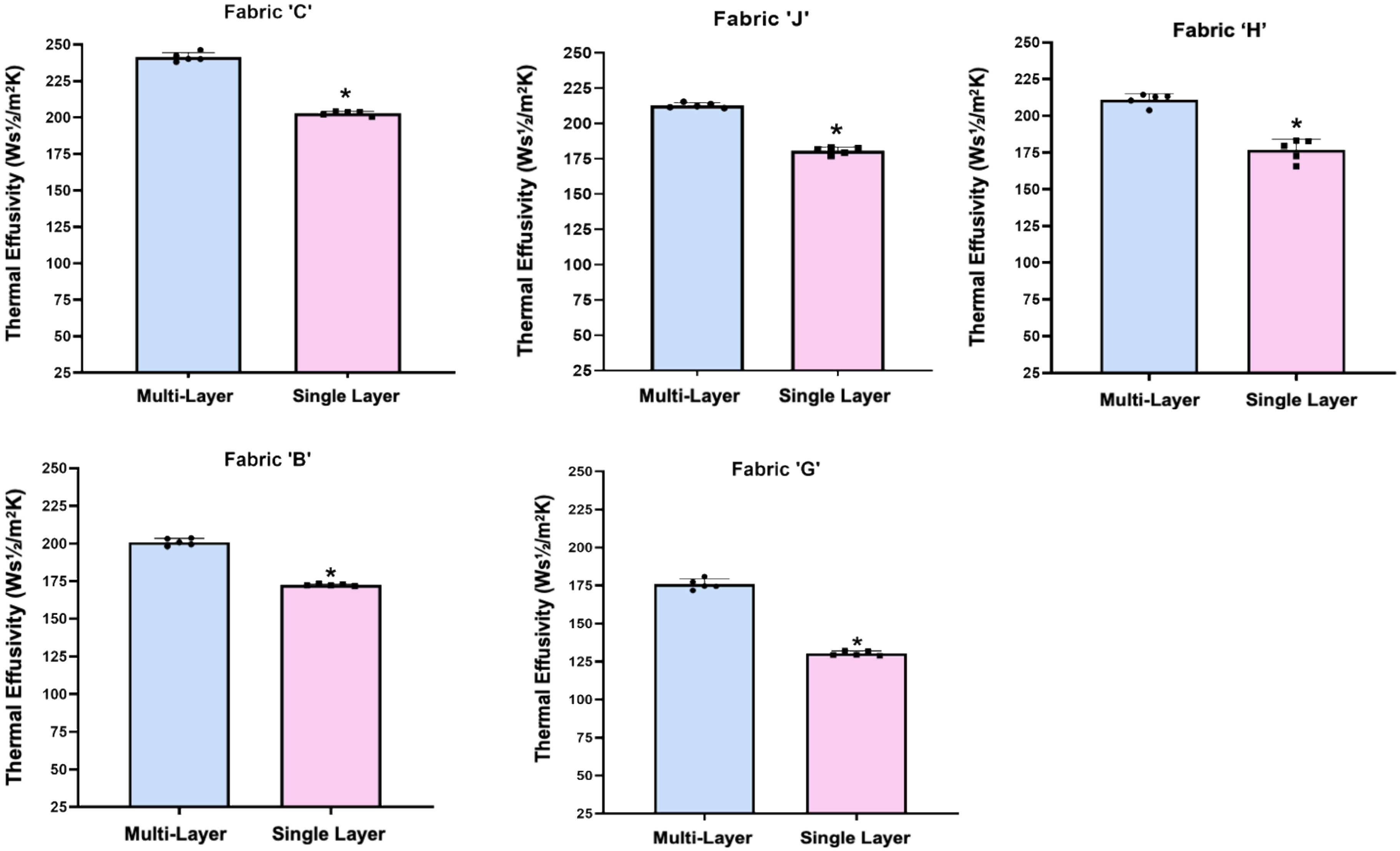


*Figure 4.12: Differences in ε between samples and specimens within each fabric. *, significantly difference to multi-layer sample.*

4.4.7 Agreement Between Single Layers and Multi-Layers

Statistical analysis reported a significant positive correlation between the mean of the single layers and the mean of multi-layer samples in both *k* and *ε* (p<0.0001, figure 4.13A & B, respectively). The Pearson's correlation coefficient was strong with *r* values of 0.961 and 0.958 for conductivity and effusivity, respectively. However, when the relationship is further compared to the line of equality, it shows that the single layer method of measurement consistently underestimates the thermal conductivity and effusivity measurement, compared to the multi-layer measurement method (Figure 4.14 A & B).

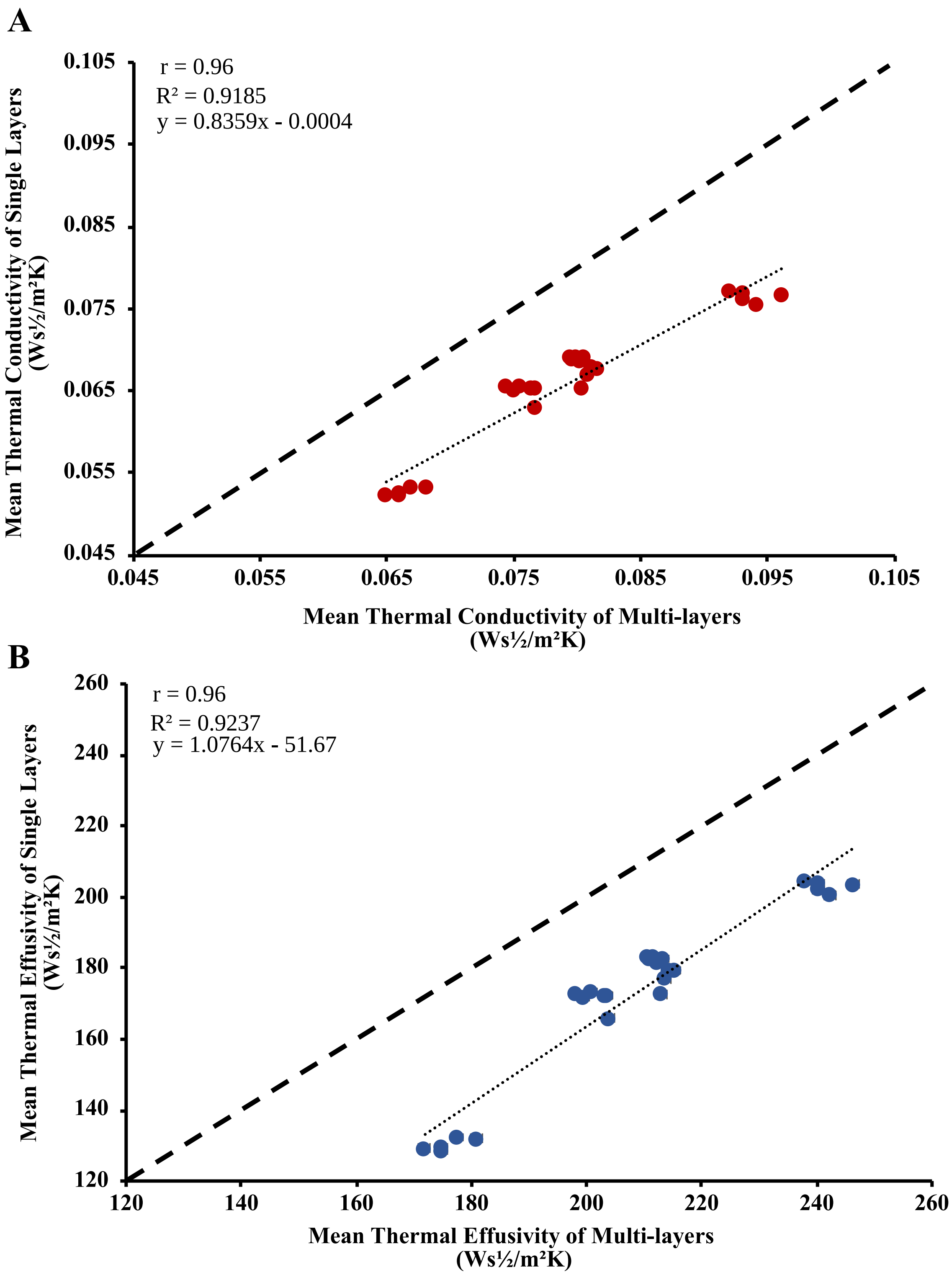
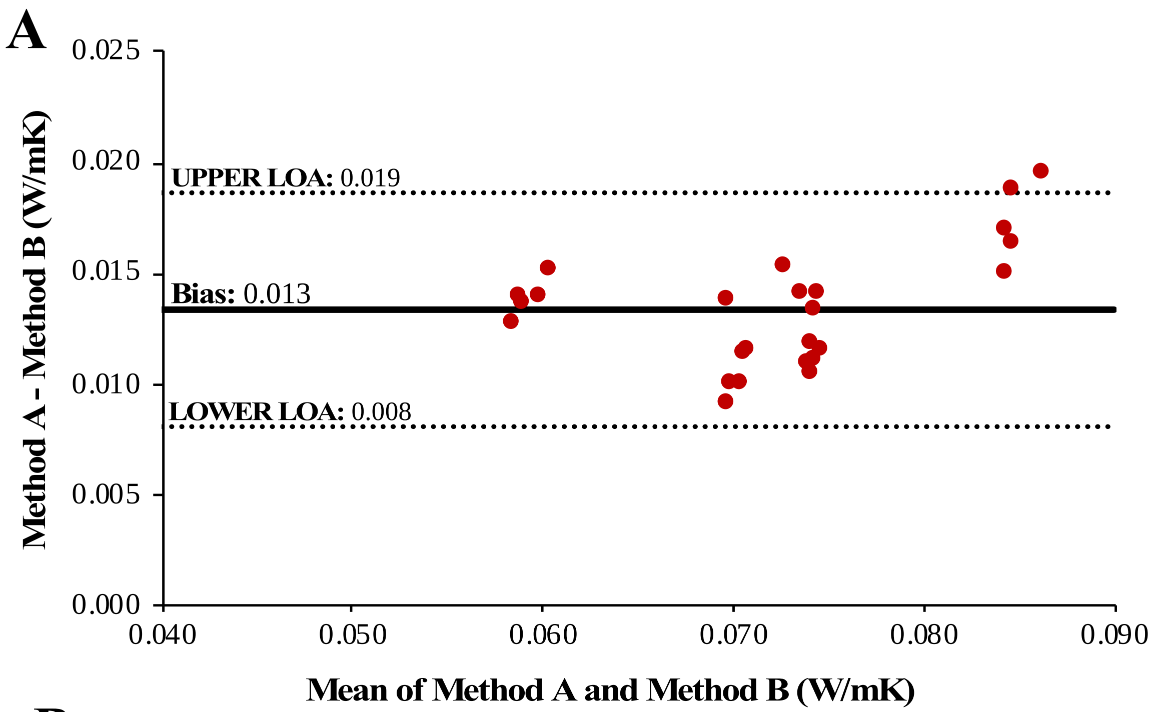


Figure 4.13: A) A significant correlation between mean thermal conductivity of single layers and mean thermal conductivity of multi-layer samples ($p<0.0001$), (B) A significant correlation between mean thermal effusivity of single layers and mean thermal effusivity of multi-layer samples ($p<0.0001$). Line of equality is displayed for reference.



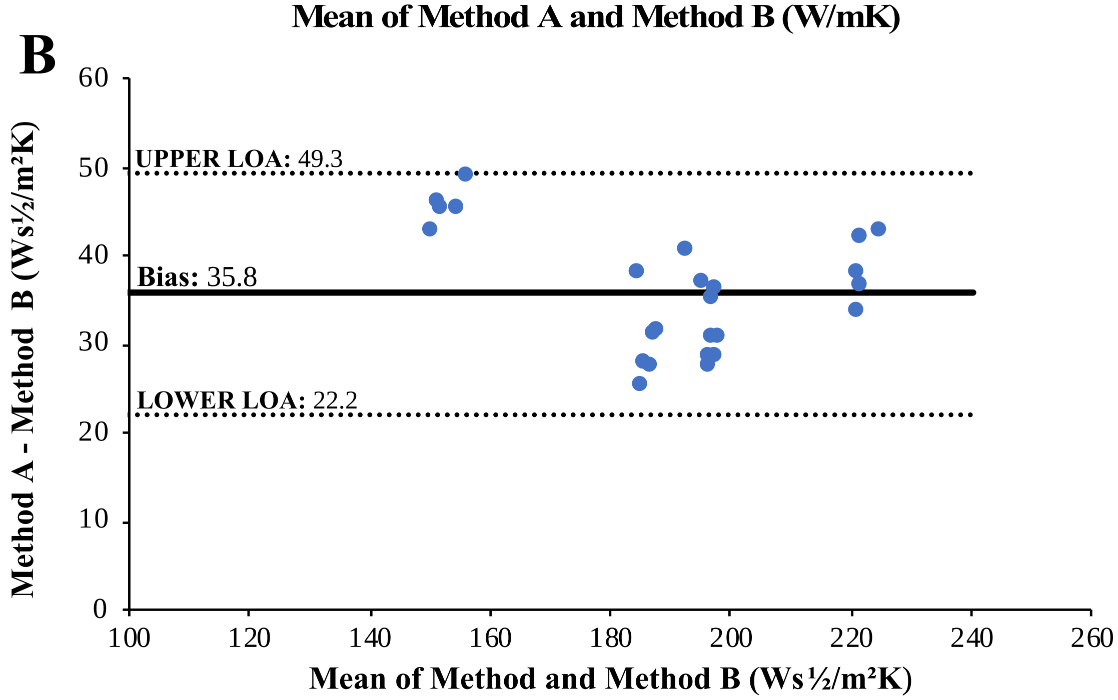


Figure 4.14: Bland-Altman plots displaying the mean difference between mean single layer measurements and mean multi-layer sample measurements against the mean of all measurements in thermal conductivity (A) and thermal effusivity (B). Method A, multi-layer, Method B, single layer.

Results from the Bland-Altman analysis shows there is still a bias and systematic error between the two methods as the data sets do not lie around zero (*k* is 0.013 W/mK and in *ε* is 35.8 Ws½/m^{2}K, figure 4.14 A & B). There are currently no set range limits to quantify acceptable impact this bias in thermal conductivity and thermal effusivity measures between methods and thus, the practical impact must be considered to establish whether one method can still be used instead of the other. These data were thus modelled in a practical application of heat loss at a single point during steady state exercise. Differences between the *k* of the materials was 0.013 W/mK, reflecting the bias. Results show a 2.4% higher dry heat loss in the fabric with the higher thermal conductivity fabric and lower evaporative heat loss is required to attain heat balance (table 4.3).

Table 4.3: Differences in heat loss variables between two fabrics with thermal conductivity values differing by 0.013W/mK.

	Fabric X	**Fabric Y**
Thermal Conductivity (W/mK)	0.0650	0.0780
Thermal Resistance (m^{2}K/W)	0.0154	0.0128
Dry Insulation of Clothing (I_{clo})	0.0993	0.0827
Clothing Area Factor	1.031	1.004
Dry Heat Loss (W)	236	249
Respiratory Heat Loss (W)	75	75
Evaporative Requirement for Heat Balance (W)	583	569
Maximum Evaporative Heat Loss Potential from Skin (W)	210	210

Where the following variables were fixed for both calculations; Body Mass 65kg, Height 1.75m, Whole Body Sweat Rate 17g/min, Ambient and Radiant Temperature 28°C, Relative Humidity 65%, Barometric Pressure 133kPa, Wind Speed 8m·s^{-1}, Oxygen uptake 3.27 l·min^{-1} STPD, Respiratory

Exchange Ratio 0.87, External Work 215W, Mean Skin Temperature 34°C, Emissivity 0.965, Effective Radiative Area 0.715, Evaporative Heat Transfer Resistance 0.018m·kPa·W^{-1}.

Despite this small difference, the multi-layers layers measured consistently higher *k* and *ε* across the range of fabrics measured meaning they cannot be used interchangeably. However, as all data points lie within both the upper and lower limits of agreement for *ε* and all but one data point in *k*, in both single and multi-layer and measurements. This means a linear regression equation calculated from the data in the present study can be used to calculate one value from the other. The regression equations are as follows:

$$\boldsymbol{k} \qquad y = 0.8363x - 0.0003918$$

$$\boldsymbol{\varepsilon} \qquad y = 1.0764x - 51.67$$

4.4 Discussion

The primary aim of the present study was to test the repeatability of both *k* and *ε* measurements in both single and multi-layer samples, using the C-Therm Tx Touch Tester. A secondary aim was to investigate the differences in *k* and *ε* measurement between single layers versus multi-layer samples to find out whether the single layers can be used in place of the multi-layer samples and thus more closely replicate how technical fabrics would be used.

Repeatability of the measurements in single layers was excellent according to the ICC and typical error from 10 single layers. This means that when testing fabrics for an application that requires just a single layer of fabric, such as sports clothing, there no longer needs to be a measurement of multi-layer samples nor the time-consuming measurement of 25+ single layers to gain an ecologically valid and repeatable measure. Although statistically there were differences between some of the multi-layer samples (<3%) and single layers (<5%), the variability was also low. The importance of this kind of characteristic measure is the application for which it is to be used. The variance between the single layers and variance between the multi-layer samples is likely to be due to the difference in thickness of the two methods.

Thus, the hypothesis can be accepted. During measurements of the single layer, the C-Therm is likely to have fully penetrated the fabric and interpreted the k and ε of the ambient air behind the single layer as part of the material. Whereas the thicker multi-layer sample will have prevented the full penetration of the heat pulse, only measuring the fabric. Despite this, it is important to remember the application of the data when identifying differences in measurement methods. Commonly, a value of k is incorporated into an equation that models potential heat storage or heat loss (Fiala et al. 2010; Kopeckova et al. 2021). The high repeatability and low variability using 10 single layers using the C-Therm allows for valid and accurate modelling of the interaction of clothing and the human physiological response to exercise in extreme environmental conditions without having to undertake lengthy protocols to establish a steady-state equilibrium first.

However, the two methods cannot be used interchangeably as measurements produced significant and practical differences. Practically, it would be nonsensical to test a multi-layer sample when you are applying it to a single layer clothing application. However, to initially identify optimal fabrics the multi-layer method could be used followed by the single layer method on the to identify more specific differences that may be observed during material use specifically in a triathlon suit. As the single layer method read consistently lower values, a linear regression could be used to derive a multi-layer measurement from a single layer measurement for the fabrics tested, if needed. For example, if the aim is to compare the k of a fabric from literature that has used the multi-layer method. It must be considered that the limits of agreement and thus interpretation of the results were based on +/- 1.96 x SD. Ideally, more specific limits of agreement would be set based on what is known around the potential impacts of different fabric conductivities on physiology, however little data exists for a definitive limit to be set.

The same investigation of single versus multi-layers should be further researched in fabrics that expand the narrow range of k and ε used in the present study to assess whether the linear relationship observed continues or whether the agreement wavers at higher or lower values. Additionally, within a sporting application, athletes do not always compete in the environmental conditions that were used in the present study. Therefore, it would be more practical to test the characteristics of the fabrics in environments reflecting training or racing conditions, especially if a suit were designed for use in specific environmental conditions.

4.5 Conclusion

In conclusion, the C-Therm device provides a valid measurement of k and ε using both the single layer and multi-layer testing methods. However, the methodology used should be chosen based on the practical application of the data. When measuring the k and ε of a fabric intended to be worn as a single layer on the body, like that in sports clothing, 10 single layers of fabric should be tested as repeatability between measurements using the C-Therm was high and variance was low. Despite there being a strong relationship between the multi-layer and single layer methods, the difference in absolute k and ε measured between the methods has practical implications in terms of body heat loss and therefore, cannot be used interchangeably. However, as the single layer method provided a consistently lower measurement, a liner regression can be used to derive results of one method from the other.

Chapter 5

Aerodynamic and Thermal Characterisation of Performance Fabrics

5 Chapter Summary

The previous chapter aimed to firstly test the repeatability of both thermal conductivity (*k*) and thermal effusivity (*ε*) measurements in both and single layer and multi-layer samples which will also help establish a new standard testing protocol for the measurement of *k* and *ε* in textiles using the C-Therm Tx Thermal Effusivity Touch Tester. Secondly, the study aimed to investigate the differences in *k* and *ε* measurement between single fabric layers versus multi-layer samples and thirdly to find out whether the two methods can be used interchangeably. The results showed good repeatability in the measurement of *k* and *ε* in single layers (ICC > 0.9) and multi-layer methods (ICC > 0.9). Low coefficient of variance was also observed for both single-layers (CV: $k = 2.0 \pm 1.0\%$, $\varepsilon = 2.3 \pm 1.2\%$) and multi-layers (CV: $k = 1.5 \pm 0.5\%$, $\varepsilon = 1.4 \pm 0.5\%$). Thus, when it comes to testing performance textiles, protocols only need to include either a measurement of 10 x single layers or 2 x multi-layer samples due to their high ICC values and repeatability. There were significant differences in *k* and *ε* between single layer and multi-layer measurements in all fabrics, with consistently lower values in *k* and *ε* in single layers versus multi-layers, which were different for each fabric tested. This has been attributed to the complete penetration of the heat pulse through the thin single layer leading to a measurement of air *k* and *ε* which influenced the result. This needs further investigation to help model the impact of air on measurements to see if a correction factor can be applied. Lastly, despite the differences in *k* and *ε*, there appears to be a consistent linear relationship between the single layer and multi-layer readings, despite the different fabrics. Bland-Altman analysis showed the error of measurements were within acceptable confidence intervals meaning that a linear regression can be used on either single layer or multi-layer data to derive one from the other.

This chapter aims to apply this principal by characterising smooth and textured fabrics, in terms of their aerodynamic and thermal properties, for the integration into 4 different tri-suit designs. Using the results from this study, 4 different triathlon suits will be designed for use in half-ironman triathlon. Two 'slow' suits will be made with a matching shoulder fabric that represents riders competing at a speed of ~30-40kmph for their half-ironman bike phase. The first of these 'slow' suits will comprise of the main body fabric characterised as the most aerodynamic (AERO1) and the second suit will comprise of the main body fabric characterised as the most thermally conductive (THERM1). The two 'fast' suits will be made with identical shoulder fabric but will reflect faster riders that compete at ~40-50kmph for their half-ironman bike phase. Again, the first of these 'fast' suits will comprise of the main body fabric characterised as the most aerodynamic (AERO2) and the second suit will comprise of the main body fabric characterised as the most thermally conductive (THERM2). Therefore, to assess the smooth fabrics' potential to dissipate heat away from the body, both k and ε of the fabrics was measured using a C-Therm Tx Thermal Effusivity Touch Tester. Fabrics were cut into 80mm x 80mm squares and layered until the sample reached a thickness of 1mm. The device then sent a heat pulse through the fabric and measured the rate and magnitude of the fabrics response to give results on the k and ε of each fabric to provide information on the most thermally conductive and effusive fabric to incorporate as the main body fabric in the THERM1 and THERM 2 triathlon suits. Textured fabrics used in the shoulder panels of a triathlon suit need to possess specific aerodynamic properties thus, to assess the aerodynamic drag of each fabric, fabrics were mounted onto 2 bespoke made cylinders and placed into a wind tunnel. The testing was undertaken in two different wind tunnels, one at Nottingham Trent University (NTU) and one at the Silverstone Sports Engineering Hub (SSEH). Absolute drag (F_D) and drag coefficient (C_d) were measured at 6, 8, 10, 12, 14, 16, 18, 20 and 22 m/s, which was then repeated in reverse order. These data were then used to inform which fabric was optimal for the 'slow' and 'fast' speeds. This was repeated for the smooth fabrics to identify which had the lowest aerodynamic drag and to inform the main body fabric for the AERO1 and AERO2 triathlon suits. Results showed Fabric 'C' had significantly higher k and ε compared to all other smooth fabrics tested. Wind tunnel testing showed Fabric 'H' to have the lowest aerodynamic drag, despite this not being significant, out of all the smooth fabrics tested. Lastly, the drop in C_d in fabric 'F' and fabric 'I' showed they were the most optimal fabrics for the 'slow' and 'fast' shoulder fabrics, respectively. Hence, the following fabrics were used for the AERO and THERM suits; AERO1: Shoulder = fabric 'F', main body = fabric 'H', AERO2: shoulder = fabric 'I', main body = fabric 'H', THERM1: Shoulder = fabric 'F', main body = fabric 'C', THERM2: Shoulder = fabric 'I', main body = fabric 'C.

5.1 Introduction

The ability to quantify fabric characteristics is of increasing interest and importance in a multitude of areas including engineering, biophysics, thermal physiology and clothing design. Previous consideration has been given to fabric design in the form of compression garments, aerodynamic cycling skinsuits and improved mobility in body suits and wet suits during pool and open water (Ashby et al. 2021; Underwood, Jermy 2011; Dantas De Lucas et al. 2000). However, there is a lack of research investigating the interaction between clothing design, fabric aerodynamics and fabric thermal characteristics and to what degree they influence human physiology. Adopting this three-tiered approach to cycling science could prove extremely beneficial to both cyclists and triathletes.

One way athletes can be supported to maintain sufficient continuous heat dissipation whilst preventing an increase of their position and frontal area to such a degree over the longer distance is by making more informed fabric selections in athlete racing garments. Many triathletes now wear one body suit that is designed to fit and remain in very close contact with the wearer's skin. If the fabric is appropriate, it can successfully wick away sweat and conduct heat away from the skin with the aim to maintain a continuous heat dissipation from the body via the evaporation of sweat. However, many fabrics that are currently integrated into garments are only selected on their aerodynamic properties. The differences in weave and fibre composition of these fabrics may have a profound effect on the physiology of the rider through the prevention of heat loss, modification of skin temperature and thus, potentially core body temperature. The thermal perception and comfort of the fabrics is also an important component to consider during fabric selection as measures of thermal sensation and thermal comfort are reported to be important influencing factors in exercise performance in the heat (Flouris, Schlader 2015). High thermal effusivity gives a quantitative measure of how cool a fabric feels to the touch which provides obvious benefit when exercising in warm or hot conditions. No research has considered the critical three-way interaction between aerodynamics, fabric selection and human thermoregulation. By characterising fabrics, optimising evaporative cooling and maintaining optimal energy balance during the cycling phase of a triathlon, there's potential to increase heat capacity for when athletes then enter the run phase of the triathlon straight off the bike. This becomes especially important when competitions are held in environmentally stressful conditions such as in high ambient temperatures or humidity (Galloway, Maughan 1997; Maughan et al. 2012).

Fabric characterisation, in terms of thermal and aerodynamic properties, can advise what is most suitable for a specific athlete to be wearing based on race type, cycling speed and the ambient conditions to fully optimise performance. There needs to be a greater focus on the interdisciplinary approach to designing suits specifically for an individual, not only centring designs around body shape and TT position for aerodynamic optimisation but also for optimal thermal conductivity, effusivity and perception. The first research question for this chapter asks; Are there measureable differences in thermal conductivity and thermal effusivity in different performance fabrics? Secondly, are there measureable differences in aerodynamic drag in different performance fabrics? Thirdly, can these data inform the design of four triathlon suits suitable for both elite and recreational cycling speeds?

5.1.1 Aim and Hypothesis

The primary aim of this study was to characterise several performance fabrics in terms of both their thermal conductivity, thermal effusivity and aerodynamic drag properties to create four optimal triathlon suit designs suitable for half-ironman distance triathlon at 'slow' (30-40kmph) and 'fast' (40-50kmph) speeds. It was hypothesised there would be measurable differences in the thermal properties of different high-performance fabrics, specifically thermal conductivity and thermal effusivity.

5.2 Methods

5.2.1 Fabric Preparation and Pre-conditioning

Fabrics were left flat for 24-hours prior to cutting, to prevent any wrinkling or warping of the fabric impacting the final fabric structure. Single layers were then hand-cut, with scissors, into 80mm x 80mm squares with no single layer containing the same thread, as specified in ATSM D 1774-04 standard. To control for the impact of environmental temperature and humidity on the transmission of heat and moisture through the fabric samples, environmental conditions were maintained at an ambient temperature of 21 ± 1°C and relative humidity of 65 ± 2% (Kestrel 5400 Weather Station, Kestrel Instruments, Pennsylvania, USA) as required in ASTM D 1776-04. The individual fabric samples were left, test face-upwards, in the controlled environment for 2-hours prior to testing to ensure total temperature and moisture equilibrium was attained before commencing subsequent testing.

5.2.2 C-Therm Calibration

The C-Therm device was calibrated as explained in the previous chapter, section 2.2.2.

5.2.3 Thermal Testing

5.2.3.1 C-Therm Performance Fabric Testing Method

Five smooth, main body fabrics were used for thermal testing provided by HUUB Design. For each performance fabric, multiple 80mm x 80mm single layers were grouped together to make 5 multi-layer fabric samples. Layering, mounting and testing of the fabrics weas undertaken as described in the previous chapter, sections 4.2.1.1 and 4.2.1.2 respectively.

5.2.4 Aerodynamic Testing

5.2.4.1 Wind Tunnel Experimental Set Up

Rough and smooth fabric testing was performed in an open-circuit wind tunnel (VDAS AFI300S Subsonic Wind Tunnel, TecQuipment, Nottingham, UK). Rough fabric testing also took place at the Silverstone Sports Engineering Hub (SSEH) open-circuit wind tunnel (TotalSim Ltd, Northampton, UK). A similar protocol was undertaken in both wind tunnels whereby measurements were recorded at ascending and descending wind speeds. The NTU wind tunnel protocol tested at 8, 10, 12 14, 16, 18 and 20 $m \cdot s^{-1}$ and in the SSEH wind tunnel, tests were completed at 6, 8, 10, 12, 14, 16, 18, 20 and 22 $m \cdot s^{-1}$. This range of speeds aimed to allow for F_D and C_D to be measured across the velocity ranges at which competitive and elite cyclists and triathletes ride at ('slow' (<40kmph) and 'fast' (>40kmph)). Using a multitude of increasing wind speeds also allowed for the identification of the R_e number for each fabric at which a transition of laminar to turbulent flow was observed. Characteristics of both wind tunnels are shown in table 5.1.

Table 5.1: Wind tunnel characteristics at Nottingham Trent University (NTU) and Silverstone Sports Engineering Hub (SSEH).

WIND TUNNEL CHARACTERISTICS	NOTTINGHAM TRENT UNIVERSITY	SILVERSTONE ENGINEERING HUB
Working section (h x w, mm)	300 x 300	500 x 500
Cyclinder Length (mm)	150	500
Cyclinder Diameter (mm)	100	100
Distance from Mesh (mm)	167	UNKNOWN
Clearance from Sides of Working Section (mm)	75	0

5.2.4.2 Cylinder and Windsock Fabrication

The NTU cylinder was bespoke and made using MDF rings that were glued together and sanded down to make one smooth cylindrical shape appropriate for the wind tunnel. The hollow structure allowed for less weight and helped prevent significant oscillation during testing. A hole was made in the middle of the cylinder which allowed for attachment to the 3D printed end that was then fixed onto the bar secured into the balance force transducer of the wind tunnel (figure 5.3). Two small grooves were cut out either side of this hole to allow Allen keys to be slotted in to, once the fabric was on the cylinder, to secure the fabric down during testing and to help maintain tension. This also allowed us to make sure that the fabrics were mounted on the cylinder in the same position each time.

Smooth windsock fabrication involved cutting a 30mm x 150mm rectangle out of each fabric. This was then wrapped around the cylinder and pulled until the fabric was tight until there was no lax creasing in the material but without creating significant stretch or warping of the fabric. The fabric was then held together using ballpoint pins and tacked to hold the fabric together in place. After tacking, tape was used to hold the two pieces of fabric together. Using a needle and thread the socks were hand stitched through the tape and fabric, using 3mm long stiches across the entire width of the fabric and tied off on the back face of the fabric. Any excess fabric was trimmed with scissors to ensure it would not influence the airflow in the wind tunnel during testing. Seams were placed in the same position for every windsock to prevent its position impacting air separation from the cylinder during testing. Windsocks for the SSEH wind tunnel were cut to 500mm width with length dimensions cut to ensure a consistent 5% stretch of all fabrics once placed on the cylinder. Each end of the windsock was held together and secured with zips bonded directly to the fabric.

5.2.4.3 Experimental Protocol

The first fabric was positioned onto the cylinder and mounted onto the metal bar in the working section of the wind tunnel, which was then sealed. The orientation of the cylinder was checked to ensure it was straight as any changes in mounting have the potential to disrupt the flow around the cylinder (figure 5.1).

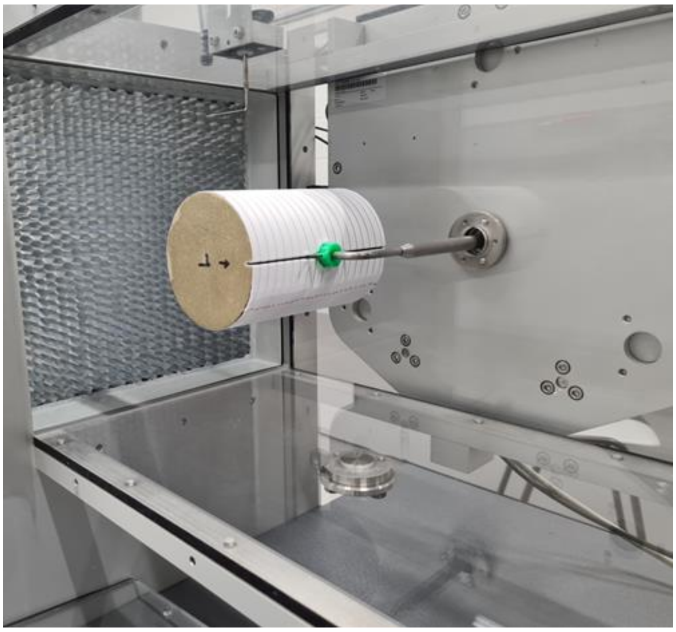


Figure 5.1: Windsock and cylinder mounted in the NTU wind tunnel.

Wind speed in the tunnel was then slowly increased until it reached starting velocity then was left to stabilise for 15 seconds. If, when stabilised, it was not at the correct speed, it was adjusted and again left to stabilise for a further 15 seconds. Once speed was stable, drag force (F_D), drag coefficient (C_d) and wind speed data were recorded, every second, over a 30-second period. Following this 30-second period, wind speed was increased to its next velocity and the protocol was repeated for all other wind speeds as described above. To account for changes in the reliability of the tunnel in measuring these variables at various wind speeds, the protocol was also repeated with descending wind speeds. After completing data recording up to and at 20 $m \cdot s^{-1}$ (NTU) and 22 $m \cdot s^{-1}$ (SSEH) , wind speeds were then reduced by the same increments to 20, 18, 16, 14, 12, 10, 8 and 6 $m \cdot s^{-1}$, depending on the tunnel. A repeat of the first fabric run was undertaken to categorise any shifts in measurements due to air density changes across the session as ambient temperature, pressure or air density fluctuated.

5.2.5 Data Analysis & Statistics

5.2.5.1 C-Therm Testing

The mean and standard deviation of the calibration reference tests was calculated using every thermal conductivity and thermal effusivity values given prior to the testing of all 5 fabrics. Only three out of the four heating-cooling cycles were used to calculate average and standard deviation for both thermal conductivity and thermal effusivity of every multi-layer sample for each fabric. The discarded outlier was identified by finding the average and standard deviation of the three cycles with the most repeatable reading with the smallest standard deviation. For each of the 5 individual main body fabrics, the mean and standard deviation of thermal conductivity and thermal effusivity were calculated. This was conducted using all 15 heat-cooling cycles collected from the 5 samples (3 heat-cooling cycles per sample with 5 samples in total). To ensure there were no violations of the statistical assumptions, tests for normality were conducted using the Shapiro-Wilk test*,* with a confidence interval of 95%. A one-way analysis of variance (ANOVA) was then conducted to analyse the differences between thermal conductivity and thermal effusivity between each of the smooth fabrics. Post-hoc one-way independent samples t-tests were performed, using the Bonferroni correction. In this instance, the acceptable alpha value was changed to 0.01.

5.2.5.2 Wind Tunnel Data

The average and standard deviation for F_D, C_d and wind speed were calculated across the entire 30-second recording period at every wind speed for both ascending and descending runs. Data for the same wind speeds were then averaged together to calculate a single number for each variable at every wind speed. Due to the small number of data points collected for each individual fabric, the number of fabrics and the subsequent multiple comparisons needed to assess differences between the fabrics, no statistical analysis was undertaken on any of the aerodynamic data. Wind tunnel testing aims to identify the R_e at which a drag crisis occurs and how this can impact performance at corresponding R_e numbers.

5.3 Results

5.3.1 Thermal Testing

5.3.1.1 C-Therm

The thermal characterisation of the smooth main body fabrics was taken from the multi-layer data from chapter 4. The differences in thermal conductivity between individual smooth fabrics are displayed in figure 5.2. Analysis of the smooth fabrics data show thermal conductivity was significantly higher in the fabric 'C' compared to all 4 other smooth fabrics (p<0.001). The fabric 'J' and fabric 'H' fabrics had significantly higher thermal conductivity values than both fabric 'B' and fabric 'G' (p<0.001) with fabric 'B' displaying a higher thermal conductivity than fabric 'G' (p<0.001). There was no significant difference between fabric 'J' and fabric 'H'.

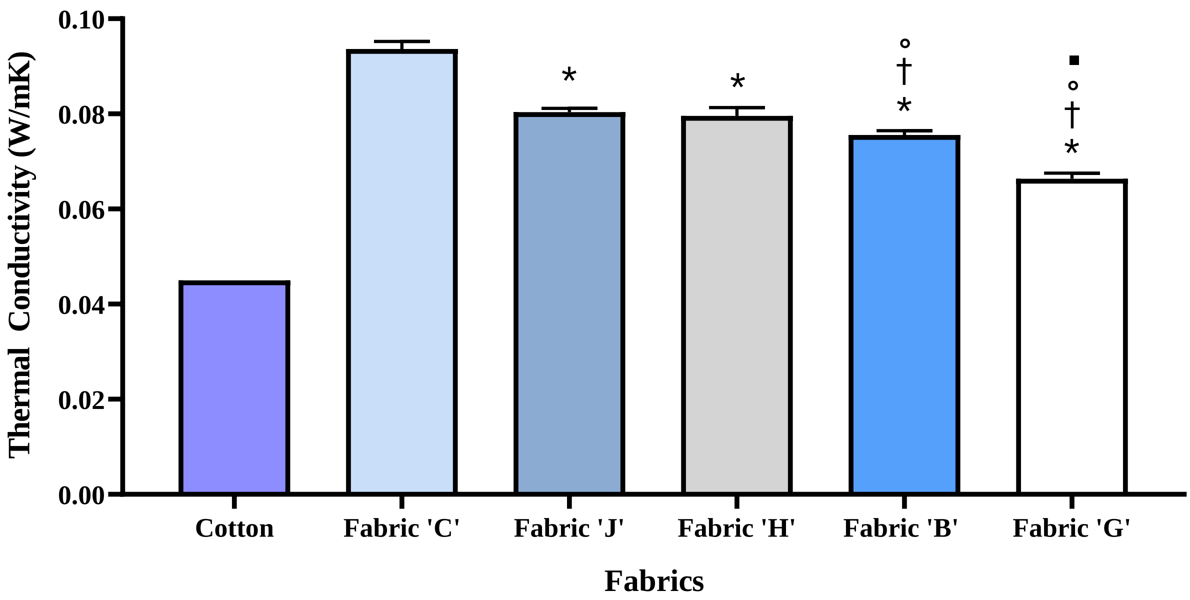


Figure 5.2: Thermal conductivity of the 5 different smooth fabrics; (, sig. different to fabric 'C'; †, sig. different to fabric from 'J'; °, sig. different to fabric 'H'; ■, sig. different to fabric 'B'; all p< 0.001).*

The differences in thermal effusivity mirrored those seen in thermal conductivity and are displayed in figure 5.3. Thermal effusivity was significantly higher in fabric 'C' compared to all 4 other smooth fabrics (p<0.001). Fabric 'J' and fabric 'H' had significantly higher thermal effusivity values than both fabric 'B' and fabric 'G' (p<0.001) with fabric 'B' displaying a higher thermal effusivity than fabric 'G' (p<0.001). There was no significant difference between fabric 'J' and fabric 'H'.

Based on these thermal data, fabric 'C' was selected as the main body fabric for the thermally optimised suit (figure 5.8, THERM1, figure 5.9, THERM 2).

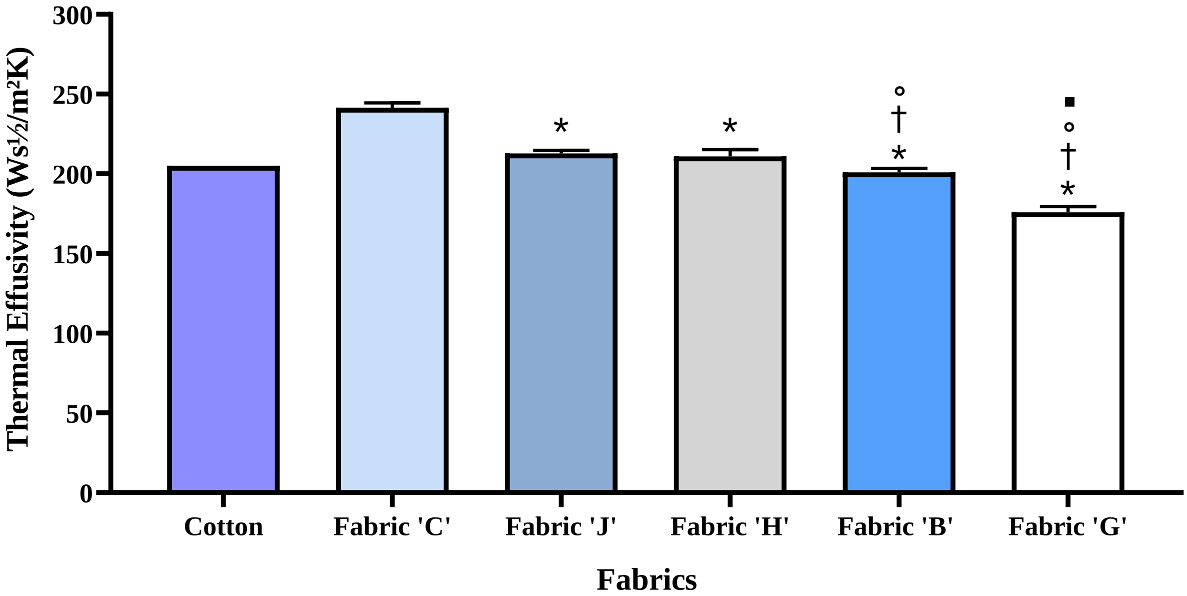


Figure 5.3: Thermal effusivity of the 5 different smooth fabrics; (, sig. different to fabric 'C'; †, sig. different to fabric from 'J'; °, sig. different to fabric 'H'; ■, sig. different to fabric 'B'; all p< 0.001).*

5.3.2 Wind Tunnel

5.3.2.1 Changes in Drag Coefficient for Smooth and Rough Fabrics

Data from the NTU wind tunnel for smooth fabrics is shown in figure 5.4. At 8 $m \cdot s^{-1}$, fabric 'H' had the lowest mean C_d at 0.83 ± 0.04 compared to all other fabrics. This was also seen at 10 $m \cdot s^{-1}$ where C_d in fabric 'H' was 0.72 ± 0.03. Following this at 12 $m \cdot s^{-1}$, fabrics 'C', 'J' and 'B' have a very similar C_d at 0.71 ± 0.03, 0.70 ± 0.02 and 0.69 ± 0.03 respectively. At this same speed, as a larger drop in C_d is observed in fabric 'G' to 0.65 ± 0.02 with fabric 'H' still possessing the smallest C_d at 0.58 ± 0.02. As wind speed is increased to 14 $m \cdot s^{-1}$, C_d continues to drop in all fabrics with fabric 'H' reducing to 0.48 ± 0.01, 'G' to 0.54 ± 0.01, 'J' to 0.59 ± 0.01,'B' to 0.59 ± 0.02 and C to 0.62 ± 0.03. At 16 $m \cdot s^{-1}$, C_d starts to level out for fabrics 'H' and 'G' as they draw closer to the values seen in the other three fabrics that have maintained a very similar C_d throughout. By 18 $m \cdot s^{-1}$, there is very little difference between the fabrics. Fabric 'H' and 'B' sees little change compared to their C_d at 16 $m \cdot s^{-1}$ as they obtain their lowest C_d (0.44 ± 0.01 and 0.50 ± 0.01, respectively). At 20 $m \cdot s^{-1}$, an increase in C_d is observed for fabrics 'H' to 0.46 ± 0.01 and a plateau observed for fabric 'B. Fabrics 'J' and 'C' continue to decrease to reach a similar C_d (0.44 ± 0.01 and 0.48 ± 0.01, respectively) to that of 'G' and 'H'. Although no drag crisis was observed in the NTU wind tunnel for smooth fabrics, within both the 'slow' and 'fast' cycling speeds of interest, these data show fabric 'H' has a consistently lower C_d than all other fabrics tested and will be the selected main body fabric for the aerodynamic suit design (figure 5.8 AERO1, figure 5.9 AERO2).

Data on the rough fabrics in the NTU wind tunnel are displayed in figure 5.5. Much like the smooth fabrics, it is hard to identify any specific drag crisis. In fabrics 'F', 'D' and 'I', a gradual increase in C_d is observed with increasing Re number starting at C_d of 0.76, 0.62 and 0.55 at 8 $m \cdot s^{-1}$ to 0.90, 0.83 and 0.73 by 20 $m \cdot s^{-1}$, respectively. A different trend is observed in fabric 'A' where there is a continuous, gradual decrease in C_d from 0.90 at 8 $m \cdot s^{-1}$ to its lowest at 20 $m \cdot s^{-1}$ of 0.46. There appears to be a drop and plateau in C_d between 10 and 12 $m \cdot s^{-1}$ in fabric 'E' to its lowest C_d of 0.55 at 12 $m \cdot s^{-1}$. This is the lowest C_d of any of the rough fabrics within the speeds of interest. However, it is difficult to make any specific conclusion on the aerodynamic characteristic of the rough fabrics as the results are not uniform suggesting there are inconsistencies in flow over the cylinder between the fabrics. Thus, it may be useful to compare the data from the NTU wind tunnel to the SSEH wind tunnel to see if they yielded similar results.

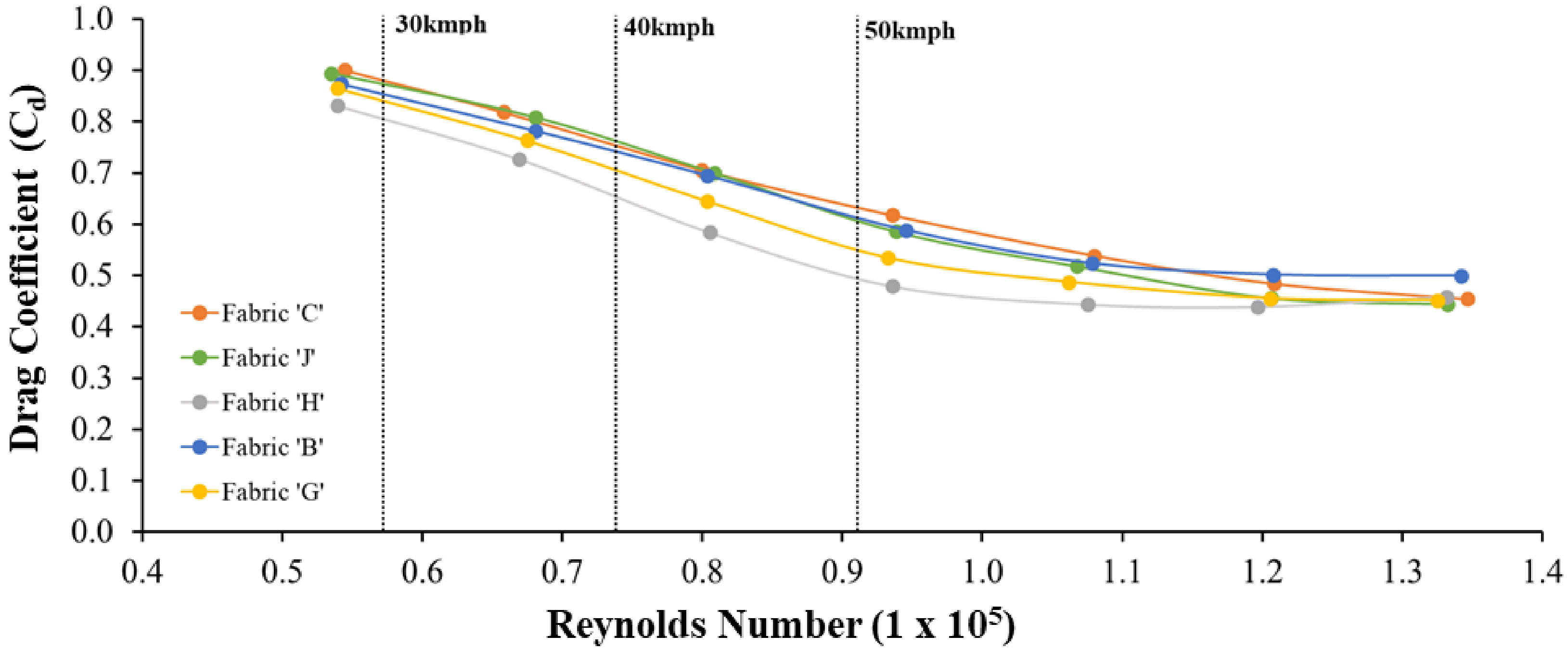


Figure 5.4: Drag coefficient changes of smooth main body fabrics with increasing Re number in the NTU wind tunnel.

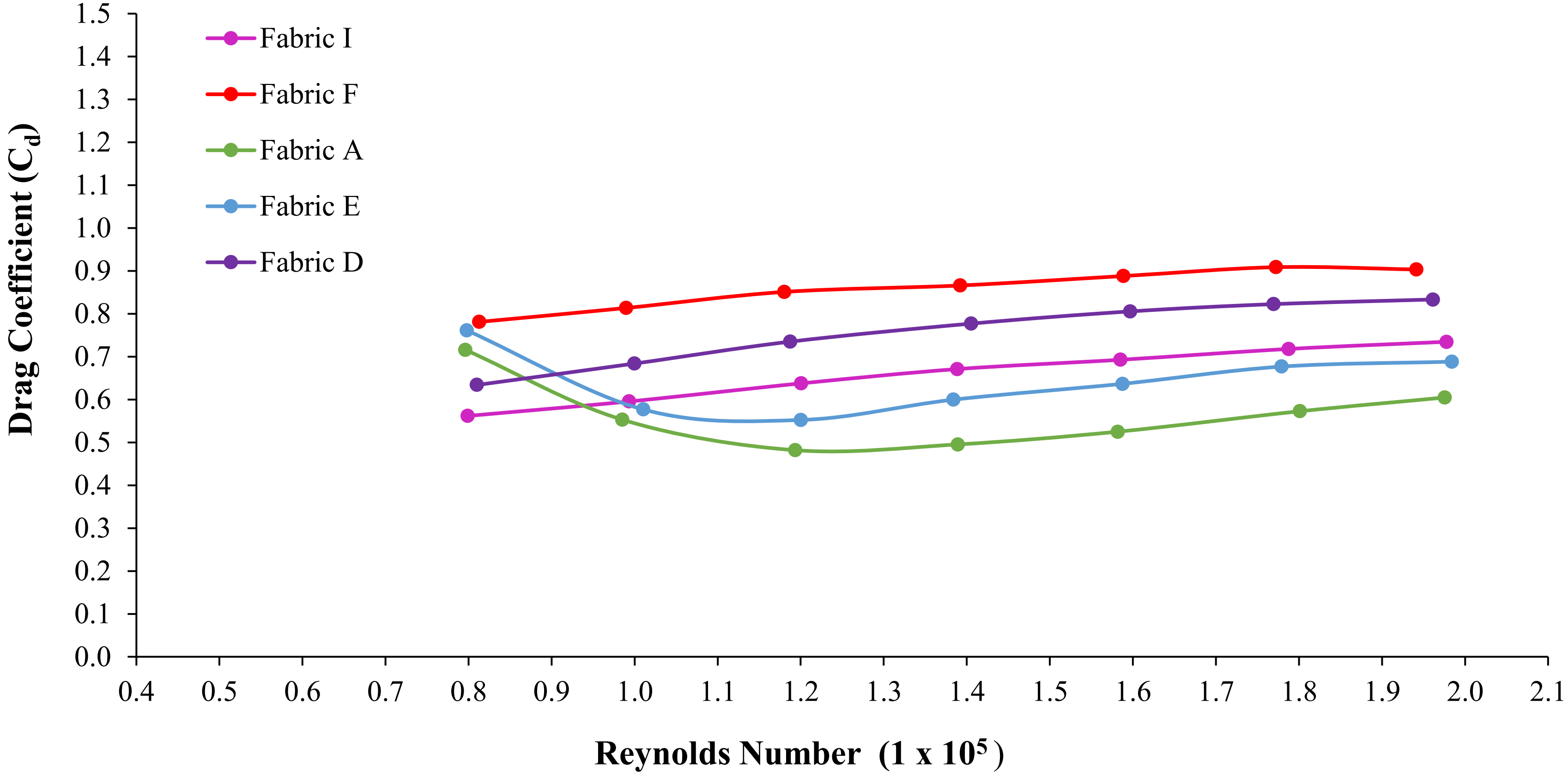


Figure 5.5: Drag coefficient changes of rough shoulder fabrics with increasing Re number from NTU wind tunnel.

Upon comparison of these rough shoulder fabric data in the NTU wind tunnel compared to the SSEH wind tunnel, there were apparent differences in C_d (figures 5.6 and 5.7, split for clear presentation). For the same fabrics and matched R_e number, the SSEH wind tunnel was able to identify a drag crisis that lay within the cycling speeds of interest in four of the five fabrics used in the present study. Unfortunately, there is no SSEH wind tunnel data for fabric 'E'.

In figure 5.6A, there does not appear to be a clear drag crisis occurring in any rough fabrics tested in the NTU wind tunnel. The lowest C_d attained for fabric 'A' was 0.48 which was not reached until a wind speed of 12 $m \cdot s^{-1}$ at the R_e of 1.19. This is equivalent to ~43kmph, just within the 'fast' range. The lowest C_d for fabric 'D' was observed just below the 'slow' speed range, at ~29kmph / 8 $m \cdot s^{-1}$. Here, the C_d was 0.63 at an R_e of 0.70, increasing concomitantly with air speed.

In figure 5.6B, there are more clear drops in C_d in the SSEH wind tunnel. Fabric 'A' did not reach drag crisis until 20$m \cdot s^{-1}$ / ~72kmph which is out of the appropriate range for the present study. The lowest C_d of 0.4 was attained at 22 $m \cdot s^{-1}$ / ~79kmph at an R_e of 1.41. Fabric 'D' attained the lowest C_d of 0.69 within the 'fast' speed range at 12 $m \cdot s^{-1}$ / ~43kmph at an R_e of 0.82.

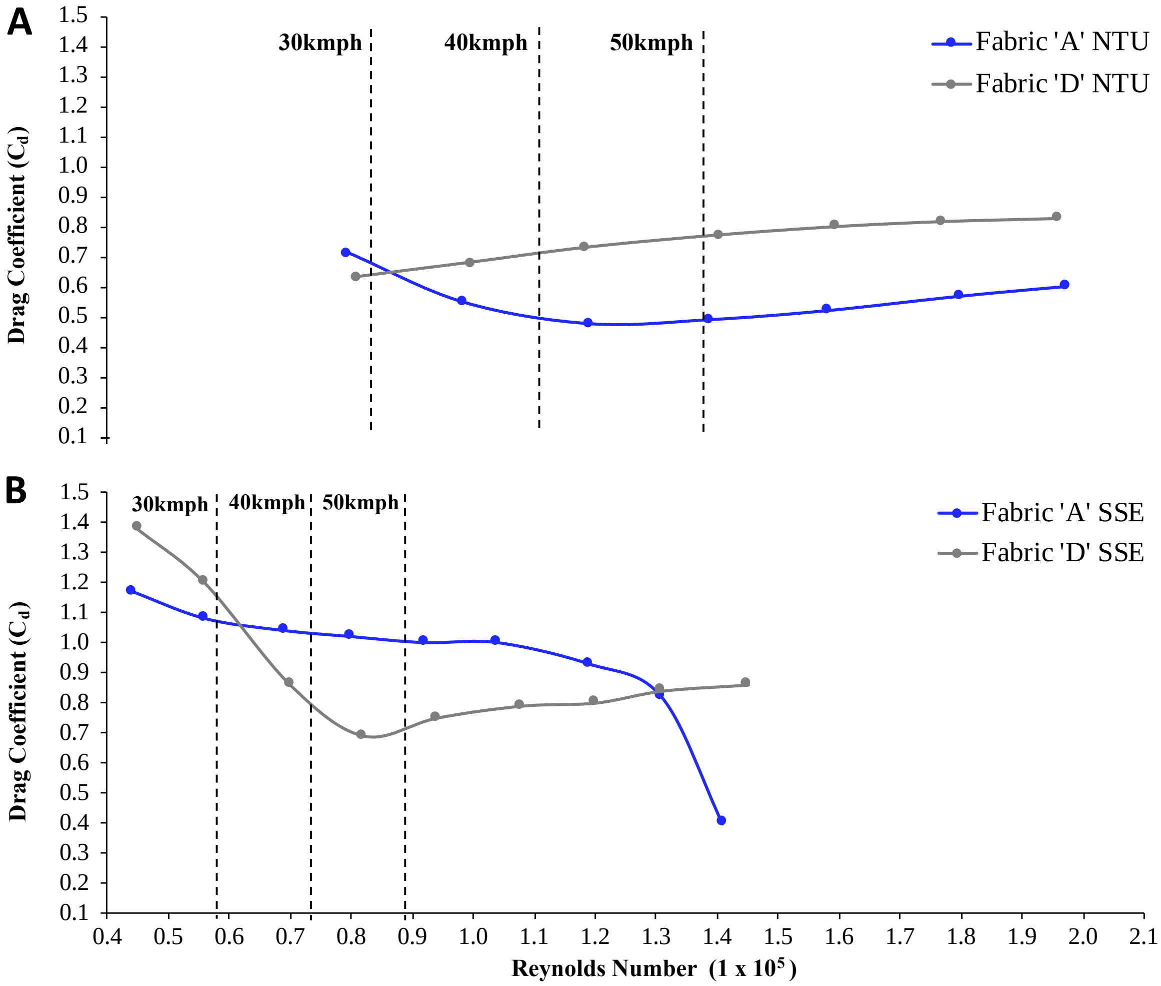


Figure 5.6: Drag coefficient changes of rough shoulder fabrics 'A' and 'D', with increasing Re number from NTU (A) and SSE (B) wind tunnels.

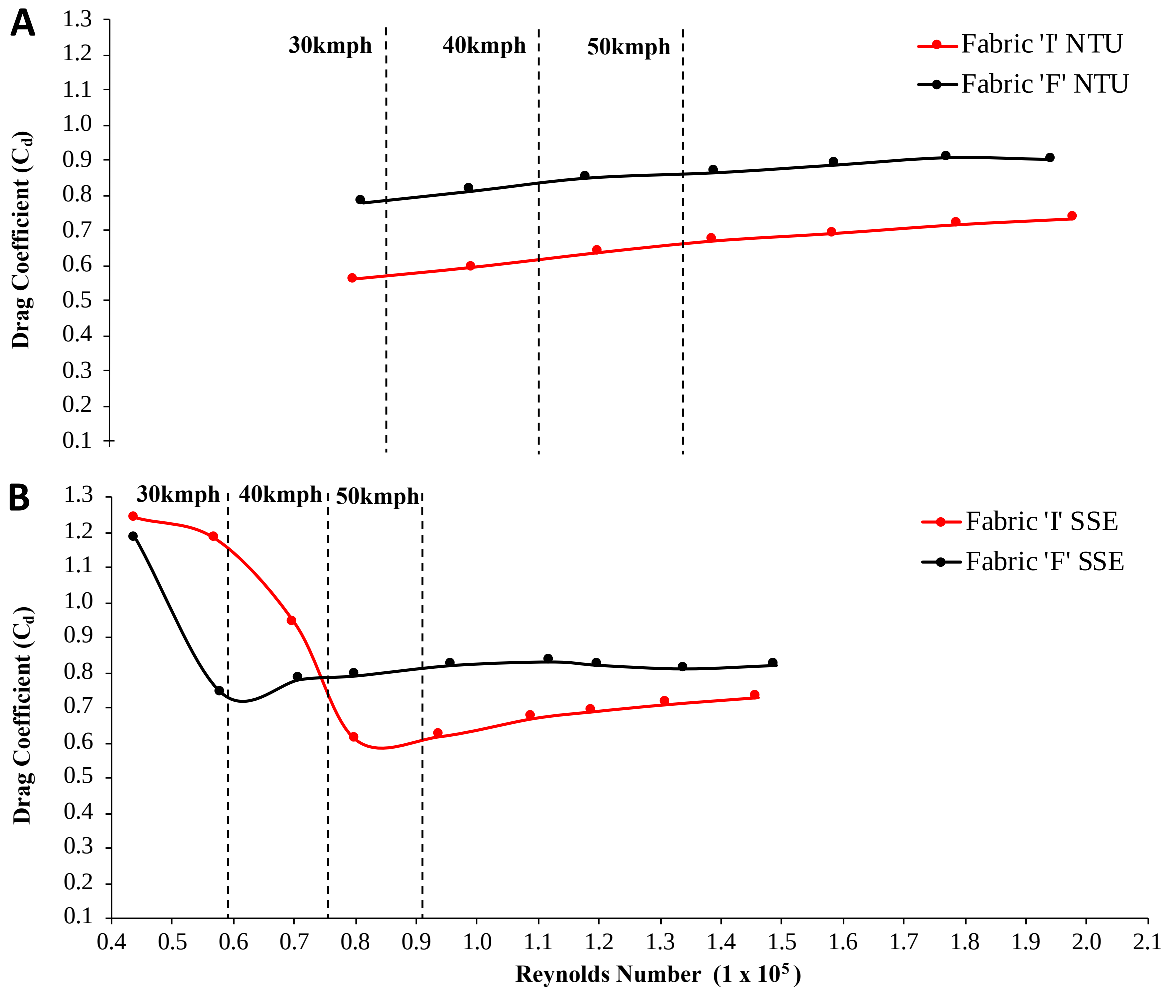


Figure 5.7: Drag coefficient changes of rough shoulder fabrics 'I' and 'F', with increasing Re number from SSE and NTU wind tunnels.

Data for fabrics 'I' and 'F' in figure 5.7A, from the NTU wind tunnel shows no significant drag crisis. The lowest C_d was 0.56 in fabric 'I' at 8 $m \cdot s^{-1}$ / ~29kmph. Within the 'slow' and 'fast' speed ranges at ~36kmph and ~43kmph, fabric 'I' had the lowest C_d of 0.60 and 0.64, respectively.

Comparing this to data from the SSEH wind tunnel (figure 5.7B), there is again a more clear drag crisis point. Fabric 'F' displays the lowest C_d across the 'slow' speed range with a C_d of 0.74. This makes it the most appropriate shoulder fabric to be incorporated into the 'slow' triathlon suit design (figure 5.8, AERO1 & THERM1). For the 'fast' speeds, ~40-50kmph, the significant drop in C_d was observed in fabric 'I' to 0.61 at 12 $m \cdot s^{-1}$. As the C_d for this fabric is lower than that attained by fabric 'D', this fabric will be incorporated as the shoulder fabric for the ‘fast’ triathlon suit design (figure 5.9, AERO2 & THERM2). When comparing the data from the two wind tunnels, despite there being no drag crisis in the NTU wind tunnel data, the C_d achieved are similar, but occurs at different Reynolds numbers.

5.3.2.2 Triathlon Suit Design

Based on the data above, four triathlon suit designs have been created. One triathlon suit for triathletes that ride at ~30-40kmph (‘slow’) and another for those that ride at ~40-50kmph (‘fast’). Two suits will be designed for each speed range, one incorporating the more aerodynamic fabric (AERO) and one incorporating the thermally optimised fabric (THERM). Suit designs and fabrics selected are shown for the ‘slow’ and ‘fast’ triathlon suits in figures 5.8 and 5.9, respectively.

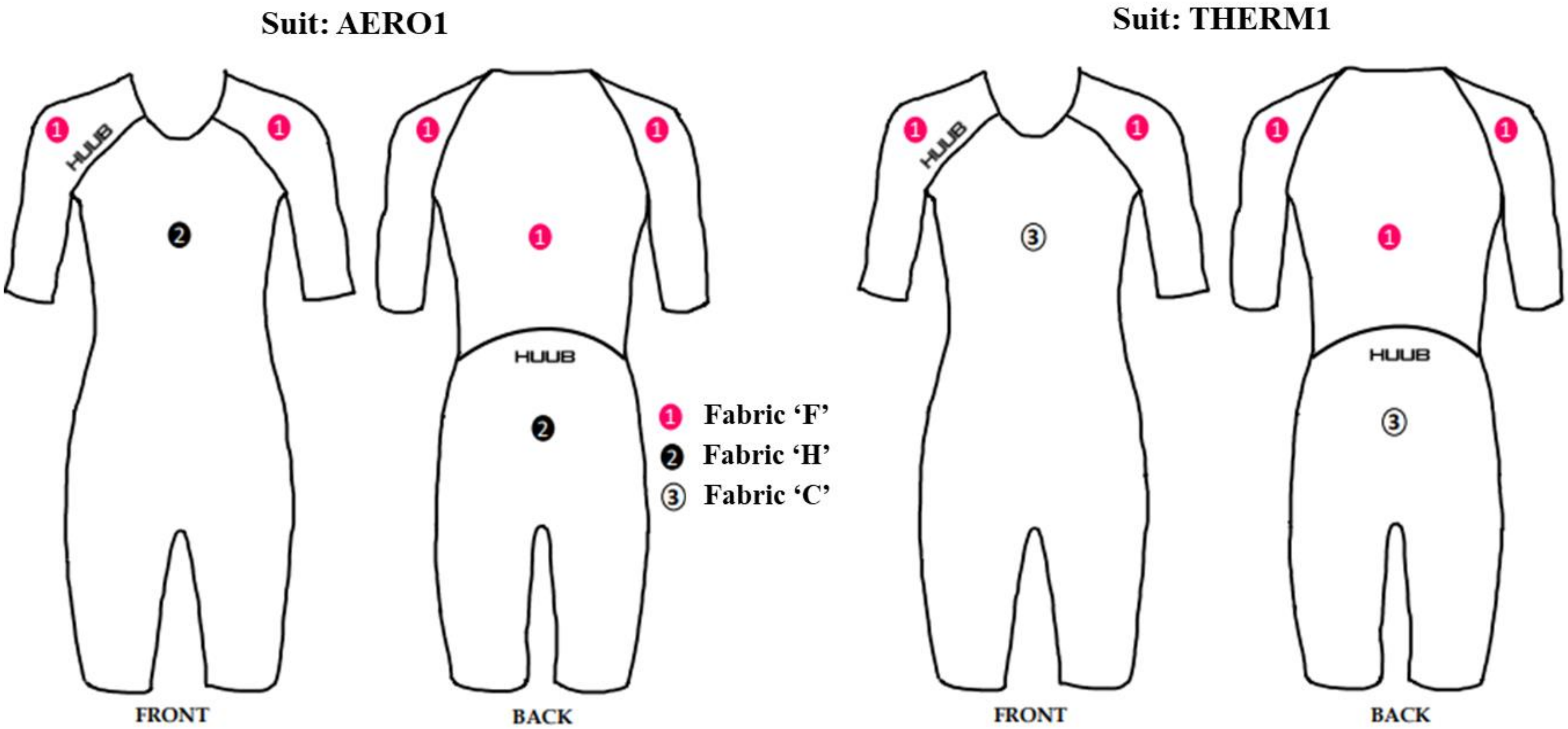


Figure 5.8: Final 'slow' triathlon suit design optimised for wind speeds ranging from ~30-40kmph.

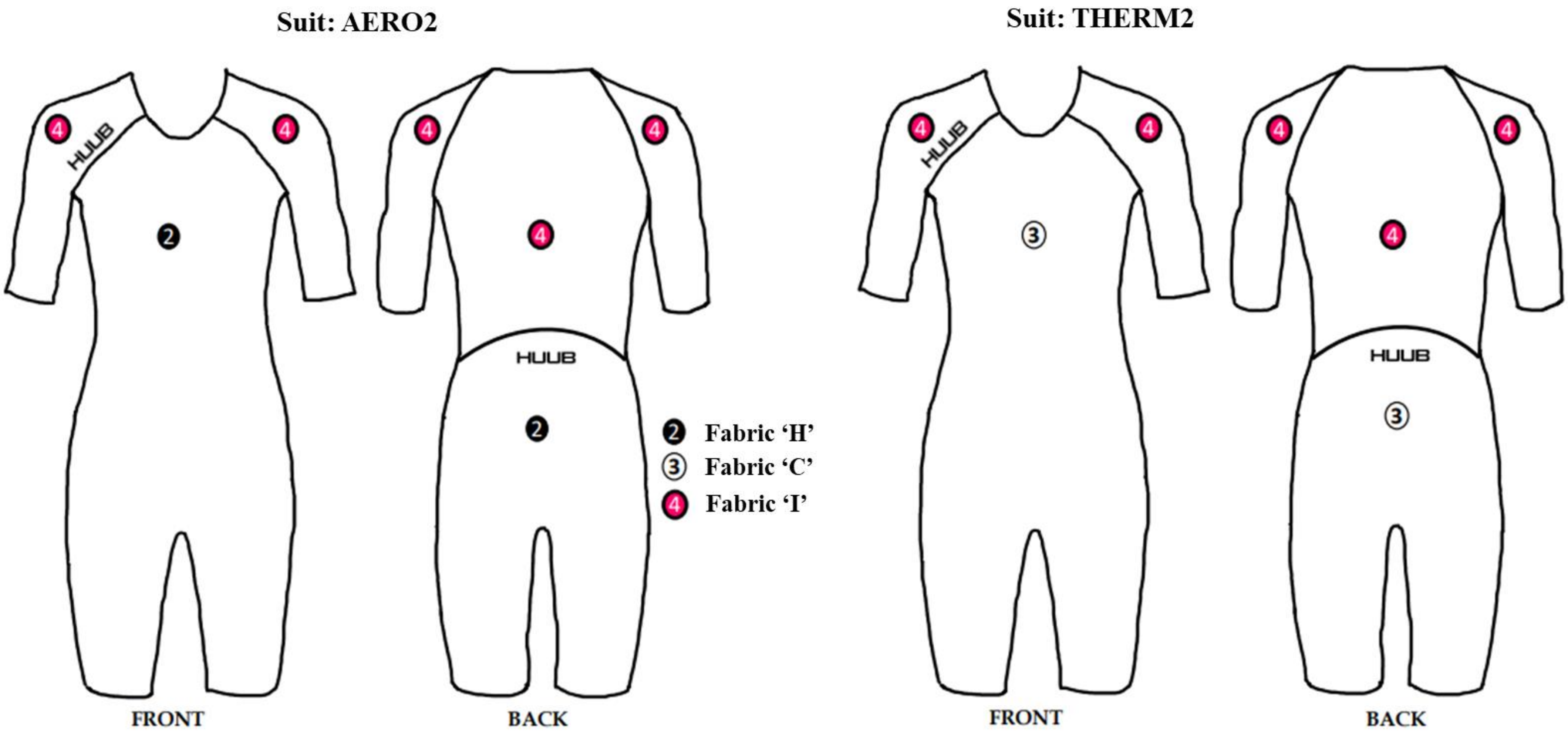


Figure 5.9: Final 'fast' triathlon suit design optimised for wind speeds ranging from ~40-50kmph.

5.4 Discussion

The aim of the present study was to characterise and investigate the differences between fabrics, in terms of their aerodynamic and thermal characteristics with the intention of designing four different tri-suits suitable for a half-ironman distance triathlon. Data from thermal testing revealed fabric ‘C’ possesses the highest thermal conductivity and effusivity when compared to all 4 other fabrics. Data from the aerodynamic testing shows fabric ‘H’ has the lowest C_d, compared to all other smooth fabrics, within both the ‘slow’ (~30-40kmph) and ‘fast’ (~40-50kmph) speed ranges of interest. Data from the rough fabrics revealed fabric ‘F’ to have the lowest C_d within the ‘slow’ speed range and fabric ‘I’ in the ‘fast’ speed range. Thus, the design of four triathlon suits have been created for different speeds, two aerodynamically optimised (figure 5.8 AERO1, figure 5.9 AERO2) and two thermally optimised (figure 5.8 THERM1, figure 5.9, THERM2).

5.4.1 Thermal Conductivity & Thermal Effusivity

The data clearly identifies that fabric ‘C’ possesses the highest ability to conduct heat away from the body whilst also maintaining the coolest feel to the wearer. This means it could be of significant benefit to athlete heat management and thermal perception during exercise in the heat when incorporated into a triathlon suit. A 1mm thick sample of fabric ‘C’ had a thermal conductivity of 0.091w/mK has similar thermal conductivity to a 90% polyester, 10% elastane mix of 0.096 W/mK, recorded by Atalie et al. (2021). Unfortunately, there is no data supporting how these small differences in thermal conductivity between sports fabrics may affect thermal sensation and comfort during exercise. However, the conductive heat loss attained from using fabric ‘C’, compared to one with a lower conductive potential could mean, over the period of a half-ironman, athletes may maintain lower skin temperatures, a higher skin-to-core temperature gradient and more continuous loss of heat throughout competition. This wider skin-to-core gradient, rather than an absolute critical core temperature, has proven to be a primary influence on aerobic capacity in the heat (Cuddy et al. 2014). Research also reports an earlier onset of lactate threshold in hot conditions due to increased body temperature (Papadopoulos et al. 2008).

Therefore, lower skin temperatures may allow athletes to maintain a higher exercise intensity for a longer period when wearing fabric 'C' compared to a fabric with less thermally conductive potential. Even if the fabric conductivity is not enough to preserve a large skin-to-core gradient, it may still be beneficial in terms of thermal comfort. Even if it does not provide significant skin cooling, the cooler touch of the more effusive fabric may provide a beneficial improvement to overall thermal sensation and comfort. Improved performance time trial times have been found using non-thermal cooling techniques using menthol in the elite population (Barwood et al. 2015; Riera et al. 2014; Gillis et al. 2016) and a similar improvement may be found using more 'cool touch' effusive fabrics.

It is difficult to define a single reason why fabric 'C' possessed a higher potential for heat transfer compared to other fabrics as there are many characteristics that influence a fabric's capacity to conduct heat. Many textile variables need to be considered during fabric selection, some including air permeability, mass density, fabric thickness, loop length, yarn count, yarn structure, yarn weave, fabric mix composition, specific heat capacity, fabric tension, wicking ability, evaporative resistance, fit and temperature (Shen et al. 2019; Siddiqui, Sun 2018). However, four major factors reportedly influence both conductivity and effusivity of a material to the largest extent: temperature, moisture content, density and environmental temperature (Hung Anh, Pásztory 2021). In the present study, the pre-conditioning of the fabrics prior to testing with the C-Therm controlled for both the fabric temperature and moisture content by creating an equilibrium which was replicated across every fabric testing session. Values of conductivity and effusivity were also normalised to a standard 1mm thickness, suggesting that in this instance, fabric density was probably the most influential factor determining the conductivity and effusivity measures. Lower density of a fabric increases its thermal conductivity resulting in a larger capacity for heat exchange (Afzal et al. 2017) and may be the reason for the result in the present study. Unfortunately, there is no density data available to confirm this hypothesis. Further to this, when a fabric possesses multiple beneficial characteristics, the characteristic potential does not always work in an additive fashion but rather, synergistically (Yu et al. 2016). Furthermore, what is not yet clear is whether these differences in thermal conductivity and effusivity between all smooth fabrics in the present study are enough to see a physiological difference and should be the focus of future research. It would also be beneficial to measure the thermal conductivity and effusivity in conditions that reflect those of a racing environment to investigate whether any differences observed in these variables would be large enough to impact skin and body temperature further.

5.4.2 Aerodynamics

Upon initial glance at the smooth fabric wind tunnel data, it appears the airflow stays laminar as it flows over the cylinder as there is no apparent drag crisis. However, when comparing these data to literature, drag crises in smooth fabrics are observed at much higher R_e numbers (Oggiano et al. 2007) and upon transition to turbulent flow then sees C_d values like those observed in the NTU wind tunnel. This suggests that the flow over the cylinder in the NTU wind tunnel when testing smooth fabrics was not laminar and is only measuring the C_d of turbulent flow over the cylinder. This is probably due to the oscillation of the wide and short cylinder in the working section as well as the interaction between the airflow, cylinder and the walls of the compact working section. Even if the NTU wind tunnel had the capability of reaching large enough R_e numbers to observe a drag crisis in the smooth fabrics, the R_e numbers and air speeds at which the airflow over a smooth fabric transitions to turbulent is generally much higher than anything that is relevantly applicable in a half-ironman triathlon and crisis' exceeding 55kmph will generally be of little use. It may however be useful for track cycling where cycling speeds can reach over 57kmph for an individual pursuit. Although the diameter of the cylinders in both wind tunnels were the same, the lengths were different as the NTU cylinder did not span the entire width of the tunnel like that in SSEH. This means there is more potential for air turbulence around the sides of the cylinder. This airflow is likely to then interact with the boundary layer and airflow around the walls of the tunnel and is probably one of the primary reasons causing the discrepancy in data. Further to this, the size of the wind tunnel working section compared to the cylinder size would also impact the potential for unwanted turbulence to occur as creating a steady free stream of laminar airflow in a smaller working area is difficult. So, although the NTU wind tunnel provides an idea of the C_d, similar to those observed at SSEH, it does not identify at which speed or R_e number the drag crisis occurs which is the critical piece of information needed when trying to apply it to designing triathlon or cycling suits for riders. Further investigation identifying the impact of a cylinder in the NTU wind tunnel, changing the aspect ratio of the cylinder and ensuring it spans the width of the tunnel. Additionally, incorporating a splitter plate in front of and behind the cylinder to encourage more laminar flow leading up to the cylinder and also to prevent vortex shedding in the wake of the cylinder (Igbalajobi et al. 2013).

5.5 Conclusion

Data from the present study has permitted the design of four triathlon suits, one aerodynamically optimised and one thermally optimised for both 'slow' speeds of ~30-40kmph and 'fast' speeds of ~40-50kmph. The data from the present study needs to be further tested in human subjects to observe whether the conductive and effusive differences between fabric 'H' and fabric 'C' are large enough to influence thermoregulation in a more practically applicable setting to identify whether the data translate to a whole-body laboratory or field setting. The same needs to be investigated in terms of the aerodynamics of each main body fabric intended to be used in the triathlon suits. The investigation of both the thermal and aerodynamic practical application of these data collected in the present study will be experimentally tested in the following chapters.

Chapter 6

Differences in Thermo-physiological and Perceptual Responses to Aerodynamically Optimised and Thermally Optimised Triathlon Suits During Prolonged Steady-State Exercise in the Heat

6 Chapter Summary

The previous chapter aimed to characterise different fabrics in terms of both their thermal and aerodynamic properties to create four optimal triathlon suit designs suitable for a triathlete to wear during a half-ironman. Data from thermal testing revealed fabric 'C' possesses the highest thermal conductivity and effusivity when compared to all 4 other fabrics. Data from the aerodynamic testing shows fabric 'H' has the lowest C_d, compared to all other smooth fabrics, within both the 'slow' and 'fast' speed ranges of interest. Data from the rough fabrics revealed fabric 'F' to have the lowest C_d within the 'slow' speed range and fabric 'I' in the 'fast' speed range. Thus, the design of four triathlon suits have been created for different speeds, two aerodynamically optimised and two thermally optimised. Although results showed significant differences in both thermal and aerodynamic properties between the fabrics tested, it is important to assess whether these differences translate into a physiological impact on a whole-body level. Therefore, this chapter aims to investigate the differences in thermoregulatory and perceptual responses to aerodynamically (AERO) and thermally (THERM) optimised triathlon suits during steady-state exercise in the heat. Participants undertook 2 hours of sub-maximal cycling exercise in an ambient temperature of 28°C and 65% relative humidity. Heat rate (HR), mean skin temperature ($\bar{T}_{sk}$), gastro-intestinal temperature (T_{gi}), oxygen uptake ($\dot{V}O_2$) and perceptual measures of perceived exertion (RPE), thermal comfort (T_{comf}), thermal sensation (T_{sens}) and skin wetness (w_{per}) were measured every 5 minutes throughout the entire exercise protocol. Based on the data collected in the previous chapter, two triathlon suits were fabricated to be tested in the present

study. Suit 1 (AERO1) was aerodynamically optimised with its main body fabric being made up of the fabric possessing the lowest drag from wind tunnel testing. Suit 2 (THERM1) was thermally optimised, and the main body fabric of the suit was made using the most thermally conductive fabric highlighted from the C-Therm data. The shoulder fabrics incorporated in both suits were the same. Based on both the *k* data collected in the previous study, partial calorimetry and ambient conditions, post-hoc analysis was undertaken to calculate energy expenditure (EE), metabolic rate (M), heat production (H_{prod}), dry heat loss (C + R), required evaporative heat loss for heat balance (E_{req}) and the maximum amount of heat loss conditions allow for (E_{max}). It was hypothesised that the thermally optimised suit will facilitate higher heat loss than the aerodynamically optimised suit. Participants undertook 5 minutes of seated rest followed by a 15 minute warm up consisting of 5 minutes at 75% of lactate threshold (LT2), 5 minutes at 80% LT2 and 5 minutes at 85% LT2. This was immediately followed by 90 minutes at 80% LT2, 15 minutes at 75%LT2 and 15 minutes seated recovery. Environmental conditions were 28ºC, 65% relative humidity. Results showed no difference in HR, $\bar{T}_{sk}$, T_{gi}, $\dot{V}O_2$, $V\dot{C}O_2$, RER, RPE, T_{comf}, T_{sens} or w_{per} between the suits at any time point during the experimental trial. However, there were differences over time within conditions as well as individual differences. Additionally, no differences were reported between or within the AERO and THERM conditions in EE, M, H_{prod}, E_{req} or E_{max} between 60 and 105 minutes of steady state exercise. This suggests that the apparent differences shown in the previous chapter are not large enough to elicit a measurable difference in the physiological variables although individual differences highlight the importance of an individual approach.

6.1 Introduction

In long-distance triathlon, it is important to understand and account for the trade-off between aerodynamics and thermoregulation to mitigate the dangers of heat stress during competition in hot and/or humid conditions. Decrements in performance in these conditions can be owed to dehydration, high body temperatures and cognitive decline. Additionally, fatigue from reduced muscle activity is also observed and thought to protect thermal homeostasis by preventing further heat production (Tucker et al. 2004b; Schmit et al. 2017). High body temperatures and detrimental dehydration are generally circumvented due to adequate feeding strategies and utilisation of pre-competition acclimatisation/acclimation strategies in the weeks leading up to a race (Racinais et al. 2022). Although higher sweat rates are observed with heat acclimation strategies, there is a closer match with the body's demand for water and the individual's thirst sensation together with lower resting and exercising body temperatures after acclimation procedures (Kenny et al. 2018; Burk et al. 2012). This does not mean however that an athlete is protected from heat stress altogether. The interaction between an athlete and clothing worn during competition should also be considered in the development of heat stress alleviation strategies due to a garment's potential to significantly influence heat balance. Sports clothing represents a layer of insulation that provides thermal resistance and imposes a barrier to heat transfer, dissipation and sweat evaporation from the skin. It possesses the potential to increase body heat storage and make environments intolerable to an individual, especially if exposed for long periods of time.

Ideally, when racing, the aim is to be as efficient as possible to preserve energy and to reduce unnecessary heat production. Metabolic heat production is the difference between an individual's external work and their overall metabolic rate (Cramer, Jay 2016) and when exercising in hot conditions, the aim is to keep the difference as small as possible to help prevent the onset of high body temperatures and maintain a tolerable heat balance. Most athletes now adopt an aerodynamic position during the bike phase to increase their exercise efficiency as it allows them to reduce their form drag. This means that for the same power output, a cyclist would be travelling at a higher velocity in a more aerodynamic position, compared to a less aerodynamic position. This is due to the shape of their body facilitating a more laminar flow across the body which, in turn, reduces the wake region behind the rider. By manipulating the roughness of the suit shoulder fabric, friction drag is increased and paradoxically further decreases form drag to make the rider more aerodynamic and efficient. The same principal is also applied to the smooth main body fabrics of triathlon suits to maintain the laminar flow across the body. However, investigating the impact these aerodynamic main body fabrics have on athlete heat management and what role they play in the aerodynamic-physiological trade-off has not been investigated. This is especially important as triathlon suits cover a large area of the body. If better informed fabric choices are made based on the inclusion of known thermal characteristics of a fabric, such as thermal conductivity, garments can be designed to not only be aerodynamically optimised, but also thermally optimised to contribute towards the prevention or delay of heat stress onset. From a practical perspective, creating a garment that allows for greater heat loss could result in lower skin temperatures, lower core temperatures, improved thermal perception and in turn, improved performance through increased heat capacity. Data from the previous chapter informed suit design in the present study. The two suits being tested in the present study are AERO1 and THERM1. The two 'slow' triathlon suits (figure 5.8). The research question in the present chapter asks; Are there any differences in thermoregulatory or perceptual variables between an aerodynamically optimised and thermally optimised triathlon suit?

6.1.1 Aim and Hypothesis

The aim of the present study was to determine whether there is a difference in thermoregulatory and perceptual variables between triathlon suits that are aerodynamically optimised or thermally optimised. It was hypothesised that the thermally optimised suit will facilitate higher heat loss than the aerodynamically optimised suit.

6.2 Methods

6.2.1 Participants

Seven cyclists volunteered to participate in this investigation (table 6.1). All participants were familiar with the type of testing involved and undertook at least 100km of cycling per week and were categorised into performance level 3 (de Pauw et al. 2013). All participants were required to be free from injury for the duration of the experimental period. During testing periods, participants were asked to maintain their normal exercise schedule, refrain from heavy exercise and alcohol during the 24-hours prior to each laboratory session. Each participant completed their sessions at the same time of day to minimise the effects of circadian and diurnal rhythms on performance and physiological measurements, with individual sessions being separated by a minimum of 7 days. The study was approved by the ethics board at Nottingham Trent University and performed in accordance with the Declaration of Helsinki. Prior to testing, participants completed a general health-screening questionnaire and provided their written informed consent.

Table 6.1: Participant Characteristics

	Mean ± SD
Age ***(yrs)***	25 ± 4
Height ***(m)***	1.78 ± 0.08
Weight ***(kg)***	73.18 ± 9.63
BSA ***(m^2)***	1.88 ± 0.10
$\dot{V}O_{2max}$ ***(ml/kg/min)***	54.6 ± 10.1
Body Fat ***(%)***	12.8 ± 4.1

6.2.2 Study Overview

Participants were required to visit the laboratory on three separate occasions. The first visit consisted of measuring height, weight, waist circumference and hip circumference followed by a body composition analysis using bio-electrical impedance (BIA) (Bodystat 1500, Bodystat LTD, Douglas, Isle of Man). Participants lay horizontally on a massage table for 5 minutes prior to the BIA readings to ensure hydrostatic equilibrium. Electrodes were placed on the both the hand and foot of the right-hand side of the body. Height and weight data also informed the calculation of body surface area (BSA) (du Bois, du Bois 1916):

$$BSA = 0.007184 \text{ x } (\text{height})^{0.725} \text{ x } (\text{weight})^{0.425}$$

Participants then performed an incremental $\dot{V}O_{2max}$ test on a cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands) in the heat (28°C and 65% RH). Participants cycled at their preferred cadence, starting at 95W, with a 35W increase in power output every three minutes until volitional fatigue or until cadence could not be maintained over 60rpm. Oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), respiratory exchange ratio (RER) (Metalyzer® 3D, AD Instruments, Oxford, UK) and heart rate (HR) (Polar M400, California, USA) were recorded continually throughout the test, with data averaged over the final 30s of each stage. In the last 30 seconds of each stage, a fingertip blood lactate sample was collected using a 20µl capillary tube and analysed post-test (Biosen C-Line, EKF Diagnostics, Cardiff, UK). Prior to experimental testing, spirometry equipment, water bottles and calibration gas were left in the chamber to equilibrate to the higher ambient temperature and humidity. Calibration of the Metalyser and Biosen occurred prior to each $\dot{V}O_{2max}$ test and trial according to the manufacturers' instructions. The $\dot{V}O_{2max}$ test determined the participants' lactate threshold (LT2) and thus, the intensity at which the experimental trials were to be completed at. LT2 was calculated by identifying the power output that corresponded to a blood lactate of 4mmol/L.

The following visits consisted of two experimental trials. Participants wore either an aerodynamically optimised triathlon suit (AERO) that has a complete aerodynamic focus to the design and incorporated fabric ‘H’ as the main body fabric (as reported in chapter 5), or a thermally optimised triathlon suit (THERM) whereby fabric ‘C’ was chosen as the main body fabric due to its high thermal conductivity and thermal effusivity values also described in chapter 5. The shoulder fabrics in both the AERO and THERM suits were the same and consisted of fabric ‘F’. All participants were blinded to the conditions and a balanced randomisation of the two main trial conditions was calculated and assigned appropriately.

Figure 6.1: Photograph of prototype triathlon suits worn in the present study. (A) Aerodynamically optimised triathlon suit (AERO), (B) Thermally optimised triathlon suit (THERM).

6.2.3 Experimental Protocol

Prior to testing, an ingestible telemetric pill (BodyCap, e-Celsius®, France) was given to participants to allow for the measurement of gastro-intestinal temperature. Participants were instructed to take the pill ~10 hours prior to the start of each of the two experimental trials to ensure the pill had passed through into the gastro-intestinal tract. Pill function was verified upon arrival to the lab using a receiver (BodyCap, e-Celsius®, France) and its position confirmed by the ingestion of water.

Upon immediate arrival to the lab, participants provided a urine sample and urine specific gravity (USG) was measured (Atago Pocket Refractometer PAL-10S, Japan) to ensure sufficient hydration prior to exercise. Acceptable hydration was measured at a USG of 1.020 or less. Participants were instructed to drink 400ml of water, if dehydrated. A second urine sample was analysed post-exercise to identify any degree of dehydration they may have occurred during the experimental trials. Similarly, two fingertip blood samples were collected both pre- and post-exercise, in a 75µm microhaematocrit capillary tube (Jaytec Glass Ltd, Hastings, UK) which were spun in a centrifuge (Nickel Electro Clifton Clinical Centrifuge, NE030GT/I, 1000RPM for 10 minutes) to separate serum plasma and haematocrit components to assess plasma reduction owing to sweat loss. Triathlon suits were weighed (Adam Equipment Ltd., Milton Keynes, UK) both pre- and post-exercise trial to measure the amount of sweat held in the material following each trial.

After hydration status was established, nude weight was recorded (Adam Equipment Co. Ltd., Milton Keynes, UK). A heart rate strap (POLAR M400), eight wireless thermistors (iButton DS1922, Sunnyvale, CA, USA) and four wireless hygrochrons (DS1923-F5, HomeChip Ltd, Milton Keynes, UK) were secured with porous tape (Transpore™ Surgical Tape, 25mm, 3M) at eight and four locations, respectively. Placement of the iButtons are shown in figure 6.2.

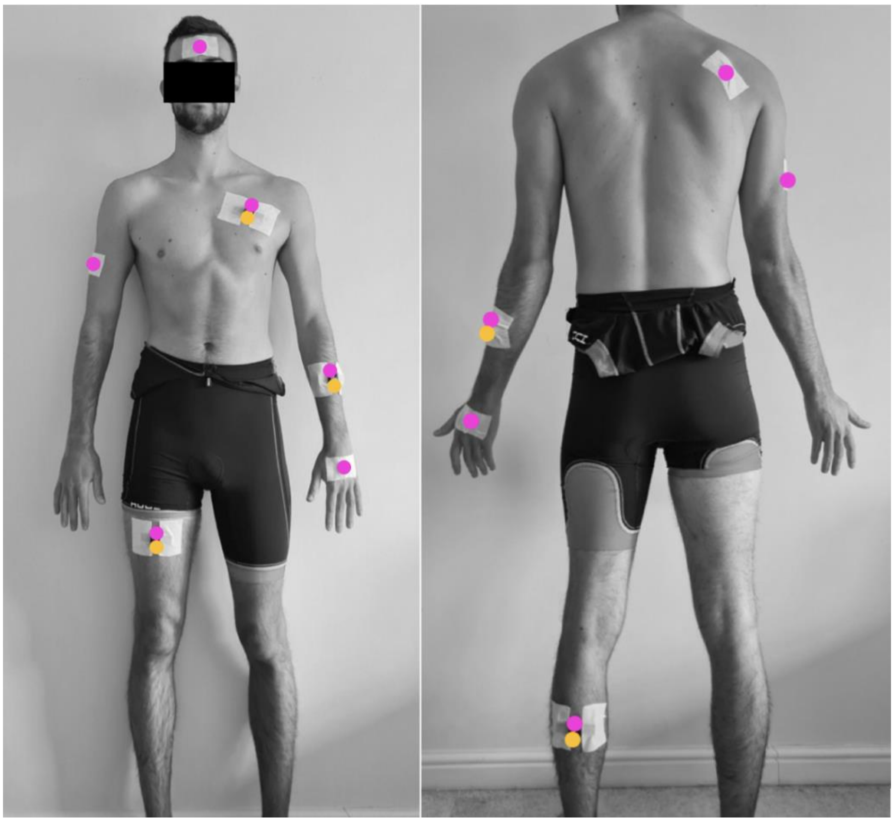


Figure 6.2: Placement of iButtons (pink) and hygrometers (yellow) during experimental trials.

Thermochrons were secured directly to the skin using the porous tape and hydrochrons were placed in a bespoke 3D-printed holder that secured them 6mm above the skin surface to prevent sensor saturation (Hinchez, Vargas & Schlader, 2019; Filigeri et al., 2015). Two slits in the side casing of the hygrochrons holder allowed for a degree of airflow and to help prevent the development of a local environment. The holders were attached to the skin using the wings of the casing taped down using the porous tape. Hygrochrons were always secured to the body, so the opening of the casing always faced downwards to avoid sweat pooling between the skin and casing. The iButtons that were to be placed in corresponding areas were also secured in this casing, directly against the skin, 2mm away from the hydrochrons. This ensured temperature and humidity readings were consistently read at the same place and at the same distance apart for each trial (figure 6.3).

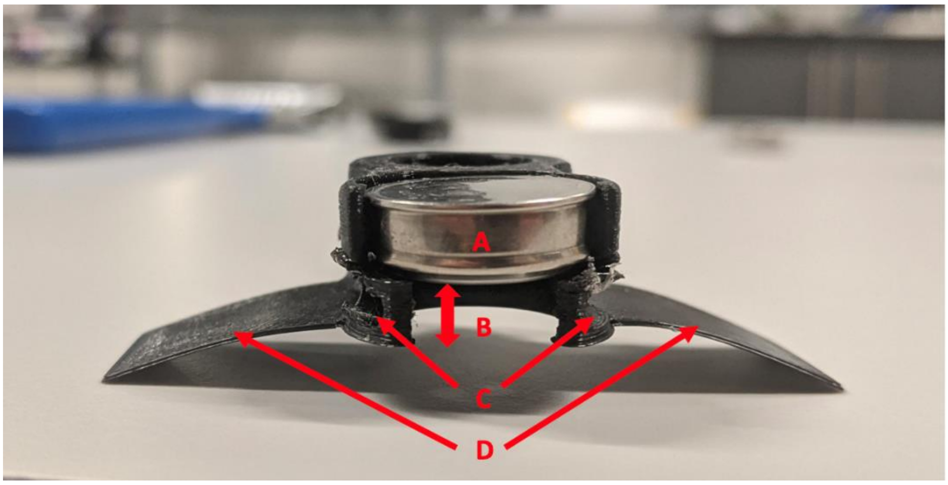


Figure 6.3: Hygrometer in 3D printed case. A: Digital Hygrometer used to measure skin wetness; B: 6mm space to lift hygrometer off skin; C: Slits to maintain airflow across skin; D: Wings to stick casing to skin.

Mean skin temperature ($\overline{T}_{sk}$) (ISO9886, 2004) was calculated using the following equation:

$$\overline{T}_{sk} = (0.07 \times T_{Head}) + (0.175 \times T_{Scapula}) + (0.175 \times T_{Chest}) + (0.07 \times T_{Bicep}) + (0.07 \times T_{Forearm}) + (0.05 \times T_{Hand}) + (0.19 \times T_{Thigh}) + (0.2 \times T_{Calf})$$

Mean body temperature (T_b) was calculated as a weighted average of gastro-intestinal temperature (T_{gi}) and $\overline{T}_{sk}$:

$$T_b = (0.8 \times T_{gi} + 0.2 \times \overline{T}_{sk})$$

Carbohydrate (CHO) drinks (6% maltodextrin w/w, MyProtein, unflavoured) were provided to the participants where they were asked to drink 167ml (10g CHO) of the carbohydrate drink at 30, 45, 60, 75, 90 and 105 minutes of cycling. This equated to 60g of CHO ingestion over the 2-hour exercise period. All fluid was ingested within 2 minutes of it being given. Drinks were left in the chamber, set at 28ºC and 65% RH, for 60 minutes prior to the experimental trials to equilibrate the water temperature with the environment and help prevent any body cooling from fluid ingestion.

6.2.4 Experimental Trials

Participants rested for 5 minutes on the bike before commencing the sub-maximal exercise protocol. A 15-minute warm-up period was then completed which involved cycling for 5 minutes at 75% LT2, 5 minutes at 80% LT2 and 5 minutes at 85% LT2. This led immediately into 90-minutes of cycling, at a self-selected cadence, at 80% LT2. Afterwards, for a final 15 minutes, power was dropped to 75% LT2 to replicate a downhill gradient of a racing course. Following this, participants got off the bike and immediately rested in a seated position for 15 minutes in the environmental chamber (figure 6.4). 80% LT2 was chosen for the main exercise block as it reflects the exercise intensity elite triathletes ride at during a half-Ironman®. For the $\dot{V}O_{2max}$ and the two experimental conditions, ambient temperature and relative humidity were 28ºC and 65%, respectively.

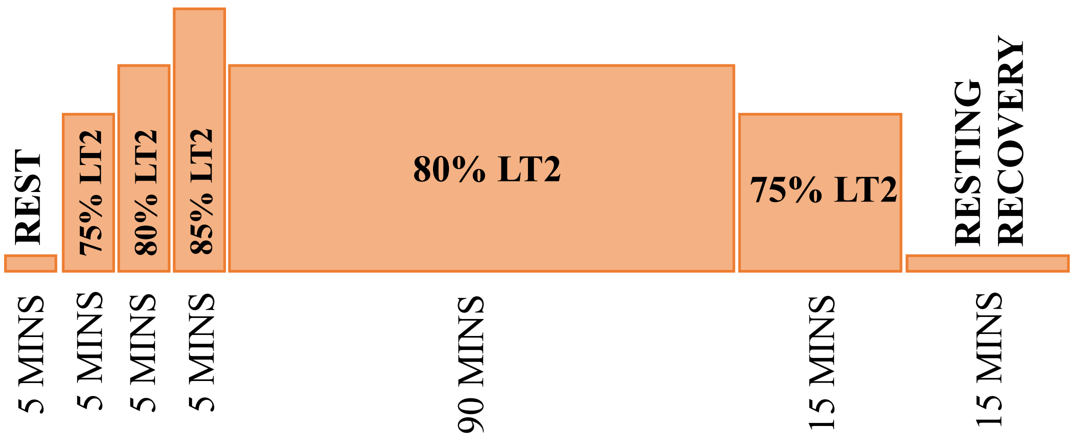


Figure 6.4: Schematic of exercise protocol intensity.

Ratings of thermal sensation (T_{sens}) (Griffiths & Boyce, 1971), thermal comfort (T_{comf}) (ASHRAE, 1997), rate of perceived exertion (RPE) (Borg, 1982) and skin wetness perception (w_{per}) were recorded in the last minute of each 5-minute stage throughout the trial. Wind speed, ambient temperature (T_A), relative humidity (RH), wet bulb globe temperature (WBGT) (Kestrel 5400 heat stress tracker, Kestrel Instruments, Boothwyn, Pennsylvania, USA), heart rate (HR) and gastro-intestinal temperature (T_{gi}) were continually recorded throughout the trial. $\dot{V}O_2$, $\dot{V}CO_2$, RER and minute ventilation ($\dot{V}E$) were measured for 5 minutes at rest and then for 5 minutes between 25-30, 40-45, 55-60, 70-75, 85-90, 100-105- and 115-120 minutes during exercise and during the last 5 minutes of resting recovery. A three-stack of fans was positioned directly in front of the participant on the bike at a 1.5m distance to provide convective cooling. Post-trial nude weight and tri-suit weight was recorded to measure both the amount of sweat loss and the amount of sweat held in the suit, respectively. All calculations for heat exchange variables are displayed in chapter 3, section 3.2.

6.3 Data Analysis

6.3.1 Analysis and Statistics

Prior to all statistical tests, data was tested for normality, homogeneity of variance and sphericity using the Shapiro-Wilk, Levene's and Mauchly's tests, respectively, with a Greenhouse Geisser correction applied as necessary. All data are presented as means ± SD. Mean resting values presented were calculated by averaging the five minutes of the resting period. Each other individual time point (15, 30, 45, 60, 75, 90, 105, 120 and 135 minutes) were calculated by averaging all data across the previous fifteen minutes of time. For all continuous data, a mean was calculated for 5 minutes rest, from the start of exercise to 15 minutes, 15-30 minutes, 30-45 minutes, 45-60 minutes, 60-75 minutes, 75-90 minutes, 90-105 minutes, 105-120 minutes and finally 120-135 minutes. This allowed for the analysis of data at 10 time points.

A two-way analysis of variance (ANOVA) was performed on T_{gi}, $\bar{T}_{sk}$, $T_{b,}$ RPE, T_{sens} and T_{comf}, VO_2, EE, M, H_{prod}, C+R, E_{req} and $E_{max.}$ Those that did not meet the assumptions for parametric tests, a Friedman's test was conducted. These variables included HR and perceived skin wetness (w_{per}). A Bonferroni correction was applied to account for multiple pairwise comparisons. Paired t-tests were performed on pre-to-post body weight change, suit weight change, ambient temperature (T_A) , RH, and wind speed with an alpha value set at 0.05. A Wilcoxon matched pairs signed rank test was undertaken on WBGT data with an alpha of 0.05. The area under the curve (AUC) was calculated using the trapezoid method, calculating the area of each equivalent rectangles and summing the areas underneath the curve. This was undertaken for each participant which were then grouped into AERO and THERM where a paired t-test was performed. Values below are displayed as mean ± SD.

6.4 Results

6.4.1 Environmental Conditions

There was no significant differences in T_A (AERO: 27.9 ± 0.1°C vs. THERM: 27.8 ± 0.1 °C, p=0.59), RH (AERO: 67.4 ± 0.3% vs. THERM: 67.3 ± 0.8%, p=0.80), WBGT (AERO: 24.7 ± 0.2°C vs. THERM: 24.6 ± 0.2 °C, p= 0.69) or wind speed (AERO: 2.1 ± 0.1 m/s vs. THERM: 2.4 ± 0.1m/s, p=0.08).

6.4.2 Area Under Curve

There were no significant differences in area under the curve between the suits in T_{gi} (AERO: 5108 ± 13, THERM: 5116 ± 43, p= 0.68), $\bar{T}_{sk}$ (AERO: 4619 ± 57, THERM: 4634 ± 41, p=0.35), T_b (AERO: 5009 ± 56, THERM: 5018 ± 38, p= 0.66), HR (AERO: 18802 ± 1244, THERM: 18985 ± 973, p= 0.60), RPE (AERO: 1451 ± 178, THERM: 1508 ± 267, p= 0.46), T_{sens} (AERO: 518 ± 149, THERM: 525 ± 105, p= 0.87), T_{comf} (AERO: 288 ± 76, THERM: 295 ± 67, p= 0.76) and w_{per} (AERO: 323 ± 78, THERM: 344 ± 64, p= 0.34).

6.4.3 Biophysics and Metabolism

The R_{cl}, f_{cl} and I_{cl} calculated for the AERO suit were 0.015 $m^2K \cdot W^{-1}$, 1.03 and 0.096I_{clo}, respectively and for the THERM suit were 0.011 $m^2K \cdot W^{-1}$, 1.00 and 0.070I_{clo}, respectively. There was no difference in EE (figure 6.5), H_{prod} (W), H_{prod} ($W \cdot m^{-2}$) (figure 6.6), M (W), M ($W \cdot m^{-2}$), C+R, E_{req}, E_{max}, VO_2 or VCO_2 (all p>0.43, Table 6.2) at 60 versus 105 minutes in either the AERO or THERM triathlon suit, nor was there a difference in the same variables between suits at either 60 minutes or 105 minutes (Table 6.2).

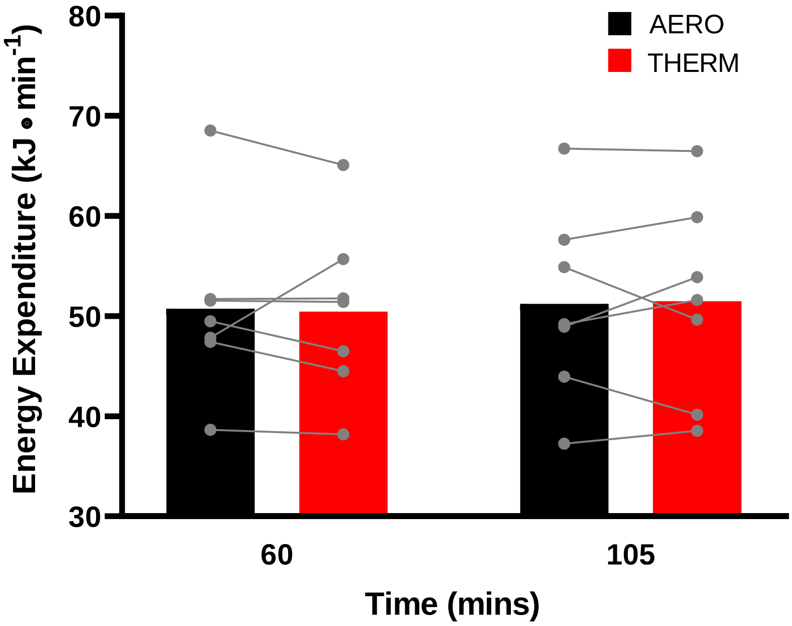


Figure 6.5: Differences in energy expenditure at 60 and 105 minutes of exercise in both the AERO and THERM triathlon suits. Each dot represents individual participant.

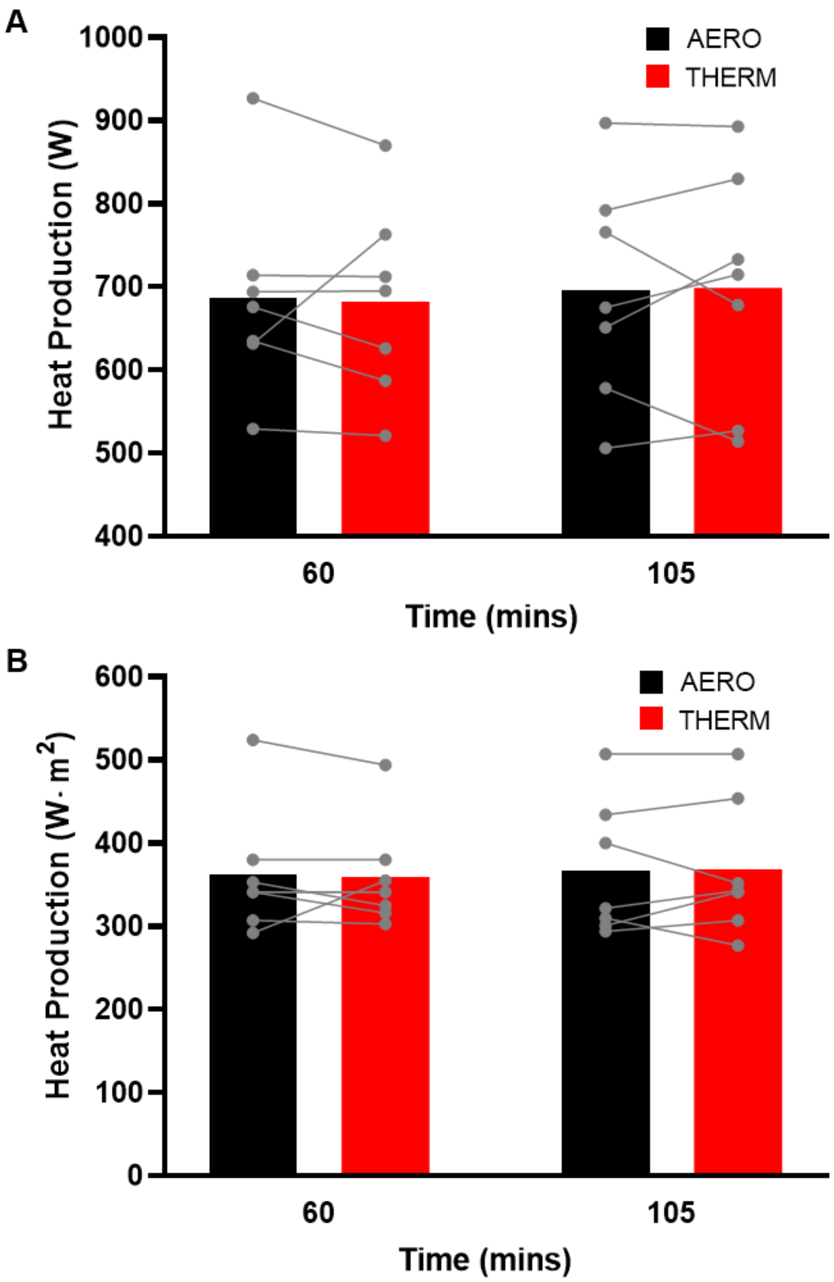


Figure 6.6: Absolute heat production (A) and heat production normalised to body surface area (B) at both 60 and 105 minutes of exercise in both the AERO and THERM triathlon suits. Each dot represents an individual participant.

Table 6.2: Differences in metabolic rate (M), dry heat loss (C+R), required evaporative heat lost to attain heat balance (E_{req}) and the maximal amount of heat loss that can be attained in the given environment (E_{max}), oxygen uptake (VO_2), carbon dioxide production (VCO_2) and respiratory exchange ratio (RER) in the AERO and THERM triathlon suits at 60 and 105 minutes.

		AERO		THERM	
		Mean	SD	Mean	SD
M (W)	60 minutes	846	150	841	144
	105 minutes	854	160	857	167
M ($W \cdot m^{-2}$)	60 minutes	447	95	443	83
	105 minutes	451	99	453	99
C + R (W)	60 minutes	171	25	190	33
	105 minutes	166	18	194	34
C + R ($W \cdot m^{-2}$)	60 minutes	90	12	100	12
	105 minutes	88	11	100	12
E_{req} (W)	60 minutes	459	109	435	91
	105 minutes	472	115	447	116
E_{req} ($W \cdot m^{-2}$)	60 minutes	243	67	230	55
	105 minutes	249	68	237	70
E_{max} (W)	60 minutes	202	21	206	23
	105 minutes	199	16	207	27
E_{max} ($W \cdot m^{-2}$)	60 minutes	106	7	108	5
	105 minutes	104	6	108	7
VO_2 (L/min^{-1})	60 minutes	2.49	0.43	2.47	0.42
	105 minutes	2.52	0.46	2.54	0.48
VCO_2 (L/min^{-1})	60 minutes	2.12	0.42	2.14	0.38
	105 minutes	2.13	0.46	2.10	0.44
RER	60 minutes	0.85	0.03	0.87	0.03
	105 minutes	0.84	0.05	0.82	0.03

6.4.4 Gastro-intestinal, Skin & Body Temperature

No difference was found in absolute T_{gi} (p= 0.99) between AERO and THERM suits at any time point (figure 6.7). There were some individual differences apparent in $T_{gi,}$ mostly arising from the fact that starting T_{gi} were different for everyone. Participant AVT10 attained the highest T_{gi} in the AERO suit. In the AERO suit, this participant experienced a continuous increase in T_{gi} suit with a +1.9°C overall change from baseline temperature (figure 6.8).

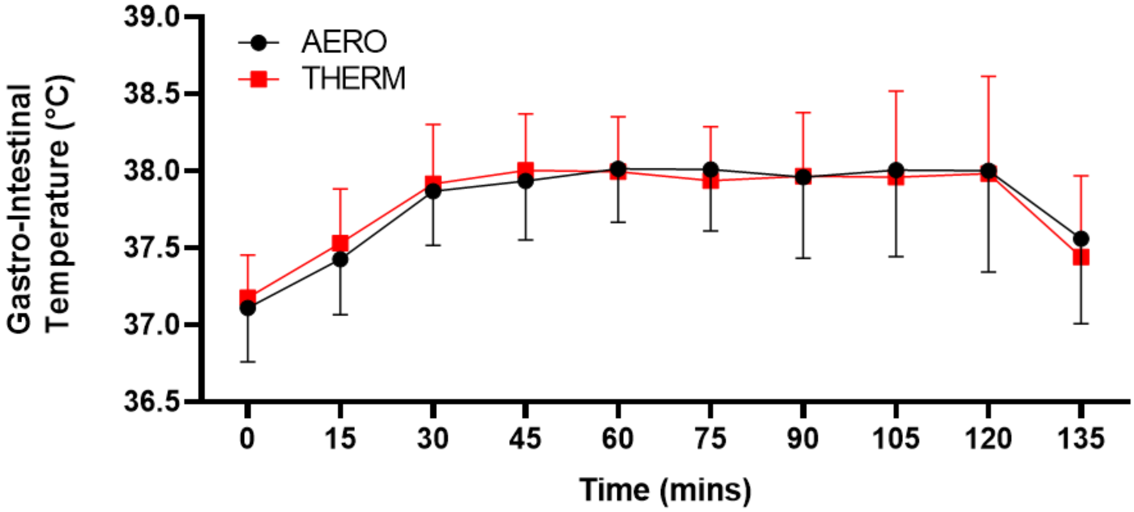


Figure 6.7: Gastro-intestinal temperature throughout the experimental protocol in both the aerodynamically optimised (AERO) and thermally optimised (THERM) triathlon suits.

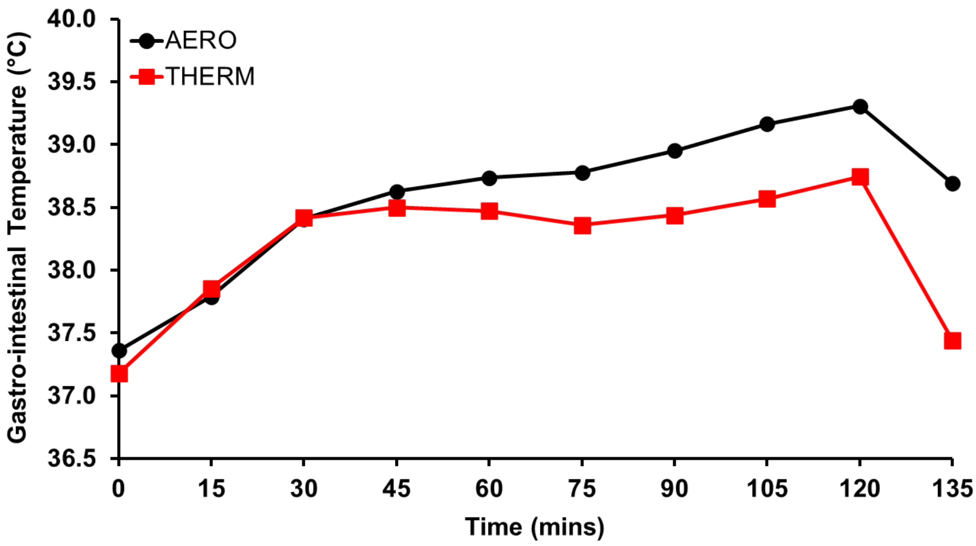


Figure 6.8: Gastro-intestinal temperature of participant AVT10 in AERO and THERM triathlon suits.

No difference in $\overline{T}_{sk}$ (p= 0.52) was found between the AERO and THERM triathlon suits at any time point (figure 6.9). The highest $\overline{T}_{sk}$ was 35.4°C in AERO and 35.3°C in THERM both achieved by AVT10 who also saw the largest change in MT_{sk} from the start-to-end exercise of 2.2°C and 1.9°C in AERO and THERM suits, respectively (figure 6.10). No other participants saw a change in $\overline{T}_{sk}$ larger than +0.7°C or cooling larger than -0.5°C in AERO and +0.9°C or cooling larger than -0.8°C in THERM with no other notable differences between the two suits.

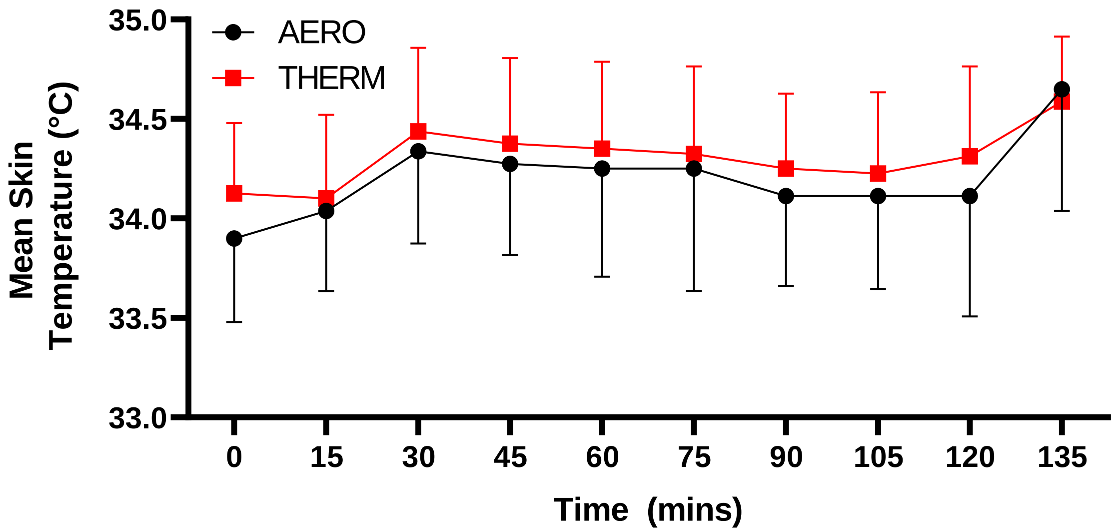


Figure 6.9: Mean skin temperature throughout the experimental protocol in both the aerodynamically optimised (AERO) and thermally optimised (THERM) triathlon suits.

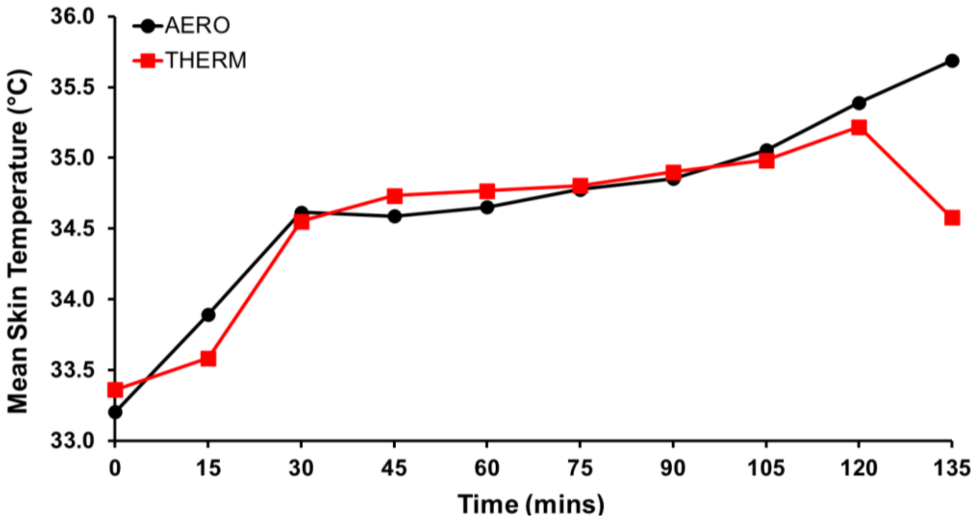


Figure 6.10: Mean skin temperature of AVT10 in AERO and THERM triathlon suits.

There was no difference in T_b (p=0.09) between the AERO and THERM triathlon suits at any time point (figure 6.11). As T_b was calculated as an 80% to 20% weighted contribution of T_{gi} and $\overline{T}_{sk}$ respectively, the same pattern was observed as described above. The maximum T_b was achieved by AVT10 in both AERO (38.5°C) and THERM (38.0°C) with a change of +2.0°C and +1.6°C, respectively. Other participants showed a T_b no higher than 37.65°C (change of +1.2°C) in AERO and no higher than 37.7°C (change of +1.1°C) in THERM.

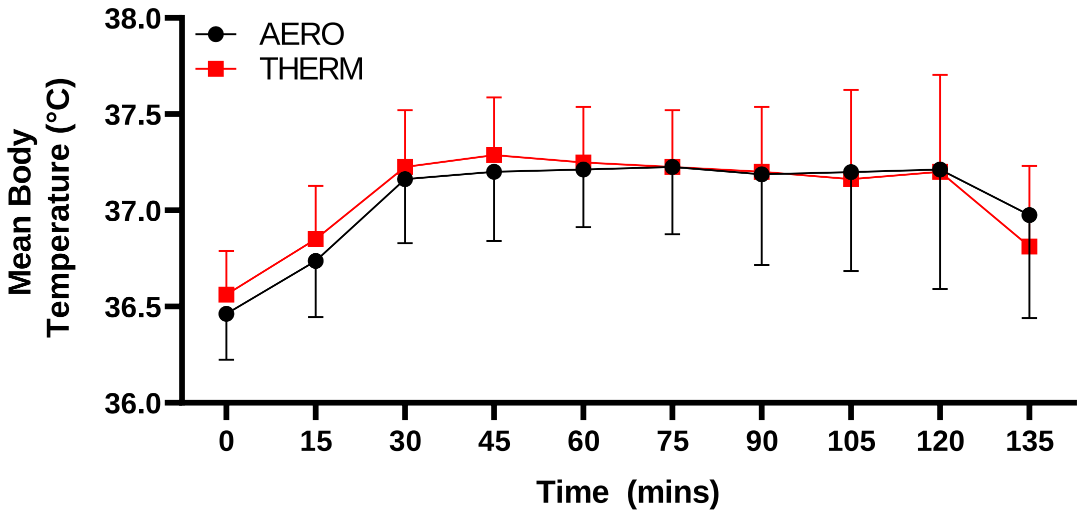


Figure 6.11:Mean body temperature throughout the experimental protocol in both the aerodynamically optimised (AERO) and thermally optimised (THERM) triathlon suits.

6.4.5 Heart Rate & Perceptual Responses

There was no differences in HR (p>0.99) between the two triathlon suits at any time point throughout the protocol. Further analysis of individual data shows HR responses were different for individuals. At 60 minutes, two participants saw a HR 10bpm higher in THERM compared to AERO. At 105 minutes, the same two participants saw a HR 8 and 12 bpm higher in THERM versus AERO. At 60 minutes, other participants saw HR 1bpm, 5bpm, 5bpm, 4bpm, and 10bpm lower in THERM compared to AERO. At 105 minutes, three found a HR 5bpm lower in THERM than AERO and the remaining two found a HR 3 and 12bpm lower in THERM than AERO (figure 6.12)

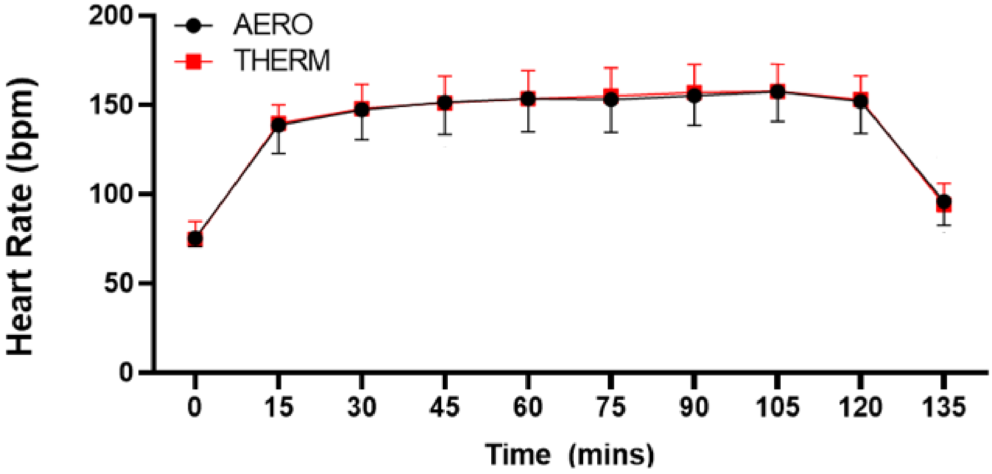


Figure 6.12: Heart rate throughout the experimental protocol in both the aerodynamically optimised (AERO) and thermally optimised (THERM) triathlon suits.

No difference was found between the AERO and THERM triathlon suits in RPE (p= 0.83, figure 6.13), T_{sens} (p= 0.92, figure 6.14), T_{comf} (p=0.79, figure 6.15) or w_{per} (p>0.99, figure 6.16).

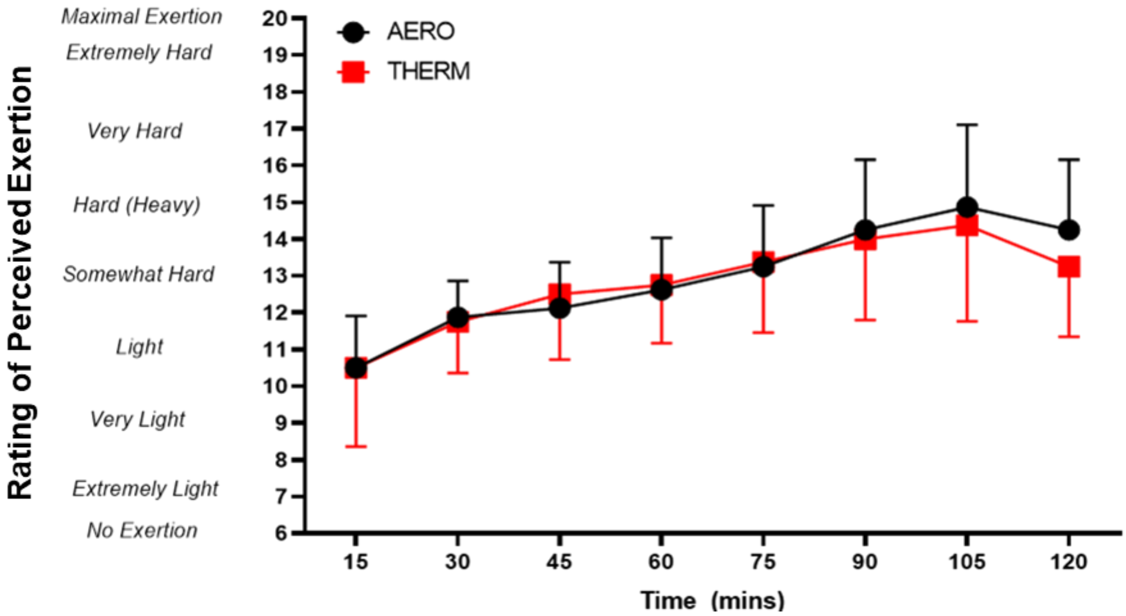


Figure 6.13: Changes in the rate of perceived exertion in AERO and THERM across the experimental protocol.

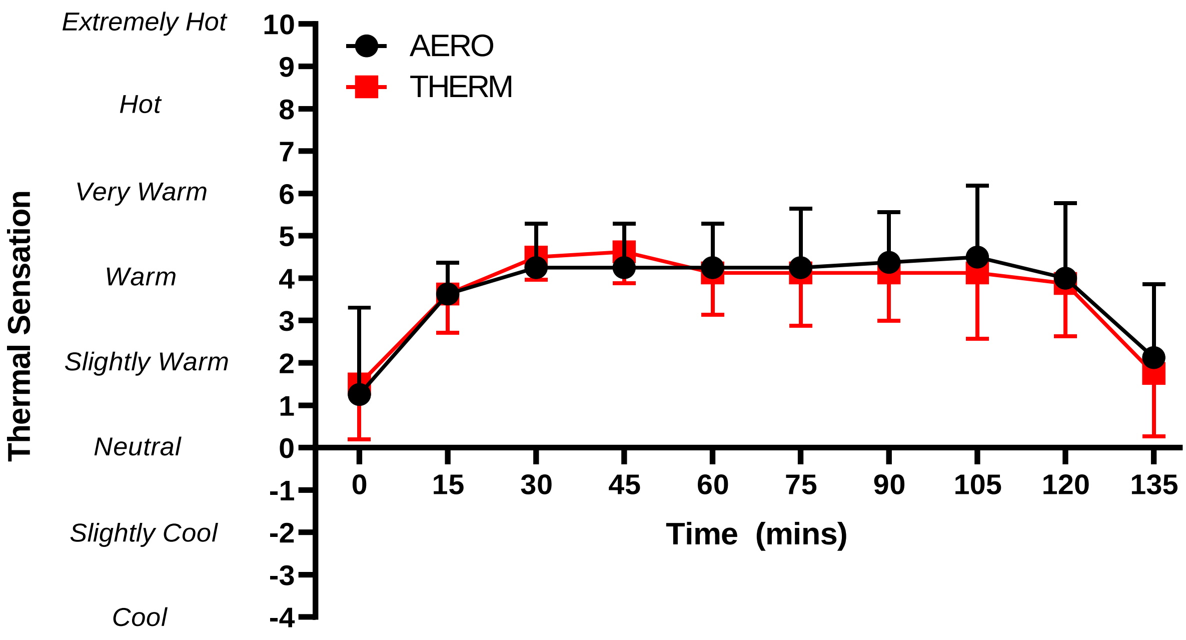


Figure 6.14: Changes in thermal sensation in AERO and THERM across the experimental protocol.

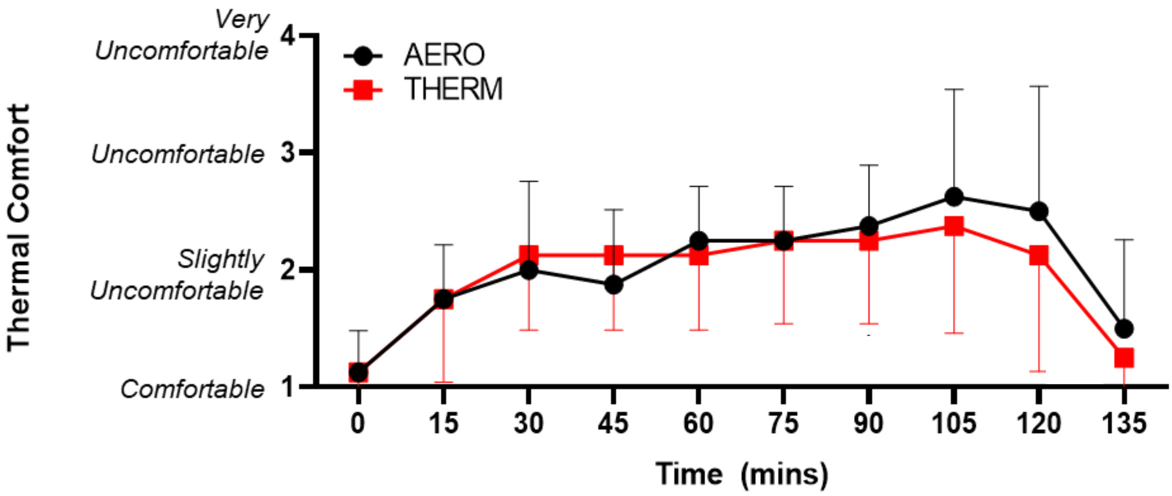


Figure 6.15: Thermal comfort in AERO and THERM across the experimental protocol.

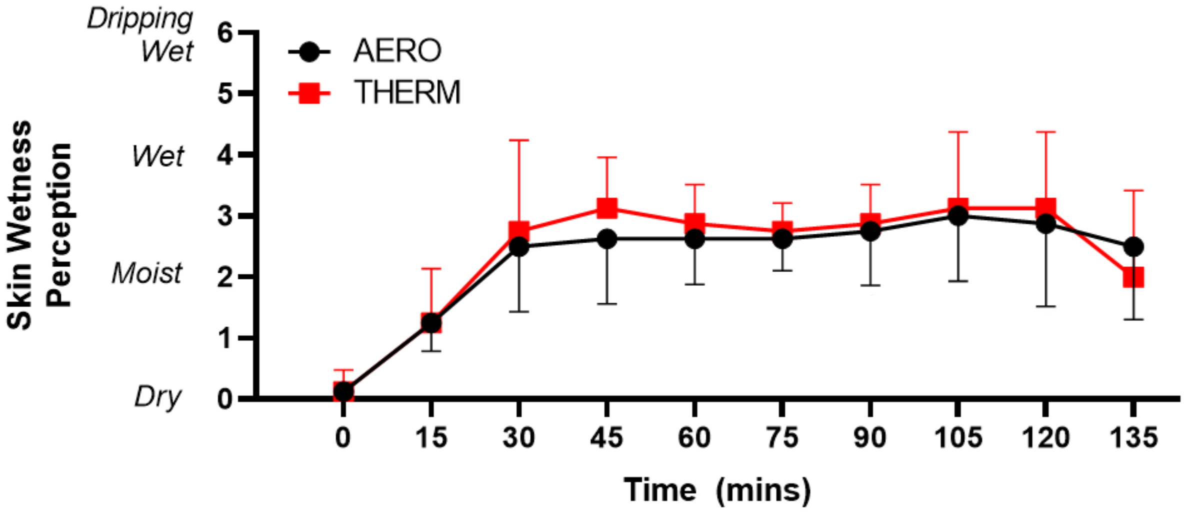


Figure 6.16: Skin wetness perception in AERO and THERM triathlon suits across the experimental protocol.

6.4.6 Body Weight and Suit Weight Changes

No difference was found in pre-to-post body weight change (*p*=0.56, Figure 6.17A) or suit weight change (*p*= 0.49, Figure 6.17B) between the AERO and THERM triathlon suits.

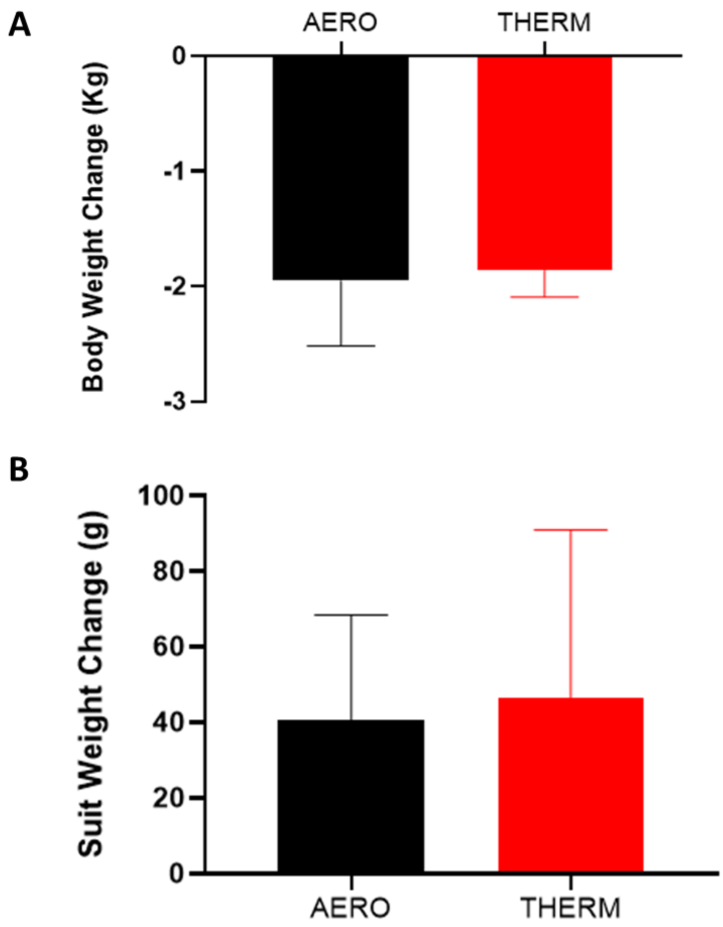


Figure 6.17 (A) Pre to post exercise protocol body weight change in the AERO and THERM triathlon suits. (B) Pre to post exercise protocol suit weight change in the AERO and THERM triathlon suits.

6.5 Discussion

The aim of the present study was to assess whether there is a difference in thermoregulatory and perceptual variables between triathlon suits that are aerodynamically and thermally optimised. Results indicate no physiological difference in the thermoregulatory responses to exercise in the heat when wearing the aerodynamically optimised triathlon suit versus the thermally optimised triathlon suit and that the differences in thermal conductivity and thermal effusivity measured in chapter 5 are not enough to elicit a whole body thermoregulatory or perceptual change when exercising in these environmental conditions.

In the present study, T_{gi} only reached ~38°C suggesting the heat strain elicited by the environmental conditions may not have been high enough to see differences between the two triathlon suits. Peiffer & Abbiss (2011) found T_{core} of 38°C just 15km into a 40km TT in higher ambient temperature of 35°C (50% relative humidity) with it increasing to 39.4°C at the end of the 40km. Although, the time to completion was only 60.7 ± 2.9 minutes compared to the longer heat exposure in the present study and average power output throughout that time was 322 ± 32 W compared to only 159 ± 30 W in the present study. H_{prod} was therefore much higher, despite the distance completed being just under half of that performed during a half-ironman. Increasing the ambient temperature in the present study to 30°C may be enough to stress thermoregulatory mechanisms to the extent where a more continuous increase in T_{gi} is observed, despite the constant workload, and where potential differences in suits are distinguishable. It is reported that T_{core} is mostly independent of the environment when conditions are compensable and allow for heat balance to be attained and instead increases proportionally to the intensity of exercise (Sawka et al. 2011). However, skin temperature changes as a direct consequence of ambient temperature and humidity (Gagge, Gonzalez 2010). In their review, Sawka et al. (2011) define skin temperature zones to be <30°C = cool/cold skin, 30-34.9 = warm skin and >35°C = hot skin although these temperatures exist on a continuum and for any given T_{core}, a warm or hot T_{sk} will result in increased skin blood flow. This subsequently instigates the competition between skin blood flow for heat loss and muscle blood flow for the maintenance of oxygen delivery and exercise performance. It is not until T_{core}

reaches ~39°C where skin blood flow, for the same T_{sk}, is reduced (Rowell et al., 1986). In the present study, T_{sk} was 34.3°C at 30 minutes, 34.2°C at 60 minutes and 34.1°C at 105 minutes in AERO and 34.4°C at 30 minutes, 34.4°C at 60 minutes and 34.2°C at 105 minutes in THERM. This sits within the 'warm skin' definition however, as T_{core} only reached a peak of 38.0°C in both conditions, it does not permit a significant redirection of blood away from the muscles for skin blood flow nor does the magnitude of T_{gi} warrant redirection of blood away from the skin to the core. It must be considered that this $T_{core,}$ T_{sk} and skin blood flow relationship described by Rowell et al. was estimated in running exercise and not cycling, although the principle is likely to be similar for both exercise modalities.

Heart rate is the primary modulator behind the increase in cardiac output during whole body heat stress (Crandall, González-Alonso 2010; Jose et al. 1970) as the body aims to maintain blood flow to the working muscles whilst aiming to meet sufficient heat loss demands through increased skin blood flow. A phenomenon called cardiovascular drift is often observed during moderate to high intensity exercise in the heat. This is the upward shift of heat rate over time, to account for a drop in stroke volume, to maintain sufficient cardiac output to meet oxygen demand and skin blood flow (Wingo et al. 2012). It is also found to be associated with dehydration and increases in body temperature (Montain, Coyle 1992). It would be expected that if any meaningful differences in the body's ability to maintain this oxygen demand/skin blood flow trade-off, higher heart rates would be observed. No such differences were observed in either absolute HR no change in HR across the entire protocol in the present study. Additionally, alongside the temperature data, ambient temperature did not increase T_{sk} enough to cause any potential significant increase in skin blood flow where redirection from the core was needed. Furthermore, exercise intensity was not high enough over the exercise protocol to elevate T_{gi}, apart from in participant AVT10.

Analysing both T_{core} and T_{sk} together, Arngrímsson et al. reported reductions in VO_{2max} of 5% with a T_b of 38.2°C in 35°C at 50% relative humidity. This translated into a 7% reduction in performance time during a treadmill test to exhaustion, compared to 25°C at 50% relative humidity, (Arngrímsson et al.

2004). The small reduction in VO_{2max} was attained at a T_b higher than that in the present study, again suggesting that the environmental conditions did not reach the threshold to significantly strain the thermoregulatory system enough to elicit any reductions in aerobic capacity or potential differences between the two triathlon suits.

The capacity of the environment to impact the participants' ability to maintain heat balance was not different between the AERO and THERM conditions as no difference in E_{max} was observed. Further to this, there were no differences in dry heat loss between the two suits at any time point throughout the exercise protocol. It may be that in these ambient conditions there became less reliance on dry heat loss thus, less importance of the conductivity of the triathlon suit fabric, and more reliance on evaporative heat loss. Especially after prolonged sweating that caused the triathlon suit fabric to become somewhat saturated. Périard et al. 2021 report that in ambient temperatures <20°C, dry heat loss is the primary avenue of heat loss whereas >20°C the contribution of evaporative heat loss becomes much higher. This continues to increase with increasing ambient temperature. It would be useful to further study the evaporative resistance differences between the AERO and THERM main body fabrics to help identify the magnitude and efficiency of heat transfer through the sweat saturated suits and whether this variable impacted the results in the present study. Individual differences in AVT10 were apparent with the participant attaining the highest T_{gi} and T_{sk} of all. In this participant, there were no differences in normalised H_{prod} in AERO at 60 minutes (380 $W{\cdot}m^2$) compared to THERM at 60 minutes (380 $W{\cdot}m^2$) but there was a 30W difference when comparing at 105 minutes in AERO (434 $W{\cdot}m^2$) versus THERM (454 $W{\cdot}m^2$). Although, this does not fit the trend of a higher T_{gi} at 105 minutes in AERO (39.2°C) compared to THERM (38.6°C). However, AVT10 saw a lower contribution of dry heat loss in AERO at both 60 minutes (95 $W{\cdot}m^2$) and 105 minutes (90 $W{\cdot}m^2$) compared to THERM at 60 minutes (118 $W{\cdot}m^2$) and 105 minutes (125 $W{\cdot}m^2$) which may have been the difference between the suits. In AERO, there may have been an earlier onset of sweating or larger reliance on evaporative cooling compared to THERM. They experienced a 134g larger change in body weight loss in AERO (-2.066kg) compared to THERM (-1.932kg) however, neither the time of sweat onset nor amount of suit sweat saturation can be distinguished to conclude this difference in the avenue of heat loss impacted thermoregulatory differences. This also supports the importance of understanding the evaporative resistance and wicking potential of each fabric.

RPE is reported to be higher in the heat compared to a cool environment and increases with time across all environmental conditions (Maw 2003). In the present study, although there was no impact of the suits on thermoregulation over time, participants found the exercise increasingly more difficult despite maintaining the same power output although this was not significant. RPE continually increased from 12 at 30 minutes in both conditions to 14 and 15 in THERM and AERO, respectively by 105 minutes. Further to this, $\bar{T}_{sk}$ and T_{gi} did not increase in the same fashion seen in RPE suggesting the increases in RPE are more likely due to fatigue induced by the physiological demand of the exercise rather than any perceived or actual thermoregulatory failure.

The largest increase in whole-body T_{sens} was observed from rest to 15 minutes of exercise with the same change of 2 ± 2 observed in both AERO and THERM triathlon suits, despite only an average change in $\bar{T}_{sk}$ of 0.1 ± 0.2°C in AERO and 0°C in THERM, from baseline. Unfortunately, there are little data explaining the threshold of $\bar{T}_{sk}$ that elicits a specific change in thermal sensation. Plateaus in warm T_{sens} were observed from 30 minutes in both conditions until resting recovery where T_{sens} returned to near resting votes, between neutral and slightly warm and $\bar{T}_{sk}$ were 0.4 ± 0.5°C and 0.3 ± 0.4°C from baseline in AERO and THERM, respectively. The small changes in $\bar{T}_{sk}$ in the present study were enough to elicit changes in whole-body T_{sens}, but not enough to elicit significant thermoregulatory dysfunction. With the exposure of a whole-body to a warm environment, Gagge et al. (1967) reported T_{sk} and T_{sens} to increase together until the onset of sweating where variables stabilised, which is what is seen in the present study up until 30 and 45 minutes in AERO and THERM, respectively. Upon the onset of sweating, Gagge also reported that no further increase in thermal sensation was apparent as was seen in the present study. Despite this, Gagge reported a continual increase in thermal comfort, meaning participants felt increasingly more uncomfortable despite no change in T_{sk} and T_{sens}. However, this continual decrease in T_{comf} was not observed in the present study. They attributed the increase in T_{comf} to the skin wettedness rather than T_{sk} and as there were no differences or increases in w_{per} from 30 minutes onwards in AERO and 45 minutes onwards in THERM, it may explain why there was no observed increase in T_{comf}. Research from Vargas et al. (2018) showed that mean skin wetness contributes to perceptions of thermal discomfort to a greater extent than both T_{core} and T_{sk} and suggests that in the present study, the exercise intensity and ambient conditions initiated a comfortable skin wetness that also allowed the maintenance of a comfortable T_{sk} and T_{sens}, concomitantly.

It is well known that VO_2 is a function of exercise intensity and when exercising at a moderate steady-state workload below lactate threshold, VO_2 gradually increases in the first 15-25 seconds of exercise until reaching a plateau after 2-3 minutes to meet oxygen demand (Roston et al. 1986). If the exercise intensity calculated for participants in the present study was >LT2, a constant increase in VO_2 would be seen from the beginning to the end of the main exercise phase (Jones et al. 2011). As all the exercise intensity in the present study was prescribed at or below 85% LT2, there is no expected increase in VO_2 throughout the exercise protocol as at this intensity, the ability for lactate buffering is higher than that being produced. This is reflected in the data through the metabolic data with no significant reduction in RER to suggest glycogen depletion (Weltan et al. 1998) or increased VO_2 to suggest fatigue and a need for increased oxygen utilisation. It provides reassurance that prescribed intensity was correct.

One limitation of the present study ishe average convective rate across both conditions was 2.4 m/s. During a race, athletes can experience 11m/s when riding at 40kph. By increasing the rate of convection, instantly there would be an increased rate of dry heat loss, irrespective of sweating and any associated evaporation. This could potentially then start to show differences between the suits due to their differences in thermal conductivity and effusivity, despite how small this may be as it is assumed there would then be less reliance on the evaporative cooling avenue of heat loss. Lastly, the study does not account for any solar load a triathlete may experience when competing in warm conditions. Solar load causes significant narrowing of the skin-to-core temperature gradient by increasing T_{sk} higher than that with less solar load or no solar load (Otani et al. 2016). This could then impact the fight for skin versus muscle blood flow and may be where triathlon fabric choices become pivotal to temperature regulation.

As the interest relating to the interaction between thermal physiology, thermal perception and sports clothing in research and industry grows, it is important to understand its relation to the practical application. Much of the previous research has taken place in cycling and running in isolation with specific disregard to the fact that in triathlon the three disciplines are completed in sequence. Therefore, not only should these data from the present study be considered in cycling alone, but also identify any impact of cycling clothing manipulations on subsequent running performance. The ability of a triathlete to competently distribute their energy expenditure throughout the duration of an event such as half-ironman is vital to performance and can be achieved with the correct pacing and feeding strategies. The success of these strategies is reportedly attributed, but not limited to, exercise duration, substrate energy availability, racing experience, cognitive function, central and peripheral feedback and thermoregulation (Wu et al. 2014). During the ride, dissipation of the high metabolic heat produced by riders is largely aided by the high convection rates. However, when they get to the run, the increase in oxygen demand required for running in comparison to riding (Scott et al. 2006), as well as continuous heat production from the exercise places further strain on the thermoregulatory system. Added to by the immediate reduction in convection and thus, convective cooling. Evidence shows reductions in stride-length, higher muscle oxygenation, reduced running economy and higher oxygen consumption when running off the bike compared to a single isolated run (Olcina et al. 2019). With less economical and efficient performance off the bike comes larger amounts of heat production that needs a pathway to dissipate to maintain both performance and health. Again, this may be in this instance where smart clothing fabric selection could have the biggest impact on body heat loss. Currently, only active cooling methods are adopted during the run phase of a triathlon, but many beneficial methods are still too impractical to be used during competition. Cooling methods such as cooling neck collars (Tyler, Sunderland 2011), ice vests (Duffield et al. 2003b; Luomala et al. 2012b; Cuttell et al. 2016), menthol (Barwood et al., 2015) and ice-slurry ingestion (Stevens et al. 2013) have all proved beneficial by increasing tolerance to higher core temperatures, longer times to exhaustion and increased thermal perception to either run or cycling performance. There is potential for the thermally optimised fabric to be advantageous in the run as it may allow for an increase in heat capacity like that attained using traditional active cooling methods and further study should investigate this.

6.6 Conclusion

The results of this study show no difference in the impact of either the aerodynamically optimised or thermally optimised triathlon suit on thermoregulation or thermal perception during steady-state exercise in 28°C and 65% relative humidity, although individual differences are apparent. In environmental conditions reflecting that in the present study, the aerodynamic optimisation should be prioritised over the thermal optimisation suit.

Chapter 7

Quantifying Differences in C_dA and Predicted 90km Time Trial Performance Between Aerodynamically and Thermally Optimised Triathlon Suits on an Outdoor Velodrome

7 Chapter Summary

The previous chapter aimed to investigate the differences in thermoregulatory and perceptual responses to aerodynamically (AERO) and thermally (THERM) optimised triathlon suits after thermal characterisation of both main body fabrics. Results showed no differences in gastro-intestinal temperature, mean skin temperature, mean body temperature, heart rate or perceptual variables of perceived exertion, thermal sensation, thermal comfort or skin wetness. Thus, suggesting the differences in thermal conductivity and effusivity reported in chapter 3 are not enough to elicit a whole body measurable difference during exercise in 28°C and 65% RH.

This chapter will firstly aim to assess any differences in aerodynamic drag coefficient between the AERO and THERM triathlon suits and secondly apply these data to predict time trial time losses or time savings. Participants undertook 2 x 1600m, equating to a ~3.2km per run, on an outdoor velodrome. Target speed for each session was 40kmph with all participants receiving feedback on their lap splits to help maintain even pacing. Participants then swapped triathlon suits (AERO or THERM) and the same protocol was repeated. All runs were undertaken on participants' own time trial (TT) bikes in their normal TT position. A Notio Konect, attached to the base bar of each participant's bike, was used to measure aerodynamic drag coefficient (C_dA) between the AERO and THERM suits with power output, cadence and speed data integrated though Bluetooth. These data were then used to model 90km time trial performance. Results showed no difference in C_dA between the AERO suit ($0.245 \pm 0.024m^2$) and the THERM suit ($0.248 \pm 0.028m^2$) however, individual differences were apparent. A lower C_dA was observed in 3 participants when wearing the AERO suit versus the THERM suit. Whilst one participant found a lower C_dA wearing the THERM suit. These data were reflected in the subsequent predicted 90km time trial performance times where one participant saw a -88.5s time saving when wearing the THERM suit compared to the AERO suit. Whereas three other participants saw time losses of +54.2, +84.2 and +139.1s when wearing the THERM suit compared to the AERO suit. Data from the present study highlight the importance of individualised aerodynamic assessment and optimisation as neither the AERO suit nor the THERM suit was beneficial to all riders but on an individual level can provide a significant performance benefit to 90km time trial performance.

7.1 Introduction

Aerodynamics is the study of the movement and pressure differences between the air and any solid body that moves through it. By understanding the pressure differentials, the aerodynamic forces acting on a body can be calculated. The relationship between clothing design, aerodynamics and performance optimisation is a complex problem investigated by many to optimise motion in several sports including motor racing, cycling, speed skating, skiing, running and triathlon (Brownlie et al. 2009; Oggiano et al. 2013). Although these sports are very different in nature, they all aim to reduce aerodynamic drag on the athlete-equipment system as much as possible, using the same principles, as it is pivotal in reducing racing time. The calculation of aerodynamic drag force ($F_{D,}$ N) is dependent on four main variables; the rider-bike system projected frontal area (A, m^2), the speed of the system (v, $m \cdot s^{-1}$), its drag coefficient ($C_{D,}$ dimensionless) and the environmental air density (ρ, $kg \cdot m^3$). Aerodynamic drag is therefore expressed as:

$$F_D = \frac{1}{2} \rho v^2 C_D A$$

The drag coefficient (C_D) is a dimensionless value commonly used to quantify the resistance or drag an object is experiencing as it moves through the air. A lower C_D indicates the rider is experiencing less aerodynamic drag than a rider with a high C_D and is calculated using:

$$c_d = \frac{2F_d}{\rho u^2 A}$$

Where, C_D = drag coefficient (dimensionless), F_D = drag force (N), ρ = environmental air density (kg·m^3), u = the speed of the system (m·s^{-1}) and A = frontal area (m^2).

Reducing C_d can be achieved by manipulating its two main contributors; form drag and friction drag. This is achieved by making the rider-bike system more streamline and by altering the flow of air that is close to the body to delay the flow separation, respectively (Figure 3.1, Chapter 3).

Form drag has by far the biggest impact on drag coefficient and is impacted specifically by the shape of the rider due to its harsh bluff shape. At high velocity, high pressure air hits the body and quickly separates leaving a large pressure wake behind the rider, increasing drag. In cycling, this is successfully reduced by decreasing the rider's frontal area using aero bars (0.4174m^2), decreasing hip angles (0.4594m^2), tucking the head between the arms (0.3850m^2) and shrugging the shoulders (0.3855m^2) (Barry et al. 2015). Despite this, the trend between C_D and A is not universal and drag is not entirely determined by A. Preventing the loss of airflow momentum as it travels around the body is also imperative to maintaining a high velocity, laminar wake behind the rider to reduce drag. This can be achieved by increasing friction drag on areas of the body, such as the shoulders, with the use of rough fabrics. From small cylinder wind tunnel tests, the use of these rough fabrics reduce the R_e number at which minimum drag is observed (Brownlie et al. 2009) being matched with the speed at which the triathlete or cyclist is travelling at, as the C_D of the cyclist is dependent on R_e (see chapter 5, section 5.1).

In cycling, there are two different airflow states; flow transition in the boundary layer and flow transition in the shear layer and differences are observed in both based on the Re and flow regime. At subcritical

Re numbers, the boundary layer airflow is laminar and the point at which this separates from the cylinder (88-82° downstream from stagnation point) means the wake region is wider than the diameter of the cylinder. This characteristic airflow is termed the subcritical regime (figure 7.1A). Further increases in R_e number results in a transition of air state from the shear layer to the boundary layer where a mixture of both laminar and turbulent air is apparent. This is termed the critical or transitional regime and increases the complexity of any simulations, modelling or predictions of airflow behaviour difficult (figure 5.1B, Kološ et al. 2021). Here, there is a reattachment of air to the cylinder after the laminar separation. This reattachment causes a smaller wake once the air detaches once again but this time, further round the cylinder. In this instance, a 'drag crisis' occurs which is characterised by a signficant drop in C_D. By increasing the surface roughness of the cylinder, the width of the critical regime narrows (Buresti 1981). Following this is the postcritical regime occurs where C_D is constant once again (figure 7.1C, Malizia, Blocken 2021).

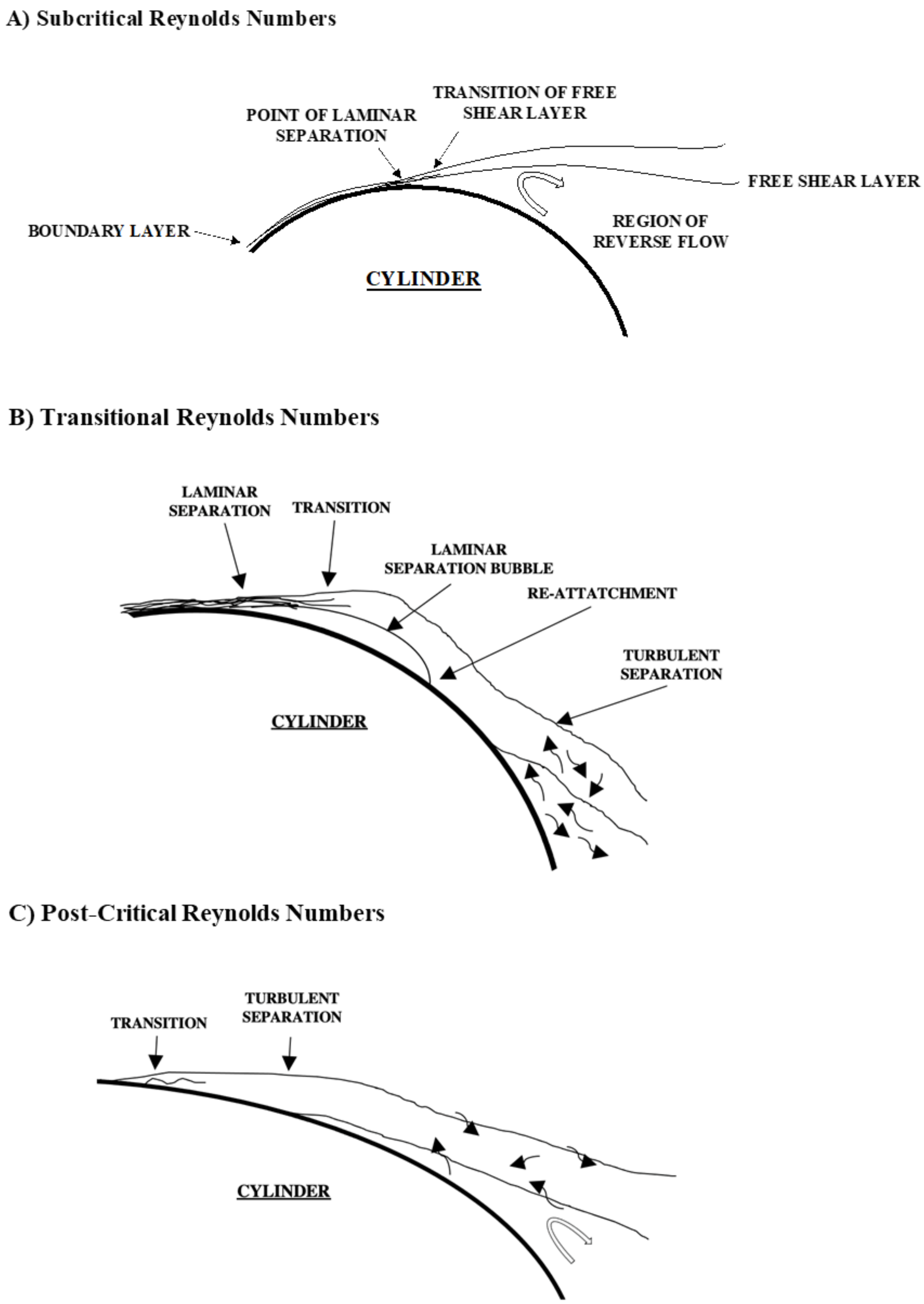


Figure 7.1: A) Sub-critical B) Transitional and C) Post-critical airflow regimes across a cylinder (Re-drawn from Malizia, Blocken 2021).

In practical terms, at the speeds observed in elite half-Ironman® races, this means that for the same power output, a cyclist will have a higher velocity when wearing a triathlon suit with rough shoulders compared to an entirely smooth triathlon suit. Wearing rough shoulder can also translate to significant energy savings, if the cyclist decides to maintain the same velocity which can prove valuable on the subsequent concluding run of the triathlon.

The aerodynamic drag of the rider-bike system can be accurately measured in a wind tunnel and the controlled environment allows for the assessment of different wind speeds and yaw angles (Crouch et al. 2021; Isvan 2015). It is of increasing interest to measure aerodynamic drag in the field to provide more ecologically valid data. Kordi et al. (2021) used a Notio Konect device to derive C_dA of riders in real time on an indoor velodrome which allowed for values that reflected what they would be experiencing in a race to a better extent than the application of wind tunnel data. This study found the Notio Konect to be highly sensitive (1.2% or 0.0002m^2) with highly reproducible data. This device utilises a pitot tube, temperature, humidity, a gyroscope and an accelerometer alongside the integration of cadence, power output and speed sensors to accurately and reliably estimate C_dA in the field.

The focus of most wind tunnel research aims to make the individual faster and discounts the integration and importance of any thermal aspects of fabrics. The thermal aspects of fabrics become important when athletes are competing in hot environments. In chapter 5, fabrics were characterised in terms of their thermal and aerodynamic characteristics. It was then seen, in chapter 6, that despite fabric ‘C’ having a higher thermal conductivity than fabric ‘H’, this difference was not enough to elicit changes in thermoregulatory parameters in the specific environment (28°C, 65% RH) when applied to the whole-body. It was also found that fabric ‘H’ had a lower F_D than all other fabrics, however, it is not known how these differences in aerodynamic data between the AERO and THERM fabrics, from the wind tunnel testing, subsequently impact rider aerodynamics in the field. The first research question in this chapter asks; are there differences in aerodynamic drag between the aerodynamically optimised and thermally optimised triathlon suit? Secondly, can these data be successfully modelled to observe differences in predicted 90km time trial performance between the aerodynamically and thermally optimised suits?

7.1.1 Aims & Hypothesis

Therefore, the aims of the present study were to firstly assess the difference in aerodynamic drag between the aerodynamically optimised (AERO) and thermally optimised triathlon (THERM) suits. The second aim was to apply these data to predict 90km time trial performance. It was hypothesised that the aerodynamically optimised suit would result in lower C_dA measurements and power savings, resulting in significant predicted time savings calculated over a 90km distance.

7.2 Methods

7.2.1 Participants

Seven male cyclists and triathletes volunteered to take part in this study (age 34 ± 13 years). All participants regularly raced in cycling time trials or triathlons. Based on the cohort’s training load, the performance level of participants was classified as level 4 (de Pauw et al. 2013). All participants gave written informed consent prior to the undertaking of the study.

7.2.2 Experimental Protocol

All experiments were carried out on a 400m outdoor velodrome (Newcastle Under Lyme, UK) on dry days with wind speeds less than 18kmph or 5 m/s. All participants wore their standard race suit, socks and shoes and familiarised themselves on the track for 10-20 minutes prior to any testing. Participants were advised on riding lines to take during each testing session to reduce any variation in lap times, lap distance and to prevent any velocity gain from the track gradient. The order of conditions was randomised to reduce any learning or order effects. The bike and Notio Konect were all kept away from direct sunlight to prevent any impact on the environmental conditions measured by the Notio Konect as well as tyre pressure and thus, rolling resistance during trials. All trials were completed in the riders’ normal TT position. Each participant completed 2 x 1600m runs, equating to a ~3.2km. Each 1600m run was separated by 3 low intensity laps around the same track. The target speed for each run was 40kmph with all participants receiving feedback on their lap splits to help maintain even pacing. Participants then swapped triathlon suits (AERO or THERM) and the same protocol was repeated. Participants were blinded to conditions.

7.2.3 Experimental Trials

7.2.3.1 C_dA and Aerodynamic Drag Measurement

Each participant used their own power meter, which was calibrated according to the manufacturers' instructions prior to testing. Participants were provided with magnetic speed and cadence sensors directly attached to their bike (Garmin, Kansas, USA). These sensors were connected wirelessly to the Notio (Notio Technologies, Montreal, Canada). The Notio was then fixed to the base bars of the bike with the pitot tube facing directly forward. The mass of the rider, bike and their clothing were then measured and recorded. The Notio was calibrated during a 3000m warm up where participants were instructed to ride at 40kmph whilst maintaining a consistent riding line, gear ratio and speed. Prior to the first 3.2km trials, participants undertook a 2-lap build up to reach target speed. All participants were then given lap-by-lap feedback on their split times every 400m lap to reduce any variation and ensure the 1600m was completed in the same amount of time. Following completion of the first 1600m, riders completed 3 low intensity laps before immediately commencing the second 1600m. Participants had 10 minutes rest between experimental conditions (AERO and THERM), including the swapping of triathlon suits.

Figure 7.2: Front and back of fully finished triathlon suit used for testing in the large wind tunnel.

7.3 Data Analysis and Statistics

The NK recorded speed, power, cadence and environmental variables, which were all recorded at 4Hz. Analysis was undertaken using the Golden Cheetah Notio software (https://goldencheetah.org/) using the velodrome function to allow for the gyroscope to identify individual laps and derive C_dA. Data for each condition was averaged across the entire 2 runs of 1600m. High measurement repeatability of the Notio Konect has been demonstrated between runs by Faulkner et al. (2022, under review, Kordi et al., 2021) with a coefficient of variance of 1.54% and ICC of 0.95.

All analysis was undertaken using Microsoft Excel and GraphPad Prism. Prior to statistical analysis, all data were tested to ensure normal distribution using Shapiro-Wilk tests. Paired t-tests were performed on power, cadence, ground speed, air density and C_dA. A Pearson's correlation was performed on the change in time trial time and change in C_dA. All alpha values were 0.05. All data is presented as mean

± standard deviation. The 90km time trial time prediction calculations are displayed in chapter 3, section 3.3.

Given that there is high expected variability in C_dA when wearing the two triathlon suits the smallest meaningful change (SMC) and effect size was calculated. Effect sizes were according to Cohen and categorised as 0.2 = small effect, 0.5 = medium effect, 0.8 = large effect (Cohen, 1988).

7.4 Results

7.4.1 Cadence, Speed and Air Density

There was no difference in cadence between conditions (AERO: 86 ± 9 rpm vs. THERM: 86 ± 8 rpm, p= 0.53). No differences in air speed were found measured by the Notio Konect device found (AERO: 41.7 ± 2.3 kmph vs. ± THERM: 41.7 ± 2.6 kmph, p= 0.60), or ground speed measured by the Garmin between conditions (AERO: 41.0 ± 2.1 kmph vs. THERM: 41.1 ± 1.9 kmph, p= 0.54). There were no differences in air density between the AERO and THERM conditions (AERO: 1.18 ± 0.01 kg/m^3 vs. THERM: 1.18 ± 0.01 kg/m^3, p= 0.35).

7.4.2 C_dA and Time Savings – Grouped Data

C_dA in the AERO suit was 0.245 ± 0.024m^2 and 0.248 ± 0.028m^2 in the THERM suit yielding a difference of 0.003m^2 between the two conditions. However, this was not significant (p= 0.30). Aerodynamic drag corresponded to 235 ± 13W in the AERO suit and 237 ± 18W in the THERM suit with no difference between conditions (p= 0.39). Cohen's *d* yielded trivial to moderate group effect sizes of the THERM suit when compared to the AERO suit for C_dA (*ES* = 0.1) and aerodynamic drag (*ES* = 0.6). The grouped time saving when wearing the AERO suit compared to wearing the THERM suit was 35.5s ± 46.7s.

7.4.3 C_dA and Time Savings – Individual Data

The SMC for C_dA was calculated to be 0.005m^2 meaning four out of the seven participants found a meaningful difference in C_dA with the remaining three finding no difference between the triathlon suits. Participant 1 had a lower C_dA in the thermal suit whereas participants 2, 3 and 4 had a lower C_dA in the AERO suit.

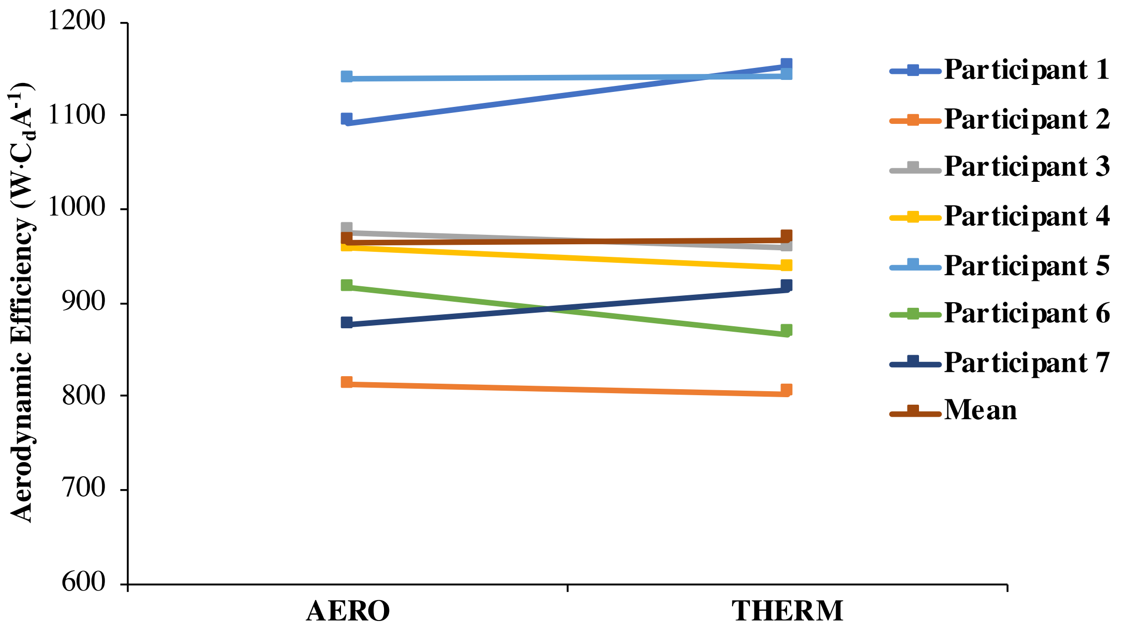


Figure 7.3: Individual differences in aerodynamic efficiency between the AERO and THERM triathlon suits.

The SMC for predicted time saving improvements when comparing the two suits was 1.0% which equated to 34s. Four out of the seven participants saw meaningful differences between the two triathlon suits. Participant 1 saw a -88.5s time saving when wearing the THERM suit compared to the AERO suit, whereas participants 2, 3 and 4 saw time losses of +54.2, +84.2 and +139.1s, respectively, when wearing the THERM suit compared to the AERO suit. The remaining three participants saw no meaningful differences in predicted times (Table 7.1).

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Table 7.1: Individual participant data from the Notio Konect of the absolute and percentage difference in C_dA, the change in power (Δ Power) when wearing the THERM suit compared to the AERO suit and the time savings or losses (Δt) between the suits (THERM – AERO).

Participant	C_dA (m^2) Difference (m^2) (THERM-AERO)	C_dA (m^2) Difference (%) (THERM-AERO)	Δ Power (W) (THERM-AERO)	Δt (s) (THERM-AERO)	Most beneficial suit based on predicted 90km TT saving
1	-0.008	-3.4	-7	-88.5	THERM
2	0.005	1.9	4	+54.2	AERO
3	0.009	3.4	9	+84.2	AERO
4	0.013	5.3	11	+139.1	AERO
5	0.001	0.6	2	+15.7	ND
6	-0.002	-0.7	-1	-18.0	ND
7	0.000	0.0	0	-0.1	ND

7.5 Discussion

The aims of the present study were to assess the differences in C_dA between the aerodynamically optimised and thermally optimised triathlon suits and apply these data to predict 90km time trial performance. In line with the hypothesis, beneficial reductions in C_dA were observed when wearing the AERO suit, compared to the THERM. On the contrary, this was not observed consistently across all participant. To a degree, this was to be expected due to the complex and individualised nature of aerodynamics. This highlights the importance of individualised aerodynamic assessment and clothing optimisation as different suits have the potential to provide a significant performance benefit to 90km time trial performance.

Although form drag has by far the largest impact on the drag force exhibited on the body, friction drag should not be discounted, more specifically for main body fabrics in cycling suits. Previous studies state that changing the shoulder fabric roughness on cycling suits produces the largest benefit to drag, at specific performance speeds and R_e numbers, as it helps maintain the attachment of the turbulent boundary layer to the body by initiating the transition of air from laminar to turbulent flow and delaying air separation and wake development (Sprukland et al., 2015, Hsu et al., 2021). However, not only do shoulder fabrics influence boundary layer separation and subsequent C_dA, main body cycling suit fabrics also play a role. It is suggested that, the friction drag profile of the triathlon suit that gave individual participants more of an aerodynamic benefit allowed for more efficient movement of air flow over the body, regardless of whether it was AERO or THERM suit. These data also indicate that small changes in main body fabric can significantly influence air movement, drag and predicted time trial performance.

The present study also challenges the need for any sizeable change in time trial position to generate both a significant aerodynamic and performance advantage. Riders commonly attempt to reduce their frontal area (*A*) and thus, C_dA by decreasing hip or torso angle with a reduction of hip angle from 24° to 0° resulting in a 14% decrease in *A* (Fintelman et al. 2014). However, this reduction in torso angle is not always beneficial as the changes in position impact both body shape and the air flow around it. Generally, lower C_dA values are reported where a rider's *A* is also low however, individual differences are common. In some riders, optimal aerodynamic torso angle is not always the smallest torso angle (Underwood et al. 2011). Further to this, the acute decrease in power output and lower aero-physiological economy that has been reported with smaller hip angles suggests the decreased torso/hip angle can be detrimental to performance (Faulkner, Jobling 2020). It would be beneficial for future research to focus on whether these acute detriments in power and economy can be reversed with training, especially if there is an aerodynamic advantage. Comparable heart rates for a lower power output have been observed at lower torso angles, suggesting a degree of cardiovascular strain (Fennell et al. 2020). Pairing this with any competition in heat, a decreased torso angle and thus lower potential for convective and evaporative cooling could have significant implications on an athlete's thermoregulatory capability. This is where the THERM fabric may prove more beneficial, when athletes are aiming to reduce frontal area through changes in hip angle alongside appropriate fabric selection, especially in hot conditions. However, the question still stands as to whether the differences in C_dA would be seen as beneficial if a thermoregulatory advantage was observed in the THERM fabric in conditions where ambient temperature was higher than that displayed in the previous chapter. Higher environmental temperatures have the potential to increase cardiovascular strain and, especially when riding with a lower torso angle. Instead of increasing torso angle and changing C_dA, the use of the thermal suit may be beneficial in offsetting an amount of thermal stress. This should certainly be considered as an aim for further study.

Individual differences observed in response to both the AERO and THERM triathlon suits may be attributed to testing sessions being undertaken on separate days with differing environmental conditions (28ºC & 65% RH). However, no differences in air density between the two conditions was found. Differences in air density across different days would have impacted the calculation of both F_D and C_D by the Notio Konect as it uses sensors of temperature, humidity and pressure to calculate air density(ρ) alongside the pitot tube to measure static and dynamic pressures to estimate C_dA. As the measurement of dynamic pressure is a direct product of fluid density and as aerodynamic forces are directly proportional to dynamic pressure, higher fluid density results in higher C_dA estimates. Air speed and ground speed did not differ between participants in conditions. A tail wind could have created an element of error within measurements as velocity will increase with no change in power output and a head wind will require riders to increase power output to maintain the same velocity. However, this effect is countered when using a track or circuit as the head and tail wind will balance. It may need more consideration when testing on an open road as marginal differences in velocity are further exacerbated in equations as the velocity is squared. This can subsequently result in an underestimation or overestimation of calculated aerodynamic drag force. Although no meaningful changes were observed in three of the four participants that observed a benefit when comparing the two suits, with regards to time savings, the absolute time differences for two of these three participants was still +16s when wearing THERM and -18s when wearing AERO. Thus, it appears that inherent form drag is primary influencing differences in C_dA between the participants and their individualised responses to the two triathlon suits. Specific fabrics may therefore work on some individuals and not others, purely based on the natural body shape when in their TT position.

Although the Notio Konect has been shown to be sensitive, repeatable and reliable enough to detect the differences seen in the present study (Kordi et al. 2021), on both an indoor and outdoor velodrome, there are clear issues with regards to controlling position and thus form drag on an outdoor track where there is an influence of wind. Additionally, it would be valuable to identify a more specific error in measurement when trying to recognise small differences in C_dA when the Notio Konect is used outdoors. Furthermore, a significant consideration is the application of the results. The triathlon suits are to be used in a racing environment where athletes are exposed to challenging environmental conditions meaning the data from the present study may be more applicable than those observed in a controlled indoor environment.

7.6 Conclusion

Results from the present study show aerodynamic drag data from small wind tunnel testing may not always reflect the absolute advantage it provides to a specific rider, due to the complex nature of individual aerodynamics. Thus, in conclusion, unless a significant thermoregulatory or perceptual benefit can be demonstrated from a fabric, the most aerodynamic fabric should be chosen over one optimised based on its thermal characteristics. It would now be of interest to investigate whether there are ways in which an aerodynamic fabric could be directly altered to help further facilitate heat loss from the body. The next chapter will discuss the impact of a phase-change polymer coating on thermoregulation and thermal perceptions during exercise.

Chapter 8

Investigating the Impact of a Polymer-Coated Triathlon Suit on Thermoregulation, Heat Loss and Thermal Perception During Steady-State Exercise in the Heat

8 Chapter Summary

The previous chapters showed no differences between the aerodynamically optimised and thermally optimised suits with neither suit impacting T_{gi}, $\bar{T}_{sk}$, $\bar{T}_{b}$, HR or thermal perception. In the environmental conditions chosen in the previous study (28°C, 65% RH), athletes should choose to use the more aerodynamic fabric as the main body fabric of their suit due to its time saving potential without any negative impact on the body's ability to thermoregulate (chapter 4). Furthermore, meaningful differences in predicted 90km TT performance were observed with manipulation of main body triathlon suit fabrics. However, individual differences were apparent. Further methods of per-cooling by direct manipulation of the fabric surface should be studied to help create one fabric that is aerodynamic and beneficial for heat loss.

This chapter aims to investigate the effect of manipulations in tri-suit textile coating on thermo-physiological and perceptual responses to sub-maximal, steady-state exercise in a warm and humid environment. Participants undertook 90 minutes of sub-maximal cycling exercise, at an ambient temperature of 28.1 ± 0.1°C and 66.6 ± 0.6% relative humidity (RH). Heat rate (HR), skin temperature ($\bar{T}_{sk}$), gastro-intestinal temperature (T_{gi}), oxygen uptake ($\dot{V}O_2$) and perceptual measures of perceived exertion (RPE), thermal comfort (T_{comf}), thermal sensation (T_{sens}) and skin wetness (w_{per}) were measured every 5 minutes throughout the entire exercise protocol. Two suits were compared in the present study; control suit (CON) with no manipulation and a polymer-treated suit (TRE) coated with MOOV&COOL™, a polymer coating designed to accelerate heat loss. It was hypothesised that the polymer treated tri-suit would aid evaporative heat loss, via greater sweat wicking, compared to the non-treated control. Contrary to the hypothesis, results showed the treated suit had no effect on HR, $\overline{T}_{sk}$, $\overline{T}_b$, T_{gi}, $\dot{V}O_2$, or perceptual measures throughout the steady-state exercise protocol or during recovery (all $p>0.05$). There was a tendancy for the polymer treated suit to withhold more sweat, suggesting an increased wicking capacity. If convection was more ecologically valid, the increased sweat retention in the polymer coated suit may have evaporated thus, facilitating more heat loss. The polymer exhibited neither a positive or negative impact on the ability to thermoregulate and did not effect participants' thermal perception. Thus, when deciding on fabrics to incorporate into a triathlon suit, if environmental conditions in a race reflect the conditions used in the present study, a more aerodynamic fabrics should be favoured with the polymer coating applied.

8.1 Introduction

In an environment with an elevated ambient temperature, evaporative cooling is the most important avenue of heat loss and is critical to maintaining optimal heat balance. Body morphology, metabolic heat production, clothing properties and environmental humidity all effect the amount of evaporative cooling (E_{req}) that is required from the skin to maintain heat balance. These variables also govern the maximal evaporative capacity (E_{max}) an individual has the potential to attain within specific environmental limits. If E_{req} is higher than E_{max}, the environment is termed 'uncompensable' and the individual will be in a positive heat balance (i.e. a rise in body temperature). If E_{req} is lower than E_{max}, this environment is termed 'compensable' and individuals have the physiological capacity to maintain sufficient heat balance. In this instance, to maintain the balance, the sweat being evaporated will cool the skin, initiate a larger core-to-skin gradient and drive heat loss from the core.

To further drive heat loss from the core to skin, pre-cooling the skin and lowering core temperature (T_c) prior to exercise, is commonly used by athletes (Hunter et al. 2006). Lowering T_c immediately prior to competition increases an individual's heat capacity by widening the gap between starting T_c and the T_c at which an athlete's thermoregulatory system is significantly stressed and where performance is negatively impacted. Thus, by starting at a lower T_c it may increase time to fatigue or positively impact self-regulated power output during a fixed duration time trial (Nielsen et al. 1993).

During a long-distance triathlon, individuals are competing at intensities with high metabolic rates and high heat production. There is also evidence that pre-cooling may be beneficial for only ~20 minutes to ~45 minutes, only prolonging the onset of heat stress for a short time near the beginning of the race (Moss et al. 2021). Therefore, investigation of appropriate methods during competition cooling, or 'per-cooling', is imperative to creating a method that maintains a continuous level of body cooling throughout competition. One potential method of per-cooling can be attained by changing the properties of the textile used in sports clothing to facilitate sweat evaporation and heat dissipation away from the skin more efficiently. Theoretically, this could be achieved by using a phase change material (PCM). PCMs allow large amounts of latent heat to be absorbed or released as their physical state changes (Pause 2010). These materials can react to several stimuli such as moisture, light, heat and pH, for purposes such as colour changing fabrics, wound monitoring, protection from the environment and protection from hazardous substances (Pause 2010).

PCM treatments present in a solid state in an environment below their melting point. This is identified as its 'solid phase'. When exposed to a temperature beyond this, the polymer treatment changes from a solid to a liquid as it begins to store and move heat away from the object or body in question. This phase is known as the 'melting' phase. Once the PCM reaches is crystallisation temperature, it releases heat and returns to its solid state ready for the process to begin once again. However, elevated ambient temperatures, reflecting environments where the textile treatments would potentially have the most beneficial effect may directly impact the phase change. Warmer temperatures could cause the polymer to melt, leak and migrate as it absorbs high amounts of heat from the environment, rather than the body, reducing and even disabling its capacity to remove heat from any object or textile.

Recent efforts have proved more successful in the fabrication of new PCMs placed within a microcapsule that, once applied to the surface of a textile, still allows for the phase-change and latent heat absorption but prevents any leakage onto the textile once melted. Although this has provided more control of the melting phase, a significant negative consequence of this encapsulation is a reduction in moisture wicking and air permeability (Pause 2010). In a physiological context, this poor moisture management could lead to the prevention of heat loss from one of the most important channels during heat stress. Therefore, it may not necessarily provide any further benefit to heat loss than wearing a suit comprised of a non-treated textile.

In 2018, Devan Chemicals invented a modified phase-change polymer textile treatment named MOOV&COOL™ (Devan Chemicals 2019). It claims to mitigate the disadvantages of melting migration while providing better moisture management through its specialised, direct covalent bonding to the surface of the textile. If successful, it could be highly beneficial during long-distance triathlon by maintaining a continuous heat loss from the body through its phase changes, resulting in cooler body temperatures. The polymer is activated when the fabric gets wet, for example when an individual sweats in the suit. This causes a shape change in the polymer that helps facilitate and wick the sweat away from the skin and through the fabric. This will then allow the sweat and heat to be evaporated away from the suit, cooling the skin. As the sweat is evaporated, the suit will dry and the whole cycle of phase change can begin again. At present, there is no data investigating the impact of polymer PCMs on thermoregulation using human participants during exercise. The research question in this chapter asks; Are there any differences in thermoregulatory or perceptual differences between the control and polymer treated triathlon suits?

8.1.1 Aim

The aim of the present study is to investigate the effects of the new polymer textile coating tri-suit on thermoregulatory and perceptual variables during sub-maximal, steady-state exercise.

8.1.2 Hypothesis

It is hypothesised that the polymer treated tri-suit will facilitate heat loss via increased sweat evaporation compared to the non-treated control.

8.2 Methods

8.2.1 Participants

Ten well-trained cyclists volunteered to participate in this investigation (Table 8.1) and were equivalent to a performance level of 3 (de Pauw et al. 2013). All participants were familiar with the type of testing involved and competed in time trials and/or triathlon. All participants were required to be free from injury for the duration of the experimental period.

During testing periods, participants were asked to maintain their normal training schedule, refrain from heavy exercise and alcohol during the 24-hours prior to each laboratory session. Each participant completed their sessions at the same time of day to minimise the effects of circadian and diurnal rhythms on performance and physiological measurements, with individual sessions being separated by a minimum of 7 days.

The study was approved by the ethics board at Nottingham Trent University and performed in accordance with the Declaration of Helsinki. Prior to testing, participants completed a general health-screening questionnaire and provided their written informed consent.

Table 8.1: Participant Characteristics

	Mean ± SD
Age *(yrs)*	30 ± 10
Height *(m)*	1.82 ± 0.07
Weight *(kg)*	77.7 ± 9.1
BSA *(m²)*	1.98 ± 0.14
$\dot{V}O_{2max}$ *(ml/kg/min)*	56.16 ± 4.33
Body Fat *(%)*	11.2 ± 2.0

8.2.2 Study Overview

Participants were required to visit the laboratory on three separate occasions. The first visit consisted of 17-point skinfold anthropometry, height and weight. These data informed the calculation of body composition and body surface area (BSA):

$$BSA = 0.007184 \times (height)^{0.725} \times (weight)^{0.425}$$

Participants then performed an incremental $\dot{V}O_{2max}$ test, on a cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands) in 28°C and 65% relative humidity. Participants cycled at their preferred cadence, starting at 95W, with a 35W increase in power output every three minutes until volitional fatigue. $\dot{V}O_2$, $\dot{V}CO_2$, RER (Metalyzer® 3D, AD Instruments, Oxford, UK) and HR (Polar M400, California, USA) were recorded continually throughout the test, with data averaged over the final 30s of each stage. Prior to experimental testing, spirometry equipment, water bottles and calibration gas were left in the chamber to equilibrate to the higher ambient temperature and humidity. Calibration occurred prior to each $\dot{V}O_{2max}$ test and trial. The $\dot{V}O_{2max}$ test informed the participants' maximal aerobic power output and thus, the intensity at which the experimental trials were to be completed at.

The following visits consisted of two experimental trials whereby the properties of the tri-suits worn by the participants were manipulated. Condition 1 (CON) consisted of participants wearing a commercially available tri-suit (Core, HUUB Design, Derby, UK) with no prior physical changes to the fabric. Condition 2 (TRE) consisted of participants wearing the same tri-suit which had been entirely treated with the MOOV&COOL™ polymer coating. All participants were blinded to the conditions and a balanced assignment of the two conditions was calculated.

8.2.3 Experimental Protocol

Prior to testing, an ingestible telemetric pill (BodyCap, e-Celsius®, France) was given to participants to allow for the measurement of gastro-intestinal temperature (T_{gi}). Participants were instructed to take the pill ~10 hours prior to the start of each of the two experimental trials to ensure the pill had passed through into the gastro-intestinal tract. Pill function was verified upon arrival to the lab using a receiver (BodyCap, e-Celsius®, France) and its position confirmed by the ingestion of water.

Upon immediate arrival to the lab, participants provided a urine sample and urine specific gravity (USG) was measured (Atago Pocket Refractometer PAL-10S, Japan) to ensure sufficient hydration prior to exercise. Acceptable hydration was a USG of 1.020 or less. Participants were instructed to drink 400ml of water, if unacceptably hydrated. A second urine sample was analysed post-exercise to identify any degree of dehydration they may have occurred during experimental trials. Similarly, two fingertip blood samples were collected both pre- and post-exercise, in a 75μm microhaematocrit capillary tube (Jaytec Glass Ltd, Hastings, UK) which were spun in a centrifuge (Nickel Electro Clifton Clinical Centrifuge, NE030GT/I, 1000RPM for 10 minutes) to separate serum plasma and haematocrit components to assess plasma reduction owing to sweat loss. Tri-suits were weighed both pre- and post-exercise trial to measure the amount of sweat held in the material following each trial.

After hydration status was established, nude weight was recorded (Adam Equipment Co. Ltd., Milton Keynes, UK). Eight wireless thermistors (iButton DS1922, Sunnyvale, CA, USA) and four wireless hygrochrons (DS1923-F5, HomeChip Ltd, Milton Keynes, UK) were secured with porous tape (Transpore™ Surgical Tape, 25mm, 3M) at eight and four locations, respectively, as described in chapter 3. A heart rate monitor was placed around the torso to record heart rate (Polar M400, Kempele, Finland), The set-up, equipment and calculations used to measure skin temperature and skin wetness is described previously in chapter 6, section 6.2.3.

Thermoneutral carbohydrate drinks (6% maltodextrin w/w, MyProtein, unflavoured) were provided for the participants to drink *ad libitum* for the length of time spent in the environmental chamber. All fluids were kept in the chamber during the trial and bottles changed at regular intervals to prevent any conscious hydration strategy or targeted fluid intake. Bottles were weighed pre- and post-trial to assess differences in water and energy intake between trials.

8.2.4 Experimental Trials

All experimental trials took place in 28.1 ± 0.1°C ambient temperature and 66.6 ± 0.6% relative humidity. Participants rested for 5 minutes on the bike before commencing the sub-maximal exercise protocol. A 15-minute warm-up period was then completed which involved cycling for 5 minutes at 55% peak power output (PPO), 5 minutes at 65% PPO and 5 minutes at 70% PPO. This led immediately into the main protocol whereby participants cycled continuously, at a self-selected cadence, for 60 minutes at 65% PPO. Afterwards, for a final 15 minutes, power was dropped to 50% PPO to replicate a downhill gradient of a racing course. Following this, participants got off the bike and immediately rested in a seated position for 15 minutes in the chamber (figure 8.1).

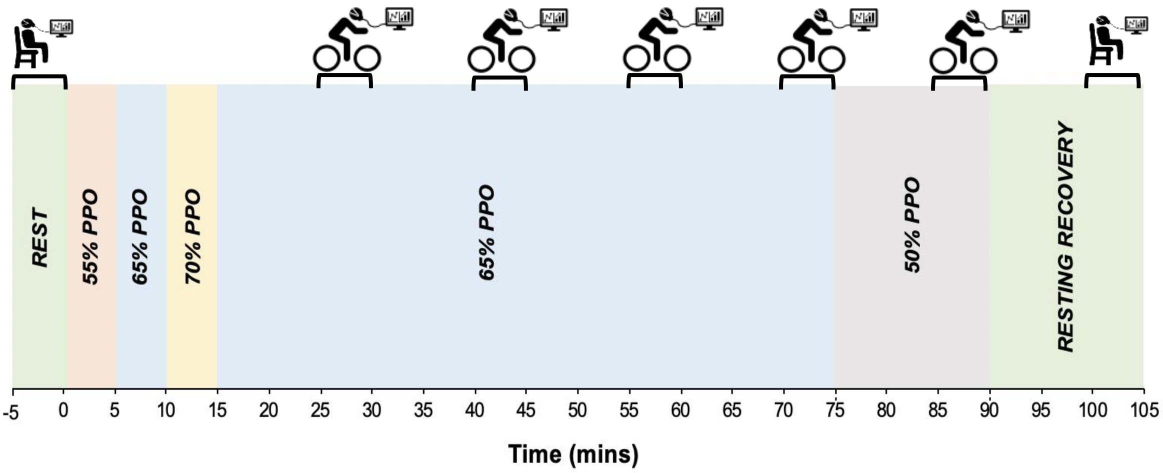

Figure 8.1: Cycling intensity and duration throughout the experimental trial. Symbols represent VO_2 collection points at rest, 25-30, 40-45, 55-60, 70-75, 85-90 and 100-105 minutes.

Ratings of T_{sens}, T_{comf}, RPE and w_{per} were collected every 5 minutes throughout the trial. Wind speed (w/s), barometric pressure (P_B), ambient temperature (T_a), relative humidity (RH), wet-bulb globe temperature (WBGT), HR and T_{gi} were continually recorded throughout the trial. $\dot{V}O_2$, $\dot{V}CO_2$, RER, $\dot{V}E$ and $\dot{V}O_2$ normalised to BW were measured for 5 minutes at rest and then for 5 minutes between 25-30, 40-45, 55-60, 70-75 and 85-90-minutes during exercise and during the last 5 minutes of resting recovery (figure 8.1). A vertical stack of three fans was positioned 1.5m in front of the participant on the bike and switched on at the beginning of the 55% PPO warm up and only turned off at the end of the 90 minutes exercise for the resting recovery.

8.3 Data Analysis

8.3.1 Calculations

Insulation values, energy expenditure (EE), heat production (H_{prod}), metabolic rate (M) and heat exchange variables were all calculated as noted in chapter 3, section 3.2.

8.3.2 Analysis and Statistics

Prior to all statistical tests, data was tested for normality, homogeneity of variance and sphericity using the Shapiro-Wilk, Levene's and Mauchly's tests, respectively, with a Greenhouse Geisser correction applied as necessary. All data are presented as means ± SD or change ± SD. Mean resting values presented were calculated by averaging the five minutes of the resting period. Each other individual time point (15, 30, 45, 60, 75, 90, 105) were calculated by averaging all data across the previous fifteen minutes of time.

Paired t-tests were performed on T_a, RH, wind speed, fluid intake (FI), sweat rate (SR), body weight change (ΔBW) and suit weight change (ΔSW) with an alpha value set at 0.05. A non-parametric Mann-Whitney U test was used to compared WBGT between the two conditions.

A two-way analysis of variance (ANOVA) was performed on T_{gi}, change in $T_{gi,}$ $\overline{T}_{sk,}$ change in $\overline{T}_{sk,}$ $\overline{T}_b$, change in $\overline{T}_b$, HR, change in HR, RPE, T_{sens}, T_{comf} and w_{per} to analyse differences between the CON and TRE conditions at different time points and differences within each condition. The alpha value was adjusted accordingly using a Bonferroni correction. Multiple Wilcoxon signed rank tests were undertaken to identify any differences in $\dot{V}O_{2,}$ $\dot{V}CO_2$, $\dot{V}E$ and $\dot{V}O_2$ normalised to BW between CON and TRE conditions.

The area under the curve (AUC) was calculated using the trapezoid method, calculating the area of each equivalent rectangles and summing the areas underneath the curve. This was undertaken for each participant which were then grouped into AERO and THERM where a paired t-test was performed. Values below are displayed as mean ± SD.

8.4 Results

8.4.1 Environmental Conditions

A difference was found in T_a (CON; 28.1 ± 0.4°C, TRE; 28.2 ± 0.5°C, p<0.0001), RH (CON; 66.8 ± 0.8%, TRE; 66.4 ± 0.8%, p<0.0001), WBGT (CON; 24.8 ± 0.4°C, TRE; 24.9 ± 0.5°C, p=0.0001), w/s (CON; 2.5 ± 0.4m/s, TRE; 2.4 ± 0.5m/s, p=0.0078) between conditions.

8.4.2 Area Under Curve

There were no significant differences in area under the curve between the suits in T_{gi} (AERO: 3969 ± 55, THERM: 3967 ± 28, p= 0.91), $\bar{T}_{sk}$ (AERO: 3548 ± 62, THERM: 3555 ± 55, p= 0.60), T_b (AERO: 3885 ± 49, THERM: 3884 ± 29, p= 0.99), HR (AERO: 14724 ± 1327, THERM: 14687 ± 1253, p= 0.91), RPE (AERO: 948 ± 149, THERM: 950 ± 129, p= 0.92), T_{sens} (AERO: 446 ± 133, THERM: 435 ± 104 p= 0.77), T_{comf} (AERO: 183 ± 39, THERM: 185 ± 41, p= 0.85) and w_{per} (AERO: 242 ± 101, THERM: 283 ± 77, p= 0.14).

8.4.3 Biophysics and Metabolism

There was no observed difference in EE in either the CON or TRE suits at 30 or 75 minutes of exercise (p= 0.26). There was no difference in EE between the CON and TRE suits at either 30 or 75 minutes (p= 0.64) (figure 8.2).

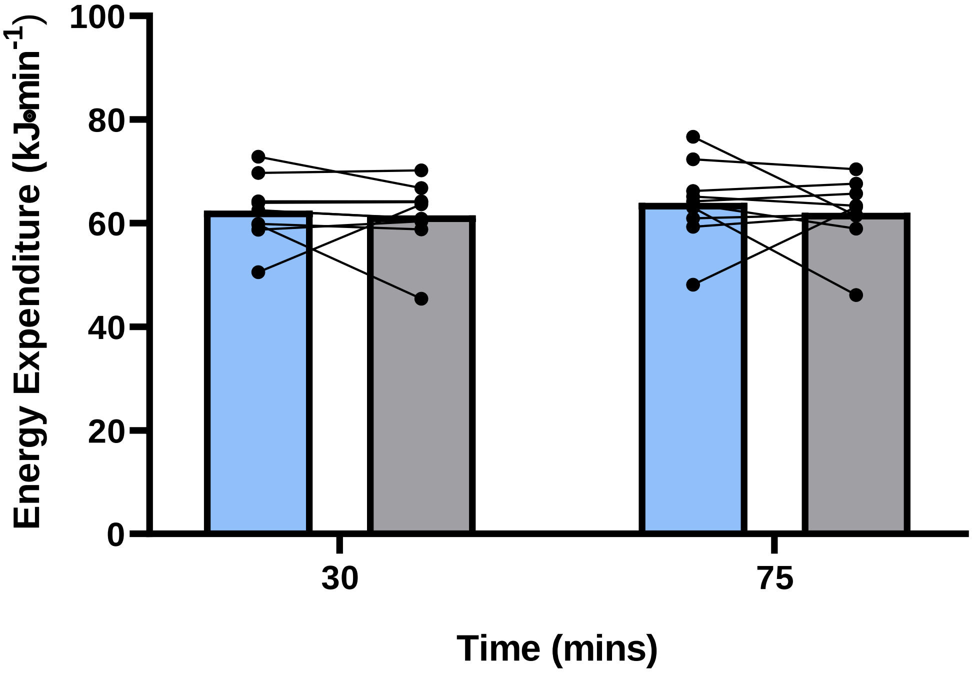

Figure 8.2: Differences in energy expenditure in CON and TRE suits at both 30 and 75 minutes. Individual data shown as black dots.

H_{prod} (W) was not different in either CON or TRE triathlon suits at 30 minutes or 75 minutes of exercise (*p*=0.26) nor was there a different between the two suits and either of these time points (*p*= 0.61). No further difference in H_{prod} was observed when normalised to BSA with no difference at 30 or 75 minutes of exercise in either triathlon suit (*p*= 0.25). There was no difference between the suits at either 30 or 75 minutes of exercise (*p*= 0.60) (figure 8.3).

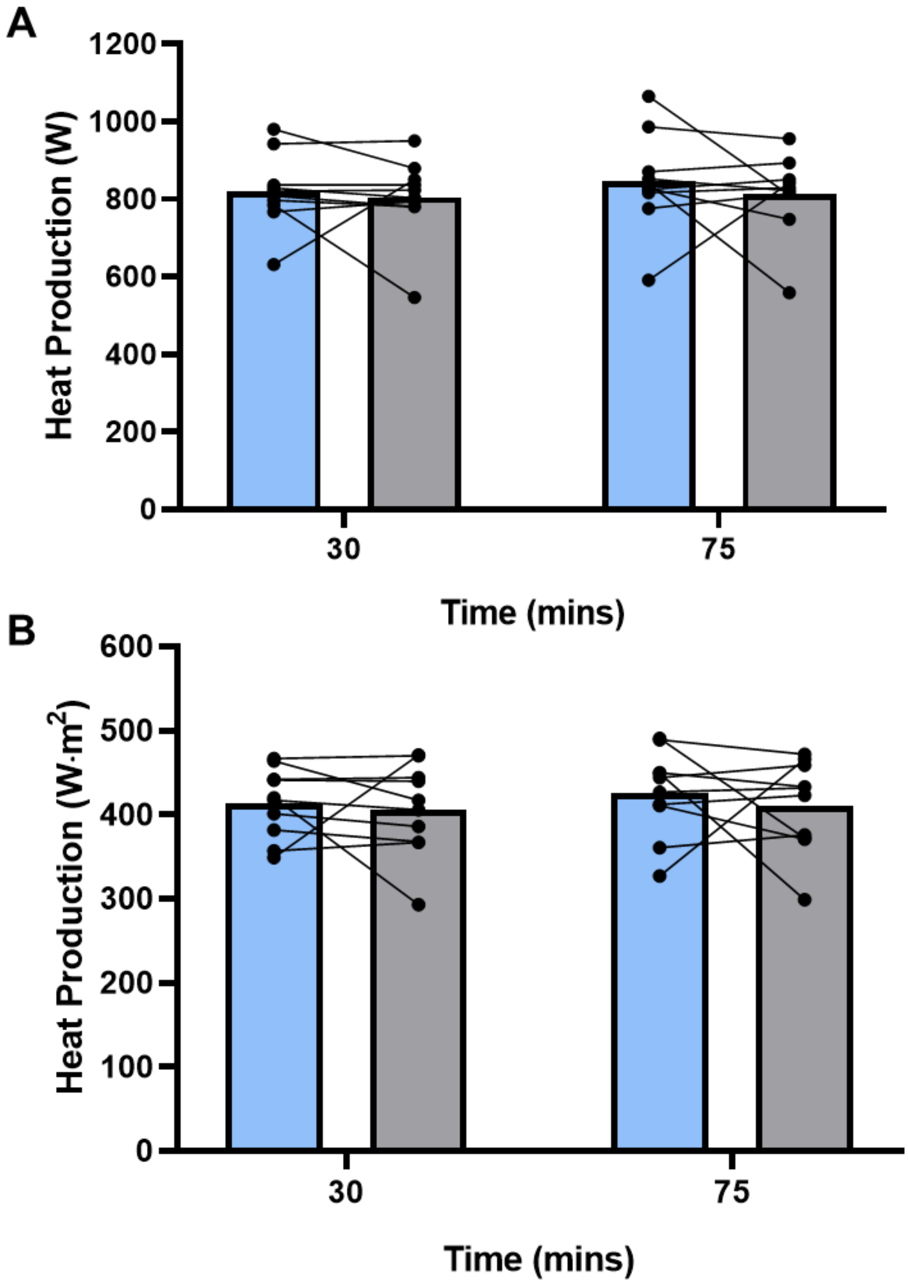

Figure 8.3: A: Differences in absolute heat production in CON and TRE suits at both 30 and 75 minutes. B: Differences in heat production normalised to body surface area in CON and TRE suits at both 30 and 75 minutes. Individual data shown as black dots.

There was no signficant difference in absolute M (W, *p*= 0.26), M (W·m^2, *p*= 0.25), C+R (W, *p*=0.24), C+R (W·m^2, *p*= 0.09), E_{req} (W, *p*= 0.09), E_{req} (W·m^2, *p*= 0.09), E_{max} (W, *p*= 0.11), E_{max} (W·m^2, *p*= 0.09), VO_2 (*p*= 0.11), VCO_2 (*p*= 0.91) within CON or TRE suits at either 30 or 75 minutes (table 8.2).

There was no difference between either of suits at 30 or 75 minutes of exercise in M (W, p= 0.62), M (W·m^2, p= 0.61), C+R (W, p=0.10), C+R (W·m^2, p= 0.96), E_{req} (W, p= 0.95), E_{req} (W·m^2, p= 0.95), E_{max} (W, p= 0.88), E_{max} (W·m^2, p= 0.82), VO_2 (p= 0.65), VCO_2 (p= 0.74) (table 8.2).

Table 8.2: Differences in metabolic rate (M), dry heat loss (C+R), required evaporative heat loss to attain heat balance (E_{req}), the maximal amount of heat loss that can be attained in the given environment (E_{max}), carbon dioxide production (VCO_2), and respiratory exchange ratio (RER) between the CON and TRE triathlon suits at 30 and 75 minutes.

		CONTROL		TREATED	
		Mean	SD	Mean	SD
M (W)	30 minutes	1019	92	1016	119
	75 minutes	1035	114	1023	117
M ($W \cdot m^{-2}$)	30 minutes	526	46	524	65
	75 minutes	534	56	527	64
C + R (W)	30 minutes	167	30	170	31
	75 minutes	161	24	136	52
C + R ($W \cdot m^{-2}$)	30 minutes	86	15	87	15
	75 minutes	83	12	70	26
E_{req} (W)	30 minutes	565	75	558	97
	75 minutes	585	92	600	112
E_{req} ($W \cdot m^{-2}$)	30 minutes	291	38	288	52
	75 minutes	301	44	309	58
E_{max} (W)	30 minutes	199	17	203	18
	75 minutes	195	15	198	16
E_{max} ($W \cdot m^{-2}$)	30 minutes	103	7	105	8
	75 minutes	101	7	102	7
VO_2 (L/min^{-1})	30 minutes	3.06	0.29	3.01	0.32
	75 minutes	3.13	0.33	3.05	0.32
VCO_2 (L/min^{-1})	30 minutes	2.62	0.30	2.58	0.30
	75 minutes	2.62	0.33	2.57	0.30
RER	30 minutes	0.86	0.02	0.86	0.03
	75 minutes	0.84	0.03	0.84	0.03

8.4.4 Gastro-intestinal, Skin & Body Temperature

No difference was found in absolute T_{gi} (p= 0.92) between CON and TRE conditions at any time point (figure 8.4).

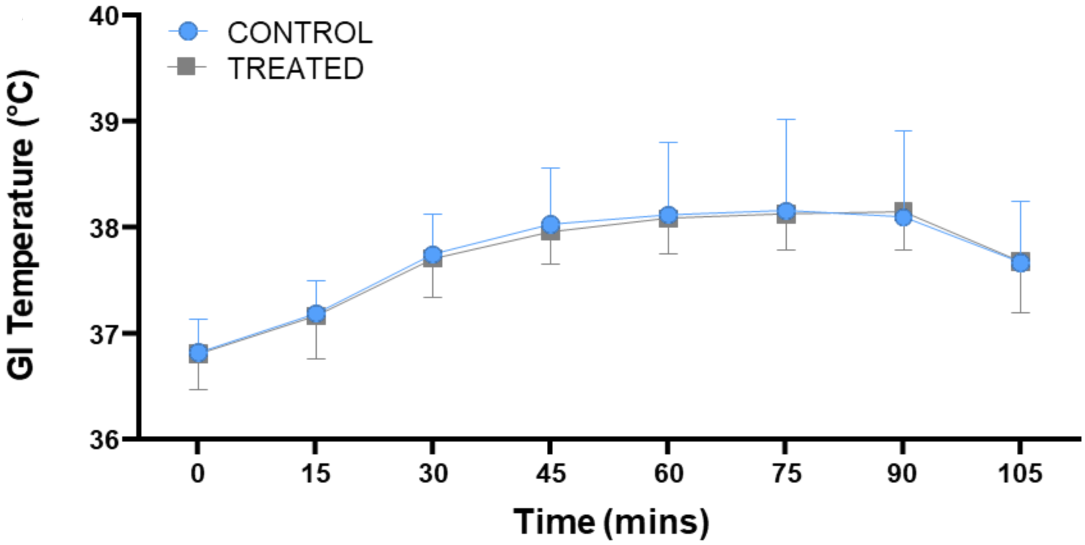

Figure 8.4: Absolute gastro-intestinal temperature at rest, 15, 30, 45, 60, 75, 90 minutes and resting recovery.

There was no difference in absolute $\overline{T}_{sk}$ between CON and TRE conditions at any time point (*p*= 0.82) (figure 8.5).

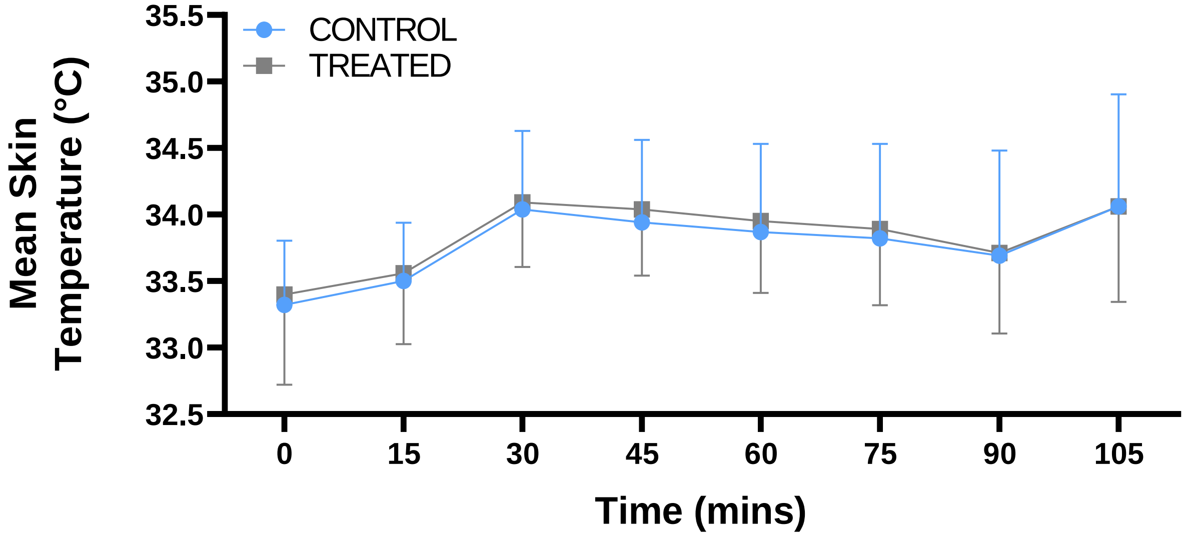

Figure 8.5: Absolute mean skin temperature at rest, 15, 30, 45, 60, 75, 90 minutes and resting recovery.

No difference was seen in T_b (*p*>0.99) between CON and TRE conditions at any timepoint in the protocol (figure 8.6)

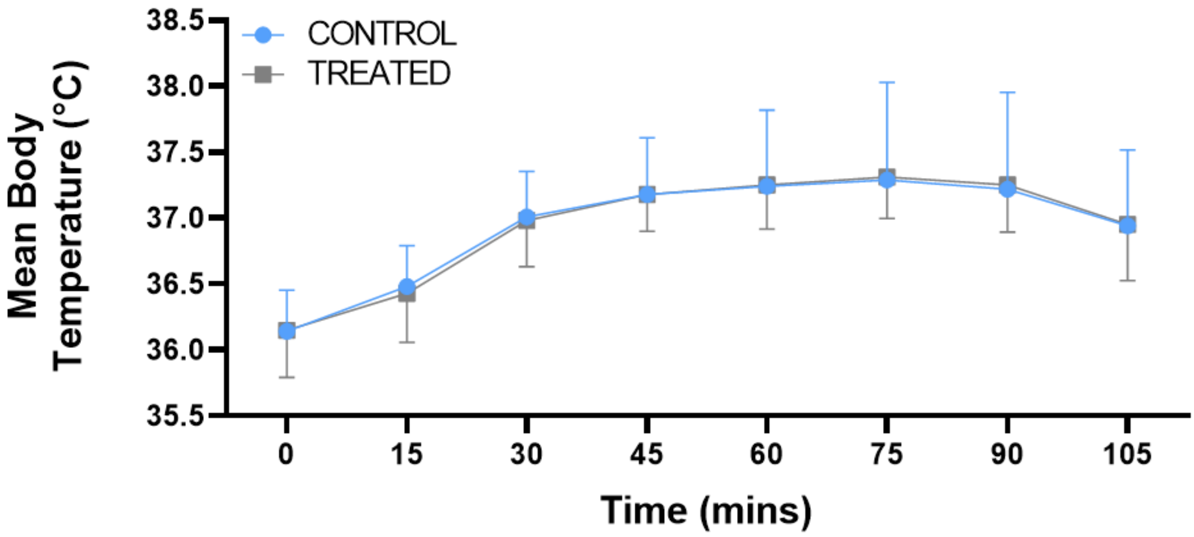

Figure 8.6: Absolute mean body temperature at rest, 15, 30, 45, 60, 75, 90 minutes and resting recovery.

8.4.5 Heart Rate & Perceptual Responses

No difference was found in absolute HR (p= 0.93) between CON and TRE conditions in absolute HR at rest, 15, 30, 45, 60 ,75, 90 mins or during recovery (figure 8.7).

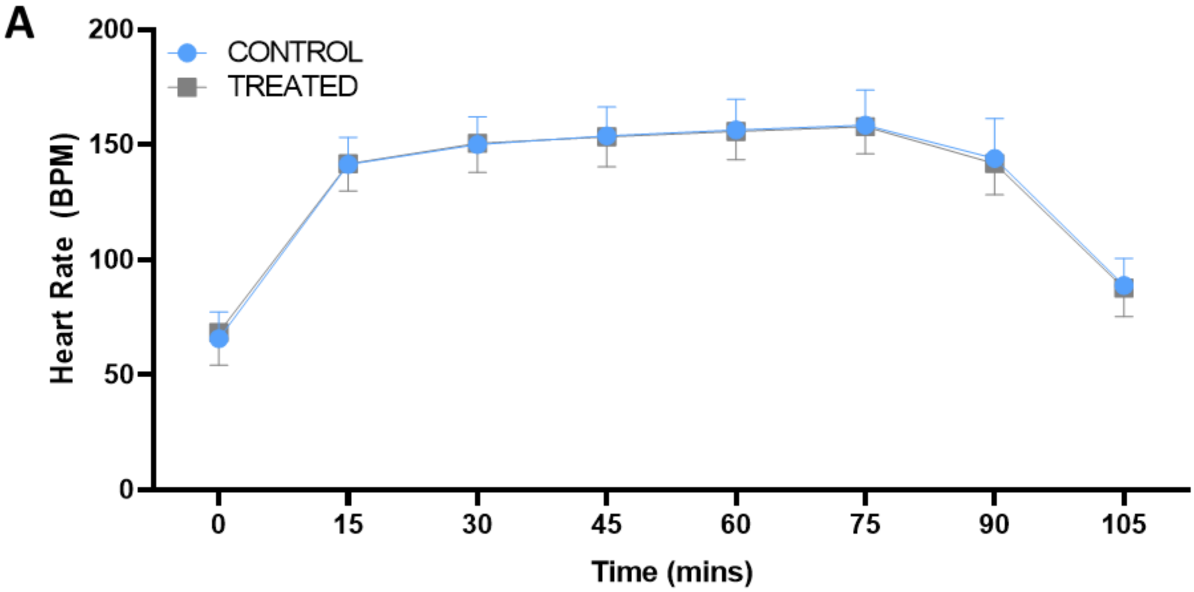

Figure 8.7: Absolute heart rate at rest, 15, 30, 45, 60, 75, 90 minutes and resting recovery.

There was no difference reported in RPE (p=0.95), T_{sens} (p=0.91), T_{comf} (p=0.84) or w_{per} (p=0.32) between the two conditions at any time point (figure 8.8, figure 8.9, figure 8.10 and figure 8.11, respectively).

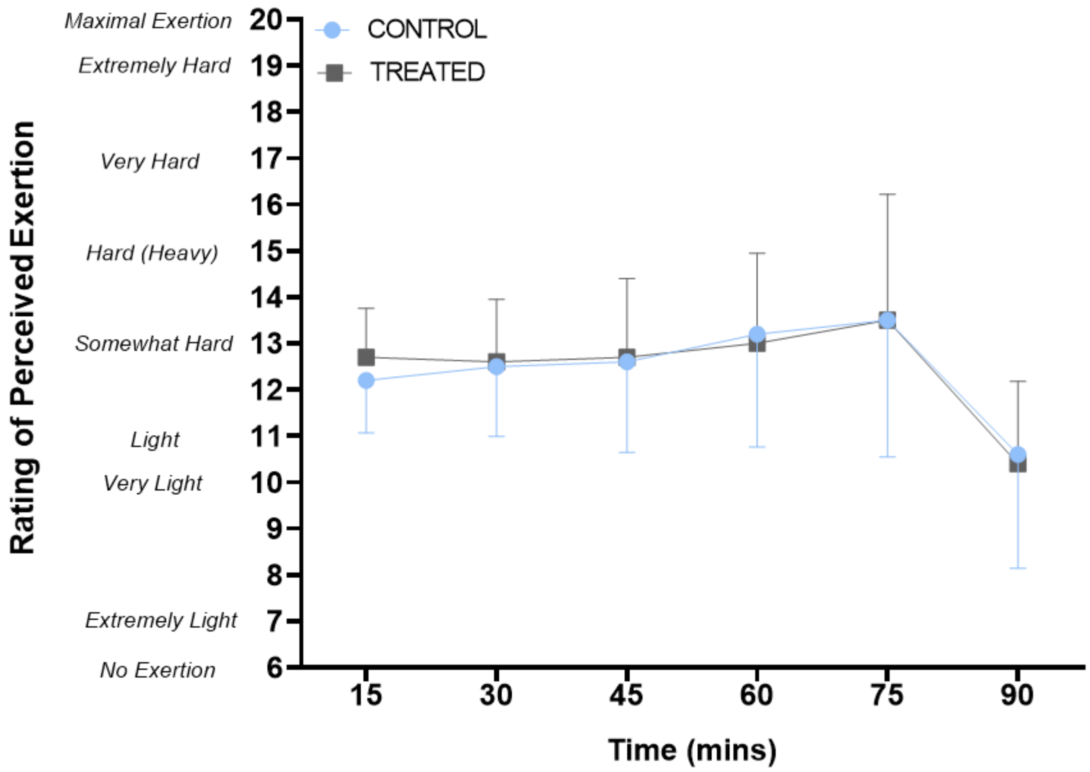

Figure 8.8: RPE at rest, 15, 30, 45, 60, 75, 90 minutes and resting recovery.

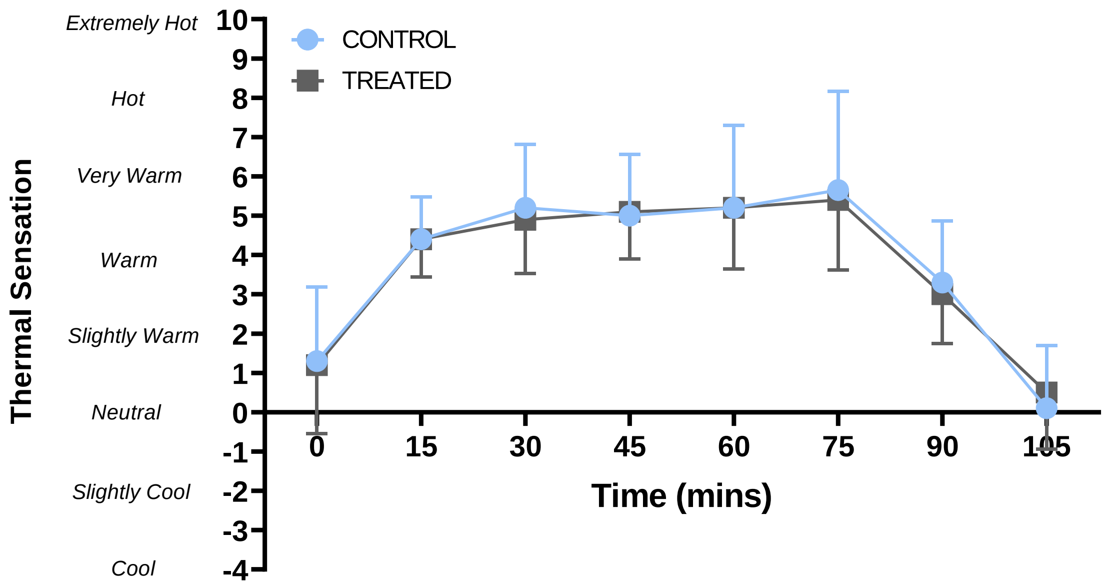

Figure 8.9: T_{sens} at rest, 15, 30, 45, 60, 75, 90 minutes and resting recovery.

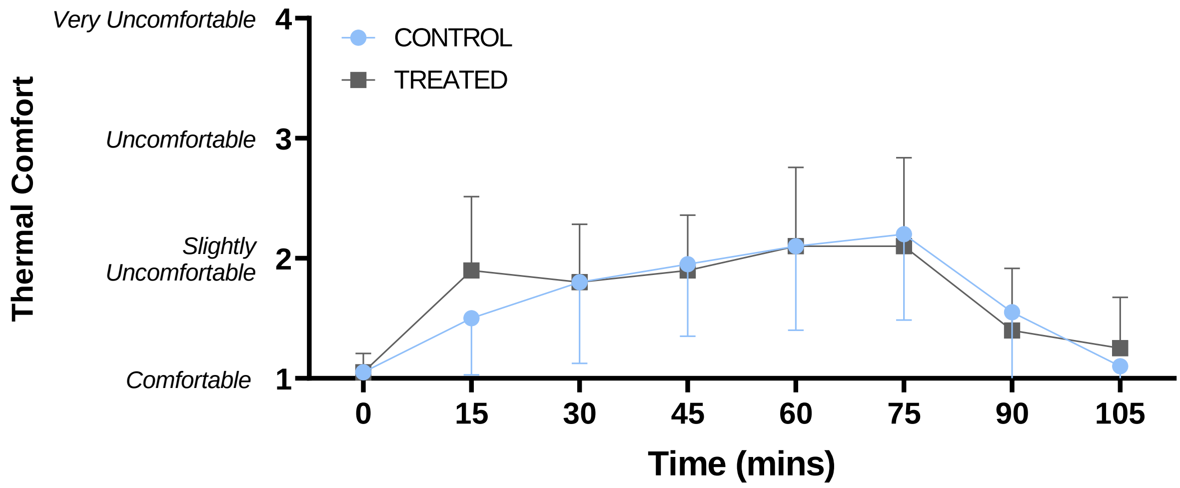

Figure 8.10: T_{comf} at rest, 15, 30, 45, 60, 75, 90 minutes and resting recovery.

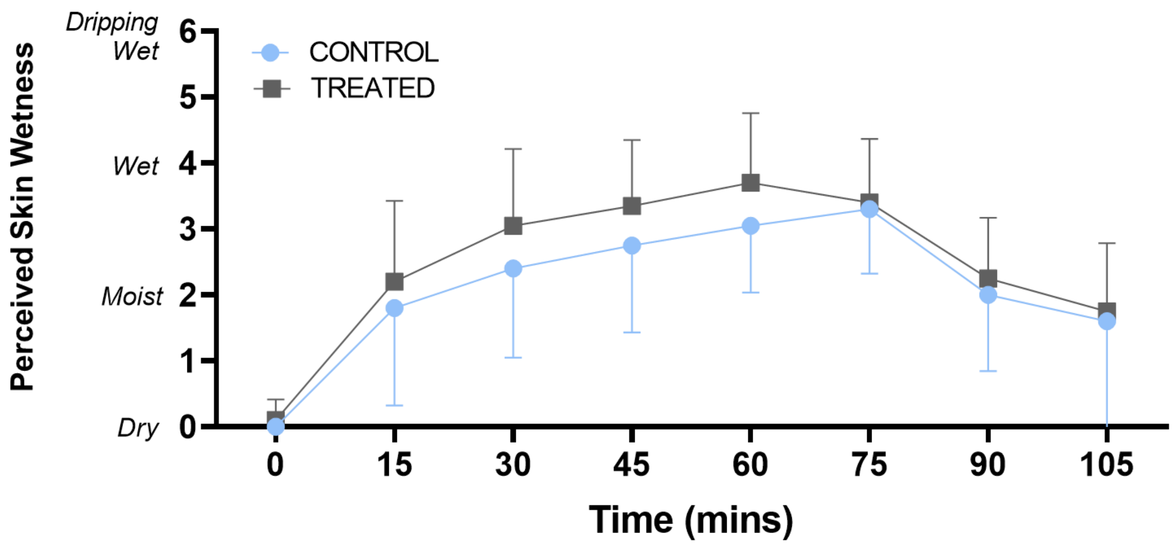

Figure 8.11: w_{per} at rest, 15, 30, 45, 60, 75, 90 minutes and resting recovery.

8.4.6 Fluid Intake & Weight Changes

No difference was observed in SR (CON; 937 ± 151ml/hr, TRE; 956 ± 119ml/hr, p= 0.12), FI (CON; 900 ± 506ml, TRE; 991 ± 474ml, p= 0.11), ΔBW (CON; -1.717 ± 0.278 kg, TRE; -1.753 ± 0.219 kg, p= 0.12) or ΔSW (CON; 36 ± 30g, TRE; 60 ± 48g, all p= 0.23) (table 8.3)

Table 8.3: Individual and mean data for body weight change, suit weight change, sweat rate and fluid intake in CON and TRE conditions.

	Bodyweight Change (Kg)		**Suit Weight Change (g)**		**Sweat Rate (ml/hr)**		**Fluid Intake (L)**	
Participant	CON	TRE	CON	TRE	CON	TRE	CON	TRE
1	-1.754	**-1.980**	**60**	8	1017	**1088**	1.139	**1.356**
2	**-1.511**	-1.446	36	**154**	860	**943**	1.355	**1.438**
3	**-2.102**	-2.079	**101**	64	**1248**	1198	0.892	**0.939**
4	-1.786	**-1.802**	28	**40**	1002	**1023**	0.178	**0.324**
5	-1.364	**-1.445**	14	**60**	758	**848**	1.073	**1.105**
6	-1.415	**-1.658**	41	**48**	813	**952**	0.965	**1.126**
7	**-2.172**	-1.954	3	**129**	**1216**	1195	0.628	**1.056**
8	**-1.779**	-1.756	50	**64**	1020	**1022**	**1.128**	1.116
9	-1.816	**-1.818**	16	**22**	1007	**1014**	0.000	0.000
10	-1.472	**-1.589**	8	**14**	811	**881**	**1.642**	1.449
Mean	-1.717	-1.753	36	60	975	1016	0.900	0.991
SD	0.278	0.219	30	48	167	118	0.506	0.474

8.5 Discussion

The aim of the present study was to evaluate the impact of a polymer-treated triathlon suit on both thermoregulatory and perceptual measures during steady-state exercise. The outcome of the study showed no difference in T_{gi}, $\overline{T}_{sk}$ or T_b or thermal perception during steady-state exercise. It may therefore be suggested that the polymer did not exhibit any significant measurable impact or that it is not functioning in the way it was hypothesised.

Lower $\overline{T}_{sk}$ and potentially a lower T_{gi} was expected to be found if the polymer helped facilitate greater sweat wicking, evaporation and thus, heat loss away from the skin compared to the CON suit. Cuddy et al. (2014) reported a threshold skin temperature of 35-35.5°C needed to be achieved before aerobic capacity was impacted. The reduced skin-to-core temperature observed in 42°C compared to both 18°C and 26°C was concluded to be the driving force of reduced exercise capacity. Linking this to the present study, a mean peak $\overline{T}_{sk}$ of only 34.0°C at 30 to 75 minutes was observed in CON with a 0.2°C mean decrease in $\overline{T}$sk despite no change in power output suggesting there was skin cooling but not enough to impact aerobic capacity or heat loss potential. This was also reflected in TRE where mean peak $\overline{T}_{sk}$ was 34.1°C at 30 minutes with the same 0.2°C mean decrease to 75 minutes. This not only indicates no difference between the two triathlon suits but also that the change in $\overline{T}_{sk}$ did not reach a threshold to inflict stress on the thermoregulatory system to impact the individual's ability to maintain the exercise.

Together with these data, T_{gi} reached a peak of 38.2°C at 75 minutes in the CON suit and a peak T_{gi} of 38.1°C at 60 minutes in the TRE suit. End-trial T_{gi} was 37.7°C for both CON and TRE suits. Both mean skin and core temperatures attained in the present study did not reach a level deemed to be synonymous with heat stress and it appears individuals were able to maintain sufficient sensible heat loss rather than having to rely on insensible or evaporative heat loss where the polymer coating was hypothesised to have been most beneficial. By 30-45 minutes, most participants then saw a plateau in their T_{gi} that was maintained until the exercise intensity dropped at 75 minutes however, there were some individual differences. The highest T_{gi} attained was at 75 minutes in the CON condition for participant 1 at 39.1°C.

The change from baseline was 2.3°C. The same participant only attained a peak T_{gi} of 37.8°C at 75 minutes in the TRE condition with a change from baseline of 1.0°C. Interestingly, they only attained a $\overline{T}_{sk}$ at 75 minutes of 33.1°C and 34.1°C with changes of -0.2°C and 0.0°C from rest in CON and TRE, respectively. These data do not support the findings previously described by Cuddy et al. and suggest T_{gi} still needs to be considered, even when $\overline{T}_{sk}$ does not reach the level deemed to impair exercise capacity. Work by (Cheung, Mclellan 1998) reported that with increased aerobic fitness, individuals can tolerate much higher final exhaustive T_c temperatures (39.3°C ethical cut off) compared to moderately trained (~38.7°C) and this might be the case in the present study for participant 1 and that the higher SR in TRE facilitated more heat loss than in CON, in that one participant, despite all participants being of similar fitness standard.

Heart rate is an indicator of cardiovascular stress as it aims to preserve both blood pressure and oxygen provision during exercise in the heat, it would be expected that any excess strain on the thermoregulatory system would result in a higher HR being observed. No differences were observed in HR between CON and TRE however, individual differences were again apparent. In CON, Participant 1 saw a change in HR of 81bpm from rest to 15 minutes of exercise where HR reached 161bpm HR then continued to rise until its peak at 183bpm at 75 minutes. Whereas, in TRE, HR increased by 71bpm from rest reaching 152bpm at 15 minutes which plateaued and only reached 157bpm at 75 minutes. These data all put together are unusual as it would be expected that as T_{gi} was continuing to increase to levels as high as 39.0°C, a higher HR would result in a large enough skin blood flow and heat transfer away from the body to maintain $T_{gi,}$ especially as there was no change in external workload. However, in this instance, although HR was higher, presumably due to account for the redirection of blood to the skin, T_{gi} did not subsequently reduce. Speculatively, this may be due to ineffective vasodilation, ineffective convection or inhibited evaporation of sweat away from the skin to allow for skin and thus, blood cooling. Apart from this one individual, no other differences were observed between the two conditions, suggesting no difference in the physical demand of the exercise nor thermal strain but obvious individual differences.

Much like the data observed in Chapter 6, environmental conditions in the present study were not enough to elicit any significant heat stress nor differences in heat exchange variables between the CON and TRE triathlon suits. It may be of interest to quantify the evaporative resistance between the two suits on the C-Therm or hot plate to identify if the polymer is truly being ‘activated’ in 28°C or whether, similarly to the results in the present study, no differences are observed. From an industry perspective, although the polymer-treated suit showed no further benefit compared to a control suit, it did not elicit any significantly negative thermoregulatory impact.

There were no significant differences in SR, FI, ΔBW or ΔSW between conditions. If the TRE suit was having any negative impact by withholding the sweat in its fibres, a higher post-exercise suit weight would have been measured. This was not observed. Although not significant, in the TRE condition ΔSW was higher in 8 out of the 10 participants meaning that in these instances the treated suit retained more sweat. The average SR in TRE was 41ml/hr concomitantly with a higher ΔSW by 24g, compared to CON. This may suggest that the polymer coating is wicking more sweat away from the body into the triathlon suit, allowing for a higher degree of evaporative cooling and higher SR. However, this higher degree of wicking evaporative cooling may have not been enough to be clearly significant in the physiological data. It must also be considered that not all the sweat that contributed to a ΔBW would have necessarily remained in the suit or been evaporated. Some of the sweat may have dripped to the floor therefore overestimating the amount of sweat thought to have been evaporated. Further to this, a previous mechanical and thermal analysis of a polymer-coated material has reported increases in its moisture regain (Shin et al. 2005). A higher moisture regain means that the fabric holds more moisture. If this approach is applied to the suit in the present study, it could help explain the larger ΔSW observed for 8 out of the 10 participants in the TRE condition. The higher regain may have been enough to allow marginally more sweat to be held in the suit without it inhibiting either SR, sweat evaporation and heat loss. The polymer coating may have transitioned into its ‘melting’ phase when exposed to sweat, allowing the suit to absorb moisture from the skin. However, due to low convection rates, the sweat and heat may have not evaporated from the skin. Thus, with higher wind speeds, the higher amount of sweat retained in the TRE suit may have been evaporated and provided more evaporative cooling. This means the phase-change back to its solid state may not have occurred resulting in no further release of heat than the CON suit. Unfortunately, there was no way of measuring how the polymer was 'working' during the protocol and how it responded to the different body temperatures, moisture, or environmental conditions. There is also little research looking at polymer coatings on wearable fabrics and their impact on thermoregulation and thermal perception.

In terms of perceptual responses, no difference in either RPE, T_{sens}, T_{comf} or w_{per} was observed. Individual perception and processing of thermal stimuli and potential impacts they impose on exercise capacity remains a complex problem. Individual differences and subjective measures that can be diurnally affected make it difficult to establish any causal denominator and reasoning behind perceptual selection (Vellei et al. 2021). The perceptual data in the present study are not surprising as thermal sensation and comfort are largely driven by skin temperatures and skin wetness (Arens et al. 2006). As no differences in skin temperature were observed between conditions in the present study, the lack of differences in perceptual responses between the CON and TRE suits is understandable. The same applies to w_{per}. As humans do not possess hygro-receptors, the integrative information signalling from both cold receptors and tactile sensations are relied upon to feel any sense of skin wetness (Filingeri et al. 2014). Once more, with no difference in $\overline{T}_{sk}$, this absence of differences between suits in w_{per} was to be expected. The fact the polymer had no negative impact on RPE is positive. The body has been shown to self-selectedly reduce power output in an anticipatory manner to reduce body heat storage, especially in high ambient temperatures. Tucker et al., discovered when cycling in 35°C, over time, self-selected power output was gradually reduced to that observed in 15°C and 25°C due to the thermal afferent signals of warm perception of the environment and the skin (Tucker et al. 2004a). In triathlon, if this were the case, it could potentially lead to underperformance despite conditions posing no threat to thermoregulation. Additionally, reflecting on these results from Tucker et al. it may be that the 28°C ambient temperature selected for the present study may have not been warm enough to elicit significant afferent signal discharge that would impact perceived exertion or any thermal or wetness perception. Upon analysis, it appears the low ambient temperature in the study is a common point across all the variables measured. Further to this, the lack of convection is certainly a big limitation of the present study. In cycling it is the main avenue of heat loss and that experienced by the participants is more than 4x less than what would be experience in real life. It would certainly be interesting to then investigate whether higher convection rates, reflecting a truer cycling velocity, and increased ambient temperature to reduce the skin to core temperature gradient may yield different results or more meaningful differences in thermoregulatory variables. In this environment (28°C, 65% RH), thermoregulation would be more reliant on the evaporation of sweat for cooling and this is where we may see more benefit of the polymer coating. Further study should also focus on characterising the two individual suits' fabrics in terms of moisture regain, moisture liberation, evaporative resistance and thermal conductivity, prior to any further human testing. This may help explain any differences found in the physiological data. If the polymer were then to prove beneficial in the environment it is intended to be utilised in, it would be the gateway to novel textile technology in athlete heat and moisture management.

8.6 Conclusion

The outcomes of this study show similar thermo-physiological and perceptual responses, between a standard tri-suit and a tri-suit coated with a polymer designed to increase sweat evaporation. In these environmental conditions, the polymer exhibited neither a positive nor negative impact on the ability to thermoregulate nor thermal perception of participants. Thus, when deciding on fabrics to incorporate into a triathlon suit, if environmental conditions in a race reflect the conditions used in the present study, a more aerodynamic fabric should be chosen, with a choice made on whether the polymer coating is applied. Further field testing is needed to conclude whether the polymer proves advantageous with different solar loads and more ecologically reflective wind speeds.

Chapter 9

Conclusions, Research Application and Future Recommendations

9.1 Thesis Overview

The focus of this thesis was to characterise fabrics in terms of their aerodynamic and thermal properties to aid the fabric selection decision when designing triathlon suits for athletes competing in middle distance triathlon. It aimed to then identify whether differences in thermo-physiology and thermal perception were apparent during steady-state exercise in the heat. Additionally, whether the differences between the fabrics measured in the characterisation would be enough to tip the aerodynamic-thermoregulatory trade off towards a more thermally optimised triathlon suit. Lastly, to investigate whether there is there any benefit to thermo-physiological variables or thermal perception by directly altering the material properties of triathlon suit fabrics with the addition of a polymer coating. The findings from this thesis can be separated into three main sections; Methods of measurement, thermo-physiological & perceptual variables and aerodynamics.

9.2 Methods of Measurement

To the authors knowledge, there has been no previous attempt to quantify the repeatability in measurements of thermal conductivity and thermal effusivity of sports clothing fabrics using the C-Therm. There also appears to be no current research identifying the differences in thermal conductivity and thermal effusivity between samples measured at >1mm stated by the standard versus a single layer that is more ecologically reflective of the fabric’s impact on the wearer. Using both single layer and multi-layer methods, intra-class correlations showed excellent repeatability in measures of both thermal conductivity and thermal effusivity. However, Bland-Altman analysis showed poor agreeability of the two methods meaning they cannot be used interchangeably but a regression equation can be used to derive one from the other due to the consistency of the under-estimation observed in single layer measurements, compared to multi-layer measurements. Thus, the single layer method should be used if the application is in single layer sports fabrics. Excellent repeatability means that future fabric testing methods using this device need only use 10 single layers. If using the multi-layer methods, measurement of only 2 multi-layer samples is required. It is understood that the C-Therm protocol used in this thesis cannot be used in place of a thermal manikin as the data does not reflect the impact of full body fabric coverage nor does it reflect changes in skin temperature. However, it can provide a valid, repeatable measure of thermal conductivity and effusivity, at a significantly lower cost, that can still be utilised when predicting heat balance using biophysical modelling.

9.3 Thermo-physiology and Thermal Perception

A large portion of this thesis involved investigating whether differences in fabric properties were large enough to elicit measurable differences in thermo-physiology and thermal perception. There were no differences observed between the aerodynamically optimised fabric versus the thermally optimised fabric despite a 0.0140 W/mK difference in conductivity and 30.5 $Ws^{½}/m^2K$ difference in effusivity. It can be therefore concluded that, within the range of values used in the present thesis, two fabrics with a similar magnitude of difference in conductivity and effusivity will not significantly impact thermoregulatory capacity. Lower skin temperatures would be expected if the thermal conductivity of a fabric was large enough as heat would be moved away from the skin more rapidly. This could have subsequently impacted both thermal sensation, through thermoreceptor signalling in the skin, whilst maintaining thermal comfort. However, in this study, thermal comfort was maintained in participants when wearing both suits suggesting the exercise intensity and environmental conditions did not inflict significant heat strain on the body so much that minor differences in perception were observable. This is also reflected in the T_{gi} as they did not reach such a temperature that suggested thermoregulatory stress was apparent. A similar story was observed when comparing the control and polymer treated suits. If the treated suit was wicking away the sweat more efficiently, lower skin temperatures would be expected. Differences in skin wetness perception and subsequent thermal sensation and comfort may have also been altered as the skin is cooled and as the sweat and heat is being evaporated from the skin.

Unlike during the comparison of thermal conductivity, a significant restricting factor when assessing the impact of the control versus the treated suit is the impact of convection. The lack of convection that is known to contribute largely to heat loss may have prevented the presence of significance between the suits in terms of skin temperature, core temperature and certainly perceptual votes.

9.4 Aerodynamics

The lack of differences in thermal impact between the AERO and THERM suits allows a conclusion to be drawn that, in the present environmental conditions, the aerodynamics of a rider should take precedent over thermal optimisation. In this instance, the use of a triathlon suit for elite riders would consist of a main body fabric using fabric ‘H’ and shoulder fabric ‘I’. For the slower speeds, a main body fabric of fabric ‘H’ and shoulder fabric ‘F’. The understanding around the importance of individual optimisation of aerodynamics is becoming more familiar with athletes, coaches, scientists and engineers. Measuring the aerodynamic drag differences in race clothing can now easily be undertaken, albeit at expensive, in a full-size wind tunnel concomitantly with rider position optimisation to find the smallest C_dA that can be maintained for the 90km bike portion of a middle-distance triathlon. The difficulty comes now in trying to further optimise the chosen aerodynamic fabric and its properties to aid heat dissipation whilst also maintaining its essential aerodynamic properties.

9.5 Application of Research

The present research was part funded by Huub Design, a triathlon clothing company. Data from chapter 5 informed the design of triathlon suits used in the Collin’s Cup triathlon for Team Europe in 2021 (https://huubdesign.com/blogs/news/huub-to-give-team-europe-the-edge). The thermally optimised fabric ‘C’ was incorporated as the main body fabric due to its higher potential for heat loss and cooler thermal perception and fabric ‘I’ due to it demonstrating the lower drag force within the high-speed range. Furthermore, using existing or new prototype designs from Huub, fabrics can be characterised in terms of their thermal properties. From this, a model can be created to understand how this relates to the biophysics of heat loss for runners, cyclists and triathletes. This can inform the decision for inclusion of specific fabrics into new triathlon suits or sports clothing. These data can also be paired with aerodynamic data to create optimal ensembles accordingly and can be further individualised with the inclusion of metabolic rates, sweat rates and environmental conditions.

Currently, the data suggests that those fabrics tested in the present thesis, including the fabric that was polymer coated, do not impose a significant thermoregulatory or perceptual strain on individuals. Further research is however required to enable them to understand the interaction and impact of solar radiation and humidity on the current designs as these variables are shown to have a significant impact on heat gain.

9.6 Recommendations for Future Research

9.6.1 Methods of Measurement

Data collected in chapters 4 and 5 were from fabrics used commonly within triathlon clothing. All fabrics appear to possess very similar characteristics which may explain why very little difference was observed between the thermal conductivity and effusivity values. The regression equation that allows for the calculation of either variable from a single layer to a multi-layer or vice versa, was only based on these small amount of data, assuming there is a consistent linear trend when there may not be. Therefore, future research should *further investigate the relationship between measurements of thermal conductivity and thermal effusivity in single layers versus multi-layers in a wider range of fabrics with much higher and lower values of conductivity and effusivity.*

The data collected in chapter 4 were collected within strict environmental limits of 21 ± 1°C with relative humidity of 65 ± 2% however, this does not reflect environmental conditions experienced in hot climates. Therefore, *further studies should investigate the changes in thermal conductivity and effusivity in different environmental temperatures and humidity that more closely reflects racing conditions that have the potential to impose heat strain.* The values that are measured under conditions relating to the current standards may not reflect the values seen under higher temperatures or higher humidity, thus challenging the validity of subsequent thermal modelling.

9.6.2 Thermo-physiology and Thermal Perception

Neither the small differences in thermal conductivity observed between the AERO and THERM triathlon suits nor the difference in evaporative capacity between the CON and TRE suits were enough to elicit significant thermo-physiological or perceptual differences during exercise in 28°C and 65% relative humidity. It may be that, in chapter 6, the environmental conditions simulated meant that the primary avenue of heat loss or the differences in conductivity between the fabrics were not enough to present an observable or measurable impact on thermoregulation. Data from chapter 8 suggests that conduction through fabrics may have not been the primary source of heat loss and that there may have been a larger reliance on evaporative cooling. However, due to the lower convection rates, the potential benefit the polymer is hypothesised to elicit may be blunted as the sweat that is being wicked away from the skin by the polymer is not being evaporated away from the body. *Future research should therefore focus on investigating the impact of different sporting fabrics in higher temperatures, higher absolute metabolic rates (higher level of athlete) and during exercise with more reflective rates of convection.* The polymer-coated suits may have improved sweat wicking ability and, with the right rate of convection, may allow for an increased sweat rate and heat dissipation. *Future studies should aim to investigate the impact of polymer coatings during exercise in higher environmental temperatures, the impact of solar load and heat dissipation with and without the polymer coating and the impact of the polymer coating with ecologically valid rates of convection that match the power output a rider is producing during cycling.* Finally, an *intervention or strategy needs to be developed that mimic the significant benefits attained from ice vests or menthol/ethanol*. Ideally the strategy would have the potential to be employed mid race when athletes are beginning to perceive and experience the physiological impacts of heat stress, after the benefit of pre-cooling has diminished. This could include phase change materials and cooling system like that observed using ammonium nitrate and calcium ammonium nitrate in ice packs. However, these chemicals in their current state cannot be applied directly to the skin.

9.6.3 Aerodynamics

Data from both chapter 6 and 8 show the differences between fabrics elicit no significant effect on thermo-physiology or thermal perception. Thus, when designing sports clothing, it is more beneficial to choose the most aerodynamic fabric rather than the thermally optimised fabric. Once an aerodynamic fabric has been chosen for inclusion, it is still important to understand whether it can be further optimised and how it relates more specifically to the requirements of the sport. For example, during a race, fabrics become wet from the wicking and absorption of sweat into the garment as well as the complete saturation that occurs during the swim phase of a triathlon. Therefore, it is of interest to further *investigate the impact of wet versus dry fabrics on aerodynamic drag.* This may impact the behaviour of air flow over the rider's body as the sweat or water can make the fabric less porous and smoother. Ideally this type of investigation would be undertaken in a full-size wind tunnel as the high sensitivity allows for more precise and valid measurements of small alterations to clothing. Furthermore, chapter 7 showed the importance of an individualised approach to aerodynamics and as airflow is so different between riders due to shape and form drag. It would be of interest to further *investigate whether differences in fabric choices can offset the need to increase hip angle to maintain sufficient heat loss.*

Chapter 4: Establishing a New Testing Standard for the Measurement of Thermal Conductivity and Thermal Effusivity of Single Layer Textiles.

Results\Conclusions: 1. Excellent repeatability for thermal conductivity and effusivity using 10 x single layers and 2 x multi-layer fabric samples. **2.** Significant and practical differences between the single and multi-layer fabric methods**. 3.** Methods cannot be used interchangeably but a linear regression can be used to derive one from the other.

Use this to measure performance fabrics

Chapter 5: Aerodynamic and Thermal Characterisation of Fabrics.

Results/Conclusions: 1. Rough fabrics 'F' and 'I' had the lowest drag coefficient in the 'slow' and 'fast' fabric ranges, respectively. Smooth fabric 'H' had the lowest drag force compared to all other smooth fabrics. **2.** Fabric "C" possessed both the highest thermal conductivity and effusivity.

Translate these fabrics into a triathlon suit and test if there are any thermoregulatory differences

Chapter 6: Differences in Thermo-physiological and Perceptual Responses to Aerodynamically Optimised and Thermally Optimised Triathlon Suits During Prolonged Steady-State Exercise in the Heat.

Results/Conclusions: 1. No differences in heat exchange variables, physiological or perceptual responses to the two optimised triathlon suit designs (AERO and THERM). **2.** Environmental temperature not high enough to elicit large enough stress to the thermoregulatory system, which could have resulted in a higher reliance on evaporative heat loss than dry heat loss. Ecologically valid wind speeds also recommended.

Are any differences in a field setting?

Chapter 7: Quantifying Differences in C_dA and Predicted 90km Time Trial Performance Between Aerodynamic and Thermal Optimised Triathlon Suits on an Outdoor Velodrome.

Results/Conclusions: 1. There are small differences in aerodynamic drag and C_dA between the aerodynamically optimised and thermally optimised suit. **2.** Differences in aerodynamic drag were translated into improved predicted 90km TT performance. **3**. Large individual differences were apparent between responses to the suits. This may be due to the fabrics being very similar in their characteristics.

Can the fabric be directly manipulated to increase heat dissipation or make it more efficient?

Chapter 8: Thermoregulatory and Perceptual Responses to a Polymer Coated Tri-suit Fabric.

Results/Conclusions:

1. No differences in heat exchange variables, thermal perception or physiological responses were found between the control and polymer treated suits. **2.** There may be a problem with 'melting' of the polymer changing the wicking characteristics of the fabric. Additionally, environmental temperature not high enough to elicit large enough stress to the thermoregulatory system. Ecologically valid wind speed also recommended.

Figure 9.1: Flow chat depicting the results and conclusions of each individual experimental chapter in the present thesis.

Chapter 10

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Appendices

Appendix A

Health Screen Questionnaire

Informed Consent

Appendix B

Rating of Perceived Exertion

Thermal Sensation Scale

Thermal Comfort Scale

Skin Wetness Perception Scale

Appendix A

Health Screen Questionnaire

Name or Number ……………………………

Please complete this brief questionnaire to confirm fitness to participate:

1. **At present,** do you have any health problem for which you are:

(a)	on medication, prescribed or otherwise	Yes ☐	No ☐
(b)	attending your general practitioner	Yes ☐	No ☐
(c)	on a hospital waiting list	Yes ☐	No ☐

2. **In the past two years,** have you had any illness which require you to:

(a)	consult your GP	Yes ☐	No ☐
(b)	attend a hospital outpatient department	Yes ☐	No ☐
(c)	be admitted to hospital	Yes ☐	No ☐

3. **Have you ever** had any of the following?

(a)	Convulsions/epilepsy	Yes ☐	No ☐
(b)	Asthma	Yes ☐	No ☐
(c)	Eczema	Yes ☐	No ☐
(d)	Diabetes	Yes ☐	No ☐
(e)	A blood disorder	Yes ☐	No ☐
(f)	Head injury	Yes ☐	No ☐
(g)	Digestive problems	Yes ☐	No ☐
(h)	Heart problems	Yes ☐	No ☐
(i)	Problems with bones or joints	Yes ☐	No ☐
(j)	Disturbance of balance / coordination	Yes ☐	No ☐
(k)	Numbness in hands or feet	Yes ☐	No ☐
(l)	Disturbance of vision	Yes ☐	No ☐
(m)	Ear / hearing problems	Yes ☐	No ☐
(n)	Thyroid problems	Yes ☐	No ☐
(o)	Kidney or liver problems	Yes ☐	No ☐
(p)	Allergy to nuts, alcohol etc.	Yes ☐	No ☐
(q)	Any problems affecting your nose e.g. recurrent nose bleeds	Yes ☐	No ☐
(r)	Any nasal fracture or deviated nasal septum	Yes ☐	No ☐

4. **Has any,** otherwise healthy, member of your family under the age of 50

died suddenly during or soon after exercise? Yes ☐ No ☐

5. Are there any reasons why blood sampling may be difficult? Yes ☐ No ☐

6. Have you had a blood sample taken previously? Yes ☐ No ☐

7. Have you had a cold, flu or any flu like symptoms in the last Month? Yes ☐ No ☐

8. Have you ever tested positive for COVID Yes ☐ No ☐

Women only (delete if not applicable)

8. Are you pregnant, trying to become pregnant or breastfeeding? Yes ☐ No ☐

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

....

....

....

Participant Statement of Informed Consent to Participate in the Investigation Entitled:

"The effect of fabric-optimised tri-suit designs on thermo-physiological parameters during steady-state exercise"

1) I, ________________________________ agree to partake as a participant in the above study.

2) I understand from the participant information sheet (Date ** Version **), which I have read in full, and from my discussion(s) with Philippa Jobling & Steve Faulkner that this will involve me completing baseline fitness testing whereby my height, weight and body composition will be measured. Following this, I will complete a fitness test to exhaustion and 3, 2-hour experimental trials whereby the triathlon suit I will be wearing will be changed.

3) It has also been explained to me by Philippa/Steve that the risks and side effects that may result from my participation are as follows: Although it is extremely unlikely, high intensity exercise has been known to reveal unsuspected heart or circulation problems and very rarely these have had serious or fatal consequences (<1:10,000). You may feel slight discomfort when swallowing the telemetric pill. This may vary from individual to individual but is not a significant discomfort. Unfortunately, if you have any issues swallowing the pill (impairment of the gag reflex, gastrointestinal problems) then you will be excluded from participating in the study. The pill will be passed naturally over time. As you are cycling in the warm conditions, your core temperature will rise. However, the researchers will be monitoring this constantly and if any concerns arise, the test will be terminated. Fingertip or ear lobe blood sampling can cause slight area discomfort and bruising but this is only short lived.

4) I confirm that I have had the opportunity to ask questions about the study and, where I have asked questions, these have been answered to my satisfaction.

5) I undertake to abide by university regulations and the advice of researchers regarding safety.

6) I am aware that I can withdraw my consent to participate in the procedure at any time and for any reason, without having to explain my withdrawal and that my personal data will be destroyed and that my medical care or legal rights will not be affected.

7) I understand that any personal information regarding me, gained through my participation in this study, will be treated as confidential and only handled by individuals relevant to the performance of the study and the storing of information thereafter. Where information concerning myself appears within published material, my identity will be kept anonymous.

8) I confirm that I have had the University's policy relating to the storage and subsequent destruction of sensitive information explained to me. I understand that sensitive information I have provided through my participation in this study, in the form of a health questionnaire, fitness data and blood sample data will be handled in accordance with this policy.

10) I confirm that I have completed the health questionnaire and know of no reason, medical or otherwise that would prevent me from partaking in this research.

11) If appropriate I understand that the information collected about me will be used to support other research in the future and may be shared anonymously with other researchers.

12) It has been explained to me that there may be additional risks arising from the current COVID pandemic. I have read the NTU recommendations for undertaking ‘Research with human participants’ and undertake to abide by the special measures which have been explained to me for this study together with such Government Guidelines that are at the time prevailing.

Participant signature: Date:

Independent witness signature: Date:

Primary Researcher signature: Date:

Appendix B

Borg Rating of Perceived Exertion

6	No Exertion at all
7	Extremely Light
8	
9	Very Light
10	
11	Light
12	
13	Somewhat Hard
14	
15	Hard (Heavy)
16	
17	Very Hard
18	
19	Extremely Hard
20	Maximal Exertion

Thermal Sensation Scale

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

Thermal Comfort Scale

1	Comfortable
2	Slightly Uncomfortable
3	Uncomfortable
4	Very Uncomfortable

Skin Wetness Perception Scale

0	Dry
1	
2	Moist
3	
4	Wet
5	
6	Dripping Wet